LIVE BRAIN-COMPUTER CINEMA PERFORMANCE

JOINT DISSERTATION WITH PORTFOLIO
SUBMITTED FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
AT THE SCHOOL OF SIMULATION AND VISUALISATION
GLASGOW SCHOOL OF ART

POLINA ZIOGA

MAY 2017

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MAY 2017

UNDER THE SUPERVISION OF
DR PAUL CHAPMAN
SCHOOL OF SIMULATION AND VISUALISATION, GLASGOW SCHOOL OF ART
PROF MINHUA EUNICE MA
SCHOOL OF ART, DESIGN AND ARCHITECTURE, UNIVERSITY OF HUDDERSFIELD
PROF FRANK POLLICK
SCHOOL OF PSYCHOLOGY, UNIVERSITY OF GLASGOW

DECLARATION

I, Polina Zioga, declare that this thesis, consisting of joint dissertation with portfolio, submitted for the degree of Doctor of Philosophy is entirely my own personal work, including relevant contributing work that is directly attributable to the author, except where explicit reference is made to the contribution of others. The thesis meets the regulations stated in the *Research Degrees Guidance* of the Glasgow School of Art and the *Regulations for Degrees, Diplomas and Certificates Awarded in Conjuction with The Glasgow School of Art* of the University of Glasgow and has not been submitted for any other academic award.

PhD Candidate: Polina Zioga

Primary Supervisor: Dr Paul Chapman

In a *post-truth* era, this thesis is dedicated to those that promote, individually or collectively, information and practices based on evidence, in the spirit of peacefully protecting equality, diversity and human rights.

ABSTRACT

Artists have been interested in the human brain's anatomy and physiology since at least the Renaissance, while in the twentieth century, the technological revolution enabled them to include in their practices methods adopted from the sciences and engineering, like Brain-Computer Interfaces (BCIs). The use of BCIs originates in the 1960s, with musicians, performers and artists being amongst the pioneers in the design of BCI applications. In recent years, after a period of little progress in the field, the introduction of new commercial-grade Electroencephalography (EEG)-based BCIs has led to a phenomenal development of applications across health, entertainment and the arts. At the same time, in the fields of neuroscience and experimental psychology, has emerged a new increasing interest in the mechanisms and processes of the interaction between multiple subjects and their brain-activity, referred to as multi-brain interaction. Although the vast majority of the applications in the arts and entertainment use the brain-activity of a single participant, there are earlier as well as an increasing number of recent examples that involve the simultaneous interaction of more than one participants, mainly in the context of installations, computer games and music performances.

This dissertation investigates the use of multi-brain EEG-based BCIs in the context of live cinema and mixed-media performances, which is a rather new field bearing distinct characteristics. Using an interdisciplinary approach, a critical overview of the development of the main BCI hardware, software and modes of interaction is presented and relevant works are examined. The aim is to identify the neuroscientific, computational, creative, performative and experimental challenges of the design and implementation of multi-brain BCIs in mixed-media performances, which leads to the main research question:
What might be an effective model for the simultaneous multi-brain interaction of performers and audiences using EEG-based BCIs in the context of live cinema and mixed-media performances?

In order to address the main research enquiry, scientific and practice-based methodologies were combined and a new passive multi-brain EEG-based BCI system was developed. The system was further implemented in the context of the research case study, *Enheduanna – A Manifesto of Falling*, the first demonstration of a live brain-computer cinema performance (CCA Glasgow 29-31 July 2015). This new work enabled for the first time the simultaneous real-time interaction with the use of EEG-based BCIs of more than two participants, including both a performer as well as members of the audience in the context of a mixed-media performance. The analysis of the participants' data has most interestingly revealed a correlation between the elements of the performance, which they identified as most special, and their indicators of attention and emotional engagement that were increased during the last two scenes, when their brain-activity was interacting with the live visuals, proving the efficiency of the interaction design, the importance of the directing strategy, dramaturgy and narrative structure. Accordingly, the original contributions of the research include the new passive multi-brain EEG-based BCI system, the live brain-computer cinema performance as a new format of performative work and as a complete combination of creative and scientific solutions. This dissertation also presents the new trends in the field, such as hybrid BCIs, the combination with virtual and mixed reality systems, together with future work.

RELEVANT CONTRIBUTING WORK

PEER-REVIEWED PUBLICATIONS

Material from Chapters 3, 4 and 5 has been published in:

Zioga, P., Chapman, P., Ma, M. and Pollick, F. 2016. Enheduanna – A Manifesto of Falling: first demonstration of a Live Brain-Computer Cinema Performance with multi-brain BCI interaction for one performer and two audience members. *Digital Creativity*. [Online]. [Accessed: 14 December 2016]. Available at: http://dx.doi.org/10.1080/14626268.2016.1260593.

Material from Chapters 2 and 3 has been published in:

Zioga, P., Chapman, P., Ma, M. and Pollick, F. 2015. A Hypothesis of Brain-to-Brain Coupling in Interactive New Media Art and Games Using Brain-Computer Interfaces. In: Göbel, S., Ma, M., Baalsrud Hauge, J., Oliveira, M.F., Wiemeyer, J., Wendel, V. eds. *Serious Games First Joint International Conference, JCSG 2015, Huddersfield, UK, June 3-4, 2015, Proceedings*. LNCS 9090. Berlin Heidelberg: Springer-Verlag, 103-113. DOI: 10.1007/978-3-319-19126-3_9. Print ISBN: 978-3-319-19125-6. Online ISBN: 978-3-319-19126-3.

Material from Chapters 1, 2 and 3 has been published in:

Zioga, P., Chapman, P., Ma, M. and Pollick, F. 2014. A Wireless Future: performance art, interaction and the brain-computer interfaces. In: Sa A., Carvalhais M., McLean A. eds. (2015) *Proceedings of ICLI 2014 - INTER-FACE: International Conference on Live Interfaces, 19-23 November 2014, Lisbon, Portugal*. Lisbon: Porto University, CECL & CESEM (NOVA University), MITPL (University of Sussex), 220-230. ISBN: 978-989-746-060-9.

PERFORMANCES

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LECTURES AND TALKS

Zioga, P. 2016. *Art, Science and The Brain: A Personal Perspective*. Royal Conservatoire of Scotland, Exchange Talks Programme, Fyfe Lecture Theatre, 7 November 2016.

Zioga, P. 2016. *Is It Art or Is It Science? A Journey Inside the Brain*. Glasgow School of Art, BA (Hons) Interaction Design, Barnes Building Lecture Theatre, 23 February 2016.

Zioga, P. 2015. *Real-Time Passive Multi-Brain Interaction in 'Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance*. University of Glasgow, School of Psychology, Perception Action Cognition Lab, 13 November 2015.

Zioga, P. 2014. *The use of brain-computer interfaces and application development in real-time audio-visual performances*. Glasgow School of Art, Digital Design Studio, 10 April 2014.

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ABBREVIATIONS

ANOVA	Analysis of Variance
API	Application Programming Interface
BBI	Brain-to-Brain Interface
BCI	Brain-Computer Interface
CNS	Central Neural System
COM	Communication
CT	Computed Tomography
DJ	Disc Jockey
DIY	Do It Yourself
DSA	Digital Subtraction Angiography
ECG	Electrocardiography and Electrocardiographic
EEG	Electroencephalography
EGTS	Eye-Gaze Tracking System
EMG	Electromyography and Electromyographic
EOG	Electrooculography and Electrooculographic
ERPs	Event-Related Potentials
FIR	Finite Impulse Response
fMRI	functional Magnetic Resonance Imaging
GUI	Graphical User Interface
HCI	Human-Computer Interaction
Hz	Hertz
ISC	Intersubject Correlation
LSL	LabStreamingLayer
MI	Motor Imagery

MRI	Magnetic Resonance Imaging
OSC	Open Sound Control
PAG	Periaqueductal Grey
PNS	Peripheral Nervous System
SDK	Software Development Kit
SSVEP	Steady State Visual Evoked Potential
TMS	Transcranial Magnetic Stimulation
UDP	User Data Protocol
VEP	Visual Evoked Potential
VJ	Visual Jockey
VR	Virtual Reality
VRPN	Virtual Reality Peripheral Network
μV	Microvolts

As you set out for Ithaca
hope the voyage is a long one,
full of adventure, full of discovery.
Laistrygonians and Cyclops,
angry Poseidon—don't be afraid of them:
you'll never find things like that on your way
as long as you keep your thoughts raised high,
as long as a rare excitement
stirs your spirit and your body.
Laistrygonians and Cyclops,
wild Poseidon—you won't encounter them
unless you bring them along inside your soul,
unless your soul sets them up in front of you. […]

C. P. Cavafy's *Ithaca* 1910-1911 (Keeley and Sherrard 1992)

1. INTRODUCTION

This research focuses on the use of new innovative systems, the multi-brain Electroencephalography (EEG)-based Brain-Computer Interfaces (BCIs), in mixed-media performances and introduces a new type of interactive performative work combining live cinema and the use of BCIs, the *Live Brain-Computer Cinema Performance*.

The BCIs are systems that provide the brain with a non-muscular communication and control channel for sending messages and commands to the external world (Wolpaw et al. 2002, 768). They were initially developed in the 1960s and after a period of very little progress, they have remerged during the past 15 years as a result of accelerating advances in neuroscience, biomedical and computer engineering, leading to a phenomenal development of applications across health, entertainment and also the arts. The result is an increasing number of new works and forms of creative practices. From the clinical-grade, high-cost, wired systems for single-users, to the commercial-grade, low-cost, wireless systems for multi-users, a new interdisciplinary field has been established that brings together computational neuroscience, experimental psychology, brain-computer interface design, interactive and digital media and performing arts. Thus, it is necessary to investigate the impact of the development of these new technologies, the characteristics and methodologies of their design, implementation and use in the frame of interdisciplinary creative practices, which present significant challenges and also opportunities.

This chapter presents an introduction to the research background, the interdisciplinary practices at the intersection of art, science and the brain, my personal involvement and perspective through my previous practice, whereas EEG and the BCIs are discussed as a new opportunity. Additionally, this chapter presents the challenges and the research problem, outlining the main research question and aims, together with the significance of the currently discussed study, the research design and the thesis outline.

1.1 ART, SCIENCE AND THE BRAIN: AN INTERDISCIPLINARY PRACTICE AND RESEARCH

Artists have been interested in the human body and brain anatomy and physiology, experimenting at the intersection of art and science and technology, since at least the Renaissance and the work of Leonardo da Vinci (1452–1519). da Vinci was not only an artistic genius, but he also contributed in many areas of science and technology, while his pioneering research resulted in significant discoveries in neuroanatomy and neurophysiology (Pevsner 2002, 217). In the *Anatomical Study of the layers of the brain and scalp* (Figure 1.1) the main drawing shows the profile of a human head with the layers covering the brain, whereas to the left these are compared to the layers of an onion. Below there is a second drawing of the central nervous system and the cranial nerves. While, in both, the three cerebral ventricles are depicted, following the medieval tradition of illustration (Pevsner 2002, 218).

Following Renaissance, during the 17th century and the Age of Rationalism, the arts and sciences were divided as separate and distinct fields. Science and technology have been regarded as the 'real pursuit of truth', whereas the arts were seen more as entertainment (Miller 2011, 2). In the twentieth century, with avant-garde and modernity, a new dialogue has commenced. Previous researchers have examined the parallel biographies and work of major catalysts of the era, like Albert Einstein (1879-1955) and Pablo Picasso (1881-1973), bringing into light how the former's scientific work was influenced by his 'aesthetic discontents', whereas the latter was influenced by the new scientific and technological developments of the time, such as the X-rays, photography and cinema, mathematics and geometry. Wassily Kandinsky (1866-1944), Marchel Duchamp (1887-1968), the Futurists, Salvador Dali (1904-1989), Piet Mondrian (1872-1944), Kazimir Malevich (1878-1935) and others followed.

As the 20th century progressed, artists engaged with the technological revolution, using as a source of material their own bodies together with machines and bio-data feedback. They combined their creative methodologies and practices with the use of scientific and engineering methods and tools, giving birth to new interdisciplinary practices and presenting installations, interactive works and performances.

A prominent example is Stelarc, a performance artist using biotechnology, robotics, virtual reality systems and the Internet, probing and acoustically amplifying his own body (Stelarc 2014). During the *Telepolis* event that took place in November 1995, a series of sensors were attached to different parts of his body, connected to a computer with a 'touch screen interface & muscle stimulation circuitry, and via the computer to the World Wide Web' (Smith 2005). Through a 'performance website' (Figure 1.2) the audience remotely viewed, accessed, and actuated the body by clicking/sending commands to the computer interface located together with Stelarc at the performance site. The result was causing the body to move involuntary (Stelarc 1995).

FIGURE 1.1 da Vinci, L. c.1490. *Anatomical Study of the layers of the brain and scalp*. [Pen, ink and red chalk on paper]. At: Windsor Castle, RL 12603 recto, The Royal Collection, Her Majesty Queen Elizabeth II.

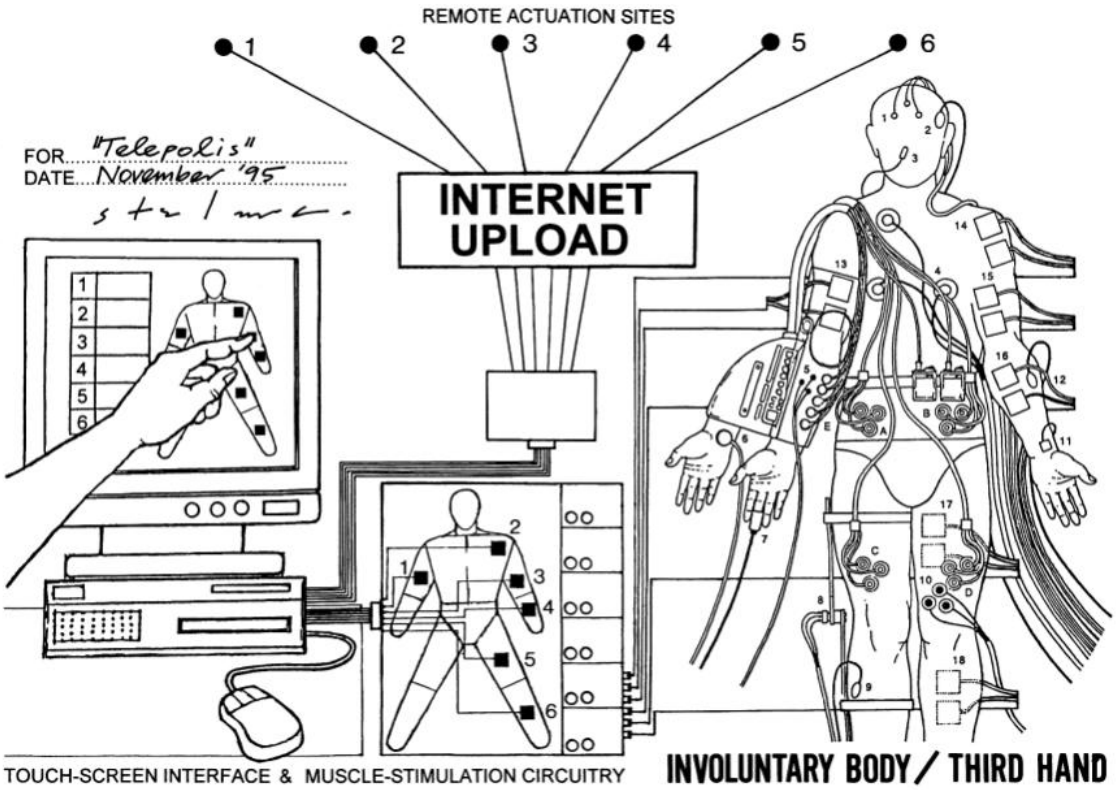


FIGURE 1.2 Stelarc. 1995. *Fractal Flesh*. [Online image]. (Stelarc 2016).

Other artists, in an attempt of visualising, but also conceptualising the human brain's structure and functions, have engaged with brain-imaging techniques, like Computed (or Computerised) Tomography (CT) that produces 'images of cross sections of the human body' combining computer-processed data from X-rays taken 'along a large number of lines through the cross section' (Herman 2009, 2) and Magnetic Resonance Imaging (MRI) scan that produces images of the anatomy and the physiological processes of the body using strong magnetic fields, radio waves and field gradients.

In 2011, in GV Art gallery (London, UK), the exhibition *Art & Science Merging Art & Science to Make a Revolutionary New Art Movement* brought together eleven artists that collaborated with scientists. Amongst them was Susan Aldworth, who underwent a functional Magnetic Resonance Imaging (fMRI) scan at Queen Square Imaging Centre in London, in order to realise her work *Cogito Ergo Sum 3*, a series of 20 digital (giclee) prints (Figure 1.3).She describes her work as 'a self-portrait located in a moment of time'. And she continues describing her creative methodology (Aldworth 2011, 6):

> *I scratched into the scan emulsion and added images and words into the fMRI sequence to try to connect these medical images to my daily experience. […] Cogito Ergo Sum 3 visualizes what an MRI scan might look like if it could show what was going on in my imagination as well as the physical structure and function of my brain.*

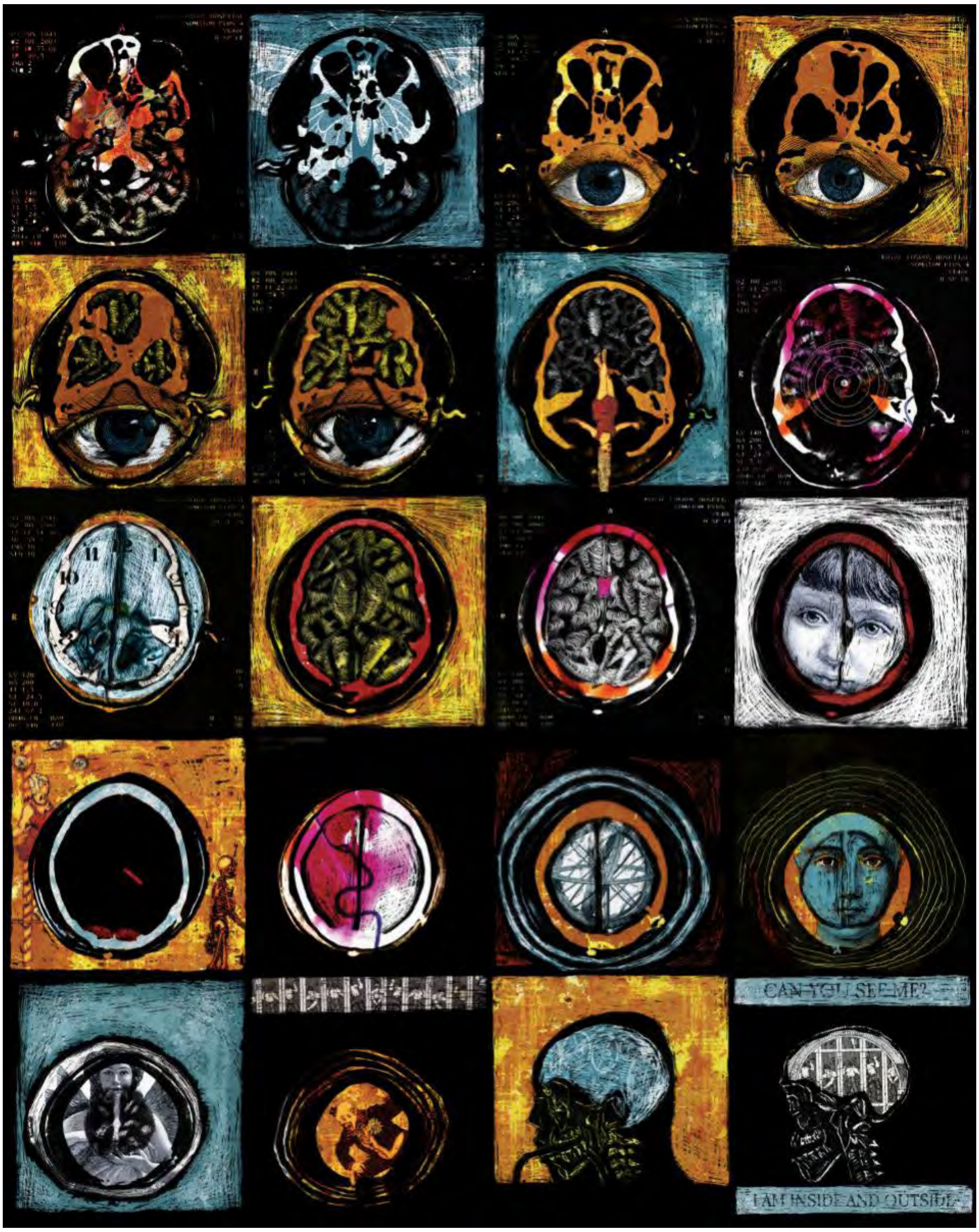


FIGURE 1.3 Aldworth, S. 2011. *Cogito Ergo Sum 3*. [Mixed-media]. (Aldworth 2011, 7).

Pleasure/Pain, by Annie Cattrell and Professor Morten L. Kringelbach (Figure 1.4), 'models the structural connections of a small region in the brainstem, the periaqueductal grey, as revealed by a method of magnetic resonance imaging called diffusion tensor imaging. The piece explores the links that might be activated during sensations of pleasure and pain.' (Cattrell and Kringelbach 2011, 15). The periaqueductal grey (PAG) is located in the brainstem and is the control centre for suppressing the feeling of pain through communication ('oscillations of neural activity') and coordination with other areas of the brain. Cattrell visualised this activity and process of communication, creating a model with the use of 'selective laser sintering', a rapid prototyping method.

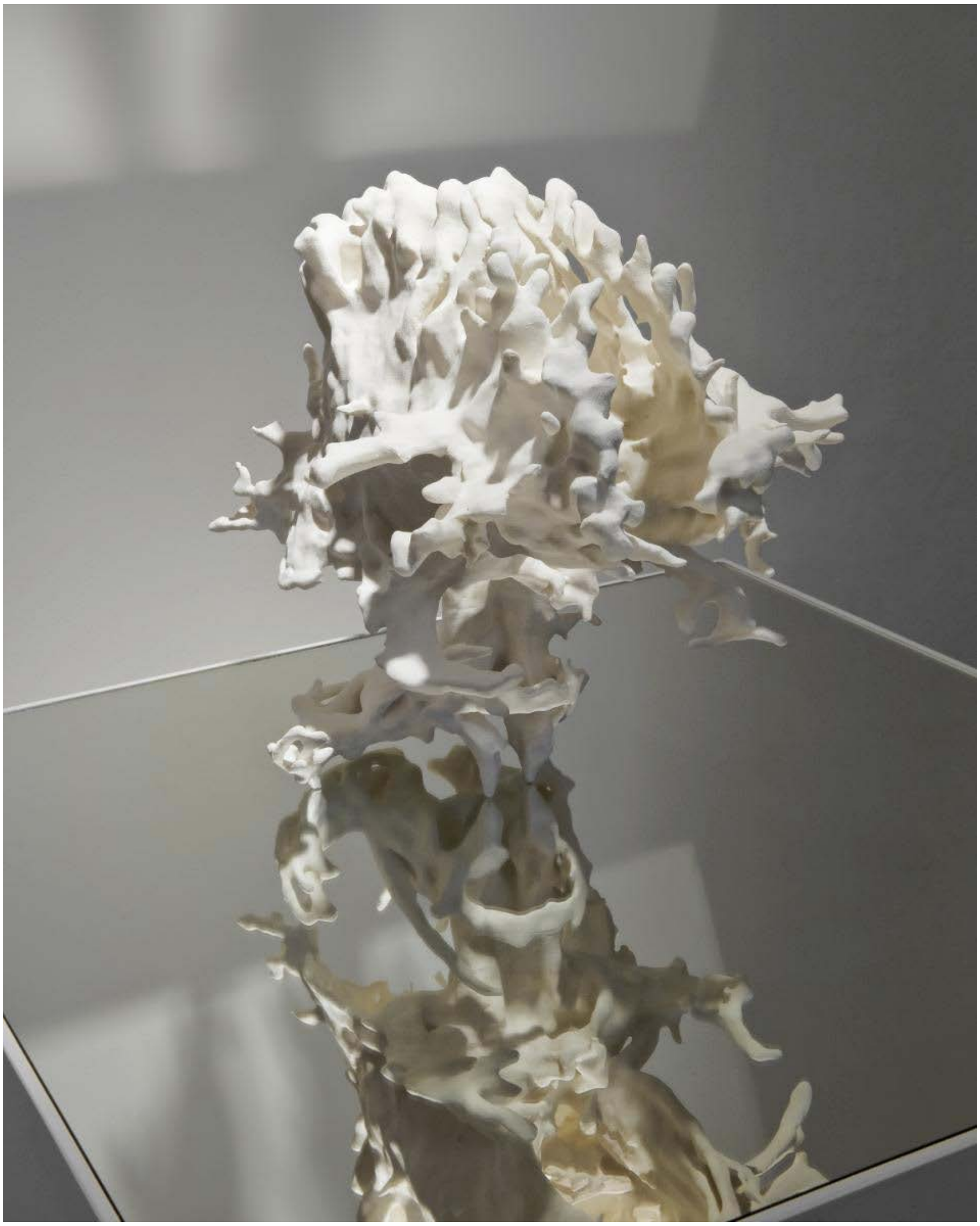


FIGURE 1.4 Cattrell, A. and Kringelbach, M.L. 2011. *Pleasure/Pain*. [Sculpture]. (Cattrell and Kringelbach 2011, 16).

Katharine Dowson presented the work *Memory of a Brain Malformation*, which was originally commissioned by the Institute of Neuroscience of the Newcastle University (Figure 1.5). She defines her interdisciplinary methodology and refers to her work, a sculpture showing her cousin's brain arterial branch that fed the tissues and tumour before the laser surgery, as 'a problem solving exercise of digital transfer from large angiogram films into modern 3D laser technology used in glass etching.' (Dowson 2011, 18).

Amongst the brain-imaging techniques used by artists are also the Electroencephalography (EEG) and the Brain-Computer Interfaces (BCIs), which are the focus of the currently discussed research and will be presented further along in this chapter.

FIGURE 1.5 Dowson, K. 2006. *Memory of a Brain Malformation*. [Sculpture]. (Dowson 2011, 19).

1.1.1 A PERSONAL PERSPECTIVE

From the previous examples of artists and works, it is already evident that art and science, art and research, are no strange couples. They share common grounds, amongst which are also the quest for meaning and the quest for originality. My own personal motives and creative practice are found at the intersection of art, science and the brain for a dual reason. On the one hand, I have been equipped with an interdisciplinary background and studies, first in sciences and then in arts. On the other hand, the quest for meaning and originality have guided my creative work for over ten years towards the field of arts and the brain. Starting from an autobiographical point of reference and using new, digital media and brain-imaging techniques, I have explored themes like corporeality, metamorphosis, time and decay, while gradually shifting from the personal to a collective dimension. In other words, I wanted to work with media consistent to a topic that would have a particular meaning for me and would fuse the different elements of my life and background into something new.

More in particular, in 2005 I commenced using a series of MRI scans of my own brain, taken as part of a medical investigation of a health problem I had encountered a few years earlier. My methodology in the first body of artworks (Figure 1.6), entitled *April 1997* (2005), involves a simple but consistent to its purpose visual exploration of the autobiographical material. I scanned the images and then digitally intervened by highlighting and visually manipulating certain anatomical structures, mainly the brain ventricles in the centre of the scans that look like different types of Lepidoptera. The result is a series of hybrid images of my brain with butterflies and fireflies that function as an allegory of metamorphosis, psychosomatic transformation and also personal catharsis. I continued to explore and further develop these notions, experimenting also with digital

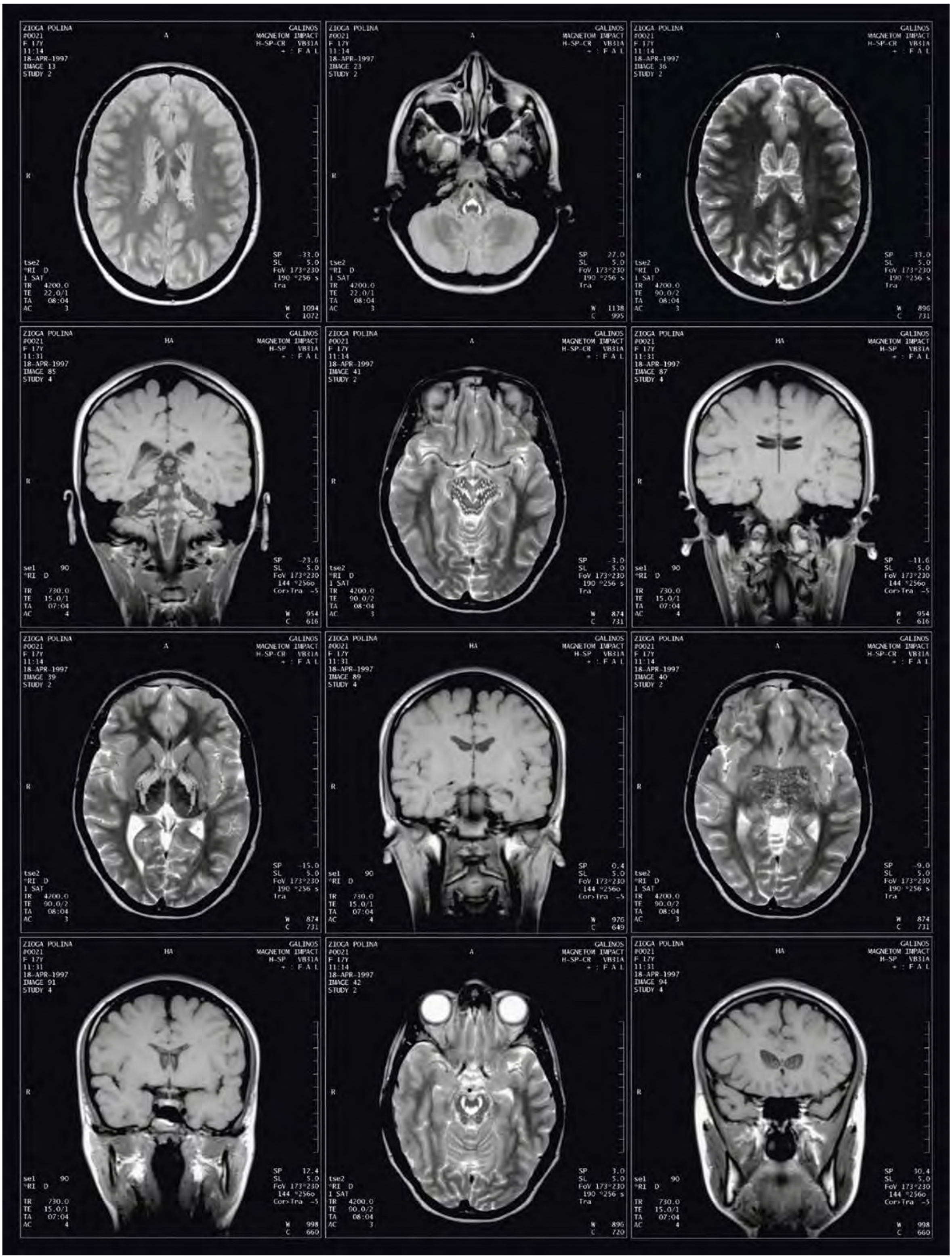


FIGURE 1.6 Zioga, P. 2005. *April 1997*. [Lambda prints, 12x 50cm x 50cm, edition of 3].

photography and other media, like in the diptych *Anatomy of a metamorphosis* (2006). The particular work makes reference to Rembrandt's painting *Anatomy lesson of Dr. Jan Deijman* (1656). The examination of the brain is isolated and appropriated as I perform my own visual anatomy lying down in an environment of saturated colours and covered by a quasi-natural evergreen grass, seemingly discharged of the personal narrative burden. At the same time, the boundaries between the inside and the outside are being virtually abolished, turning the invisible into the visible (see also http://www.polina-zioga.com/prints/2006-anatomy-of-a-metamorphosis). A similar approach is taken also in the subsequent triptych *Memento mori* (2007a), which however focuses more on the ideas of time and decay (see also http://www.polina-zioga.com/prints/2007-memento-mori). Following this initial series of digital prints, I continued working with MRI scans of my brain, adding time-based and 3D-animation techniques and methodologies, creating video-artworks, like *I dreamt I was a butterfly* (2007) titled after the homonymous story by the Chinese philosopher Zhuangzi (4th century B.C.E.). Here, central figure and protagonist is the butterfly, symbol of the soul and psychosomatic transformation, a small Odysseus that awakes inside the body and takes us in a virtual voyage (see also http://polina-zioga.com/video-art-installations/2007-i-dreamt-i-was-a-butterfly). Whereas, by adding the element of the 3D space, I created video-installations, like *1997-2007* (2007b) (see also http://polina-zioga.com/video-art-installations/2007-1997-2007). On the one side of the space is found the previous series of manipulated MRI scans and on the opposite side the hybrid brain ventricles/butterfly-like shapes are projected as if mirrored, having gained colour and motion, almost as if coming to life (Figure 1.7).

FIGURE 1.7 Zioga, P. 2007b. *1997-2007*. [Video-installation, 200cm x 150cm, lambda print, video projector, dvd-PAL, colour, audio mute].

I continued by using and creatively experimenting with other brain-imaging techniques and more specifically the Digital Subtraction Angiography (DSA), which permits high-resolution imaging of the blood vessels of an organ – in this case my brain - with the injection of a radio-opaque contrast agent. My creative approach consists of scanning, thoroughly cutting the arteries and reassembling

FIGURE 1.8 Zioga, P. 2007c. *Brain-angiography 1*. [Lambda print, 169cm x 135cm, edition of 4].

them as large digital collages and often deconstructed compositions, like a digital embroidery and reverse embroidery. The works realised with this technique and methodology include: two series of digital prints created between 2007 and 2011 and entitled *(Un)hidden layers* (Figure 1.8; see also http://polina-zioga.com/prints/2007-2011-recent-works) and *Fragments* (see also http://polina-zioga.com/prints/2011-fragments); video-artworks (Figure 1.9); video-installations that allow the body of the visitor/spectator to enter the space; and audio-visual performances that allow the body of the performer to interact with the digital projected environment (Figure 1.10).

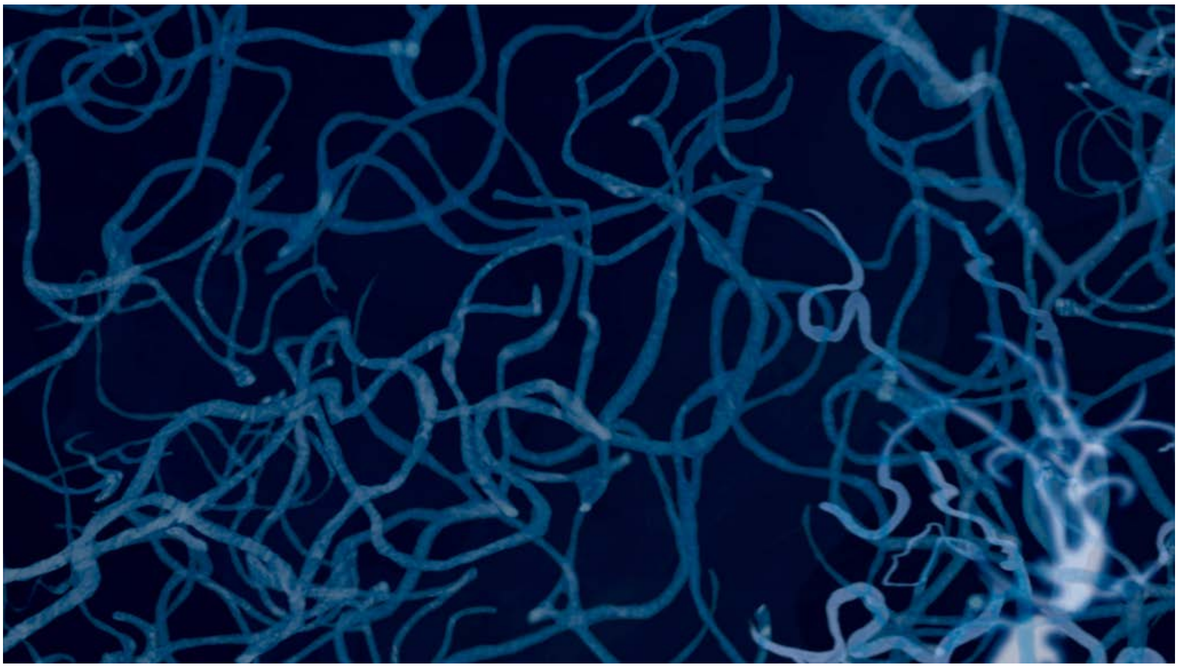


FIGURE 1.9 Zioga, P. 2009. *Imperceptibly…*. [Video, 2'16'', 16:9 widescreen, mute; wood frame].

More in particular, the *Imperceptibly…* (2009) video-artwork, titled after Constantine Cavafy's poem *Walls* (1896), refers to a personal and socio-political sense of entrapment (see also http://polina-zioga.com/video-art-installations/2009-imperceptibly). A network/web of arteries from my brain is gradually appearing and growing without sound, shutting me from the outside world - a visual allegory ever more relevant to the contemporary post-truth realities (Figure 1.9).

The Shelter (2011-2012) video-installation is inspired by Heraclitus' (540-480 B.C.E.) fragment 67a (Fragoulopoulou and Zioga 2012, 3):

Just as a spider, standing in the middle of its web,
notices as soon as a fly breaks one of its thread
and then quickly runs to the spot,
as though grieving over the cutting of the thread,
so a human's soul,
when a part of the body is hurt, moves swiftly there,
as if disturbed by the wound of the body,
to which is tightly and proportionately linked.

An internal environment is being created with two video projections (see also http://polina-zioga.com/video-art-installations/2011-2012-the-shelter). The vertical shows a web of pulsating brain arteries. This web frames, feeds and protects a central core, a cocoon with a human figure inside, an allegory for the human soul. At the same time, more elements have been inserted, such as artificial moths in movement, which mislead us regarding its biological or physical nature. The vertical video projection continues to the contiguous floor, as the natural/artificial landscape is reflected through the element of water, creating a dreamlike sense of movement. For the sound an ambient electronic score was created. A critical element is the use, apart from mine, also of other female and male recorded voices whispering Heraclitus' verses. The final audio is produced in surround mode, in order to create a sense of hearing the sounds and the voices coming out from all corners of the space (Figure 1.10). During the premiere exhibition a music performance was realised inside the video-installation interacting with the audio. This way a transition is made from the personal to a collective dimension. The 'individual/biological' body becomes an allegory and reference for the 'social/collective' (Fragoulopoulou and Zioga 2012, 29) and for the first time it is not presented in a gallery, but inside a theatre, a space traditionally used for plays – performative representations of the human condition, and which since its development during the Athenian Democracy (6^{th} century B.C.E.) also serves as a form of civic participation.

FIGURE 1.10 Zioga, P. 2011-12. *The Shelter.* [Video-installation, dimensions variable, 2 colour video projections, 5.1 channel surround sound].

As Fragoulopoulou (2012) writes, this body of work starting in 2005, including prints, videos and video–installations, depicts imaginary shelters/landscapes, with different levels of reading, not revealing whether they are organic or natural, composed of neurons and human organs or plants, a place where truth and desired truth coexist. Spaces/places, where I often add my own image in fetal position or in a subtle way, and in which the viewer can enter and experience visually and literally. In this way, the reality is reshaped, '[…] as if aiming to fill the gaps left by reason and science. […] Art complements science' (Fragoulopoulou 2012).

In the subsequent years, the elements/notions of civic participation and interaction in a theatrical or public setting have been further developed through works and projects realised in parallel with the research case study, which will be discussed in detail in Chapter 4. *Where Am I at Home?* (2013) is an inter-text and work of video art, based on Agnes Heller's original essay *Where Are We at Home?* (1995). The title and main question of the work addresses our sense of belonging, in terms of space, time, our spiritual and cultural heritage, but also in terms of politics and the constitutional democracy (see also http://www.polina-zioga.com/video-art-installations/2013-where-am-i-at-home). The *HOME network* (2013-2014) is a collaborative project with Kalina Ntampiza, 'a portable, netless (without an internet connection) Wi-Fi network, a free access unlocked digital platform, transmitting within the urban environment […] during a series of specific time periods and events.' (Ntampiza and Zioga 2014a, 936). During the *Home Sweet Home* event, that took place in Place Sainte Catherine in Brussels, the visitors were invited to watch fragments of the *Where Am I at Home?* (2013) video and answer questions, such as 'Do you feel at home?', 'Is your home in a democracy?' and others, written in three languages, English, French and Dutch. In this way, they were prompted to reflect on the notion of home and their 'sense of belonging in both the private and the public sphere' as a commonly shared experience and as a contemporary political question (Ntampiza and Zioga 2014b).

1.1.2 A new opportunity: Electroencephalography (EEG) and the Brain-Computer Interfaces (BCIs)

As presented previously in this chapter, amongst the brain-imaging techniques used by artists are the Electroencephalography (EEG) and the Brain-Computer Interfaces (BCIs), which are also the focus of the currently discussed research.

In the human body's nervous system, consisting of the Central Nervous System (CNS) and the Peripheral Nervous System (PNS), the functional units are the nerve cells (neurons), the approximate number of which per healthy adult is 10^{10}. The CNS consists of the spinal cord and the brain, which is the control centre, protected by the scalp and whose different anatomical regions are associated to different functions (Figure 1.11). More specifically, the brain is divided into: the cerebrum, which includes centres for conscious awareness, emotions and behaviour and consists of the two hemispheres, the left and the right, and the cerebral cortex, which is the surface layer; the cerebellum, which coordinates voluntary muscles' movement and balance; and the brainstem, which controls involuntary functions like respiration, heart regulation, other biorhythms, hormones etc. (Teplan 2002). The neurons under resting conditions have an electrical potential across their membranes with the inside of these cells being negatively charged comparing to the outside (Iaizzo 2003). When they are activated, local current flows are produced.

EEG, a non-invasive technique that can be applied to humans repeatedly with no risk or limitation, is the recording of the electrical activity along the scalp, by measuring the voltage fluctuations resulting from the current flows (Teplan 2002, Niedermeyer and da Silva 2004). The recording is being carried out with multiple electrodes placed on the scalp. It was invented in the late 19th century, however the first recording from a human scalp was reported in 1929 by Hans Berger (He and Ding 2013, 499). The recorded electrical activity of the brain is characterised by its amplitude, measured in microvolts (μV), and is categorised in rhythmic activity frequency bands, measured in

Hertz (Hz), which are delta (0.5-4 Hz), theta (4-8 Hz), alpha (8-13 Hz), beta (13-25 Hz), gamma (25-100 Hz) and are associated to different brain- and cognitive-states.

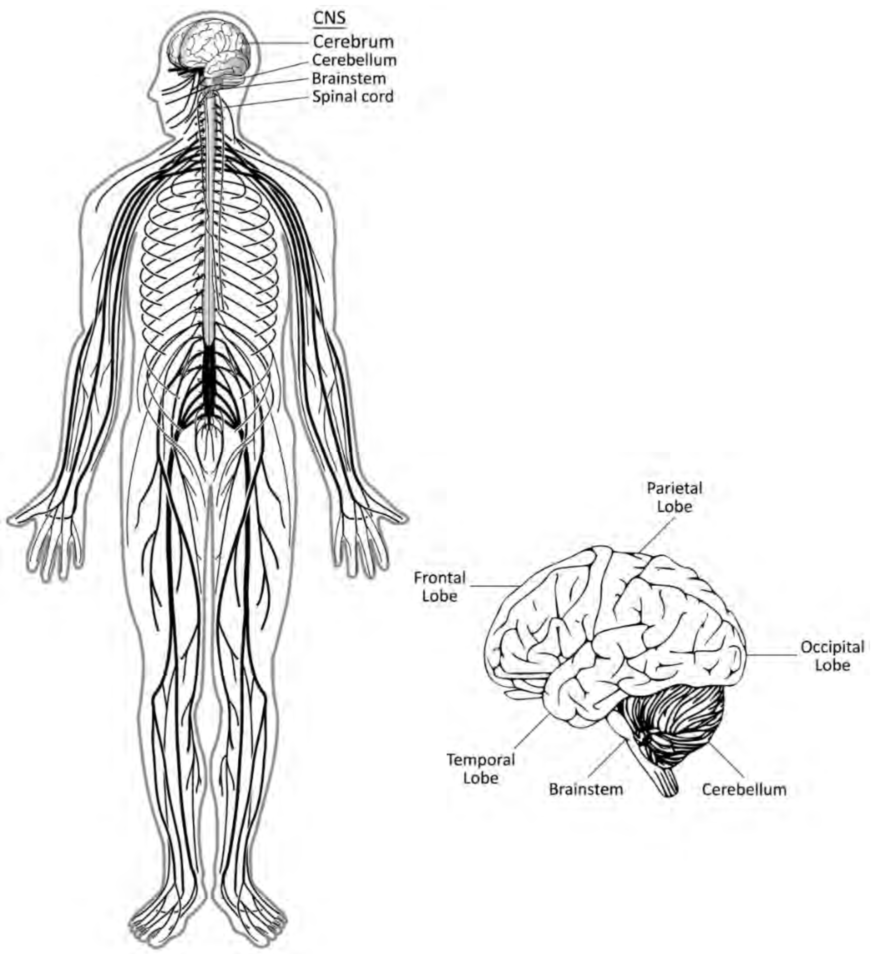


FIGURE 1.11 The human body's nervous system and the brain (adapted from Crochot 2014 and rejon 2010).

EEG can be used for different applications, amongst which are also the BCIs. Wolpaw and Wolpaw (2012) defined BCI as:

> *[…] a system that measures 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.*

For example, a BCI can be used to replace or restore activity lost due to injury or disease, such as limb amputation and spinal cord injury; it can enhance an activity periodically impaired, such as in lapses of attention; it can supplement an activity by providing an additional mechanism of control, such as in computer games and applications in entertainment and the arts; or it can improve an activity, such as in rehabilitation (Wolpaw and Wolpaw 2012).

The BCIs can operate using different techniques acquiring and measuring the brain-activity signal, however among the non-invasive, EEG is the most common. Such an interface was first demonstrated in 1964, when Grey Walter used EEG to control a slide projector, but it was in the 1970s, when Jacques Vidal introduced the term *Brain-Computer Interface* (He et al. 2013, 87). However, after the first breakthroughs in the 1960s and 1970s, the BCI research remained internationally rather limited, up until 15 years ago, when a new interest started appearing, leading to a rapid growth in the field (Wolpaw and Wolpaw 2012) and a phenomenal development of applications across health, entertainment and the arts, including the first low-cost commercial-grade wireless devices, which will be discussed in detail in Chapter 2.

1.2 THE CHALLENGES AND THE RESEARCH PROBLEM

One year later after the first demonstration of an EEG-based BCI, Alvin Lucier presented the *Music For Solo Performer* (1965), which is considered the first performance using the EEG technology. Other pioneering composers, like David Rosenboom, artists and performers soon followed, as will be discussed in detail in Chapter 3. However, relatively to the overall progress of the field, the use of BCIs in the arts remained until recently rather limited. With the recent new research and developments, nowadays there is a new increasing number of interdisciplinary creative practices, like computer games, interactive installations and music performances that involve the use of these interfaces for one or more participants/performers. However, in the context of live cinema and mixed-media performances[a], the use of EEG-based BCIs simultaneously for performers and members of the audience, is rather new and distinct. The reasons are merely two. On the one hand, the low-cost commercial-grade devices have only recently been available in the market, making the technology approachable to artists. On the other hand, the design and implementation of BCIs is dependent on unknown parameters and presents a series of limitations, as well as neuroscientific, computational, creative, performative and experimental challenges, which will be presented in detail in Chapters 2 and 3. These include for example the low accuracy of the EEG in identifying the region of the brain being activated, the unique brain anatomy of each person wearing the device, the type of sensors used, the location of the sensors which might be differentiated even slightly during each session, the task/s being executed by the users and the ratio of noise and non-brain artifacts to the actual brain signal being recorded (Swartz Center of Computational Neuroscience, University of California San Diego 2014). In this frame, I shall refer to the use of BCIs in the context of mixed-media performances as *live brain-computer mixed-media performances*.

1.2.1 THE MAIN RESEARCH QUESTION AND AIMS

Based on the aforementioned and as it will be further demonstrated in Chapter 3, the main question of the currently discussed research is framed as follows:

> *What might be an effective model for the simultaneous multi-brain interaction of performers and audiences using EEG-based BCIs in the context of live cinema and mixed-media performances?*

[a] I use the term 'mixed-media performances' as introduced by Auslander (1999, 36): '[…] events combining live and mediatized representations: live actors with film, video, or digital projections […].'

In order to address the main research question and make original contributions, the following research aims have been outlined, which also represent in a linear manner the process of the research design and implementation:

Research Aim 1: Review of BCI hardware, software and modes of interaction

The aim is to review the impact of the accelerating advances in neuroscience, biomedical and computer engineering research in the development of new low cost commercial-grade EEG-based BCIs that has led to a phenomenal emergence of new applications.

Research Aim 2: Review of the use of single- and multi-brain BCIs in mixed-media performances

The aim is to critically review the use of single- and multi-brain BCIs in performative works and works that involve the real-time participation of an audience with a double aim and result: to present the common key characteristics; and to identify the particular challenges of the design and implementation of multi-brain BCIs in mixed-media performances leading to the main research question.

Research Aim 3: A new passive EEG-based BCI system for simultaneous multi-brain BCI interaction

The aim is to follow the cognitive approach deriving from the identified challenges of the design and implementation of multi-brain BCIs in mixed-media performances, in order to design a new passive multi-brain EEG-based BCI system that will enable the simultaneous real-time interaction of more than two participants, including both performers and members of the audience.

Research Aim 4: The Live Brain-Computer Cinema Performance* as *a new format of interactive performative work

The aim is to create a research case study as a practice-based investigation of the identified challenges and as a complete combination of creative and scientific solutions to the main research question. The result is the presentation of a live brain-computer cinema performance as a new format of interactive performative work that combines live cinema and the use of BCIs.

Research Aim 5: A neuroscientific experiment in a real-life context

The aim is to realise the Live Brain-Computer Cinema Performance, collect both behavioural as well as EEG data from the participants and analyse them, as a neuroscientific experiment in a real-life context, following the relevant new trend and practices in neurosciences and experimental psychology.

1.2.2 Significance

This research contributes to the advancement of the area of interest by providing a comprehensive overview of the applicable state-of-the-art technology and science and a valuable guide in understanding the fundamental principles in BCI interaction. It proclaims that the new commercial-grade low-cost wireless systems offer new great opportunities for the artists that would like to incorporate them in the frame of interactive performative works. It outlines for the first time the interdisciplinary common grounds, approaches and challenges, which constitute a gap in the knowledge of the field, and sets the frame of a new type of performative work defined as *Live Brain-Computer Cinema Performance*. Moreover, a new passive multi-brain EEG-based BCI system is presented, which combines off-the-shelf hardware and software with custom-made real-time digital signal processing mathematics and visual programming for the control of the live video projections. Additionally, *Enheduanna – A Manifesto of Falling*, the first demonstration of a Live Brain-Computer Cinema Performance and the research case study is presented, as a practice-based investigation of the identified challenges and as a complete combination of creative and scientific solutions to the main research question. Last but not least, by designing and realising the performance as a neuroscientific experiment in a real-life context, away from the lab, this research makes a contribution in the debate about the effects of the length of time, the role of the directing strategy, dramaturgy and narrative structure on the audience's perception, cognitive state and engagement. It also serves as evidence that interdisciplinary studies not only can contribute to the advancement of the different fields involved, but can also result in new observations, not possible to be made in isolation.

1.2.3 THE RESEARCH DESIGN

This research focuses on the design of a new passive multi-brain EEG-based BCI system that will enable the simultaneous real-time interaction of more than two participants, including both performers and members of the audience in the frame of a new interactive performative work. The process, which is discussed in detail in Chapter 4, combines scientific methodologies, more specifically computational neuroscience, modern brain-computer interface design and digital signal processing, with practice-based creative methodologies, more specifically digital media, performance art, expanded and live cinema. During the design and production phases, observations are made, based on self-reflective and documentation analysis. Whereas, following the realisation of the performance the collected data are analysed using qualitative, quantitative and statistical methods. Additionally, audio-visual material from the public demonstrations of the performance has been captured and is presented in the format of images (figures) within the dissertation and as DVD-portfolio including the full length video-recording. Nevertheless, it is important mentioning at this point, and according to relevant debates, that an audio-visual reproduction, no matter how faithful and close to the original source might be, it is impossible to replace it (Abbott 2012; Auslander 2006). Therefore, the production of the film has focused in creating a representative, but also coherent and engaging material for the spectator that might not have been present in the actual performance.

1.3 THESIS OUTLINE

Chapter 2, *BCIs, Hardware, Software and Modes of Interaction*, serves as a comprehensive introduction in the terminology and current state-of-the-art science and technology of the field and explains the fundamental principles of the BCI interaction. It includes a critical presentation of the new wireless interfaces, examining both the hardware as well as the different software with a particular focus on open-source and free applications. It also presents the different types of BCIs according to their mode of interaction - active, reactive and passive - alongside different paradigms.

Last but not least, it includes a comparison between single- and multi-brain BCI interaction. This chapter places the work of the dissertation in the frame of the recent developments of the field and the impact of the accelerating advances in neuroscience, biomedical and computer engineering.

Chapter 3, *The Use of Single- and Multi-Brain BCIs in Mixed-Media Performances*, is a critical review of the use of both single- and multi-brain BCIs in performative works and works that involve the real-time participation of an audience. It presents the common key characteristics, which further leads to identifying the particular challenges of the design and implementation of multi-brain BCIs in mixed-media performances and the main research question. This chapter places the work of the dissertation in context by examining and distinguishing the different areas of relevant practices in comparison with the technology and science in use, while proposing new definitions.

Chapter 4, *'Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance*, addresses the main research question. Scientific and practice-based methodologies are combined in the frame of this new interactive performative work, realised as a complete combination of creative and research solutions and as the research case study. In this chapter, following the outline of the description and aims, the cognitive approach is explained, alongside the scientific methodologies and the design of the new passive multi-brain EEG-based BCI system. Finally, the creative methodologies are presented, focusing more specifically in directing and live cinema, interactive storytelling, the narrative structure and the live visuals.

Chapter 5, *Enheduanna – A Manifesto of Falling: Data Analysis and Discussion*, presents the observations made during the public events, the participants' demographic data, followed by the analysis of the participants' behavioural and EEG data, together with the statistical methods used. A critical discussion of the results and findings follows, in comparison with important studies and dominant positions on the cognitive experience and engagement of spectators during live performative works and free viewing of films.

The last Chapter 6, *Conclusions and Future Work*, summarises the currently discussed research by addressing the outcomes that answer the main research question and consist original contributions to knowledge, in correspondence with the initial research aims. It presents the challenges and limitations encountered, while the emerging new trends in the field are discussed, together with the future work and final reflections.

[…] Hope the voyage is a long one.
May there be many a summer morning when,
with what pleasure, what joy,
you come into harbors seen for the first time; […]

C. P. Cavafy's *Ithaca* 1910-1911 (Keeley and Sherrard 1992)

2. BCIs: Hardware, Software and Modes of Interaction

This chapter involves a comprehensive introduction in the terminology and current state-of-the-art science and technology of the research field and explains the fundamental principles of the BCI interaction. More specifically, in the frame of the recent developments and accelerating advances in neuroscience, biomedical and computer engineering, a review of the new commercial-grade EEG-based wireless interfaces is presented, examining both the hardware as well as the different software, that not only made the technology approachable, but also offered new creative freedoms to the artists. Particular focus is placed on open-source and free applications, used by scientists, engineers and artists alike. The different types of BCIs according to their mode of interaction - active, reactive and passive – are also discussed, alongside different paradigms, as these determine the possibilities and difficulties of the design and implementation of BCI applications. Last but not least, a comparison between single- and multi-brain BCI interaction is presented.

2.1 The new wireless interfaces

Since its first development in the 1960s, a typical BCI consists of a wired EEG-headset, which sends an analogue signal to an EEG-amplifier. The amplifier is then connected to a computer, where the analogue signal is converted to digital and the real-time processing is taking place with the use of dedicated software. In the end, the resulting processed signal is sent to another computer or digital device in order to control a secondary application (Figure 2.1).

The EEG-headset itself can include multiple electrodes which are attached to the scalp with the use of conductive gel and are commonly placed according to the international 10-20 system of standardised locations (Figure 2.2). The system is based on the distances between the bony landmarks of the head, in order to create a grid of lines that intersect at intervals of 10% or 20% of their total length (He and Ding 2013, 500).

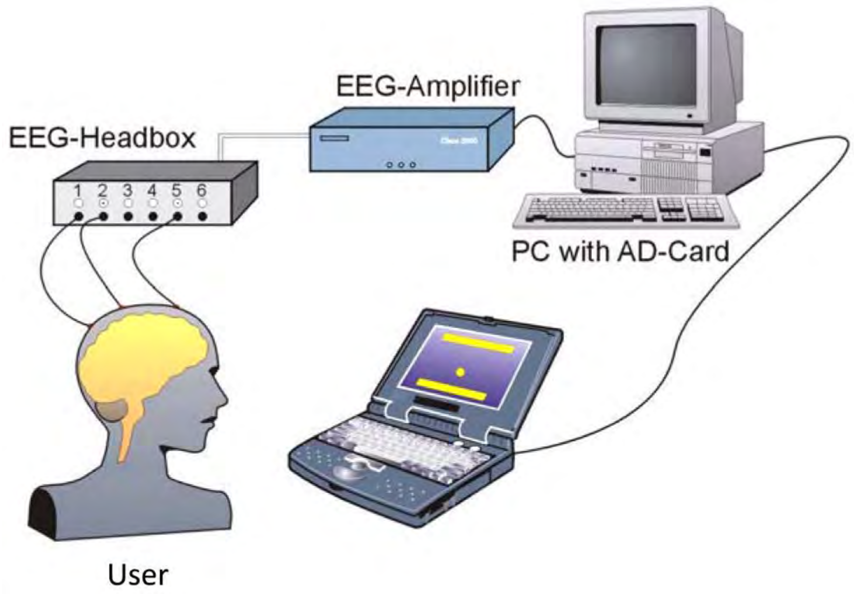


FIGURE 2.1 Parts of a basic BCI setup (adapted from Swartz Center of Computational Neuroscience, University of California San Diego 2014).

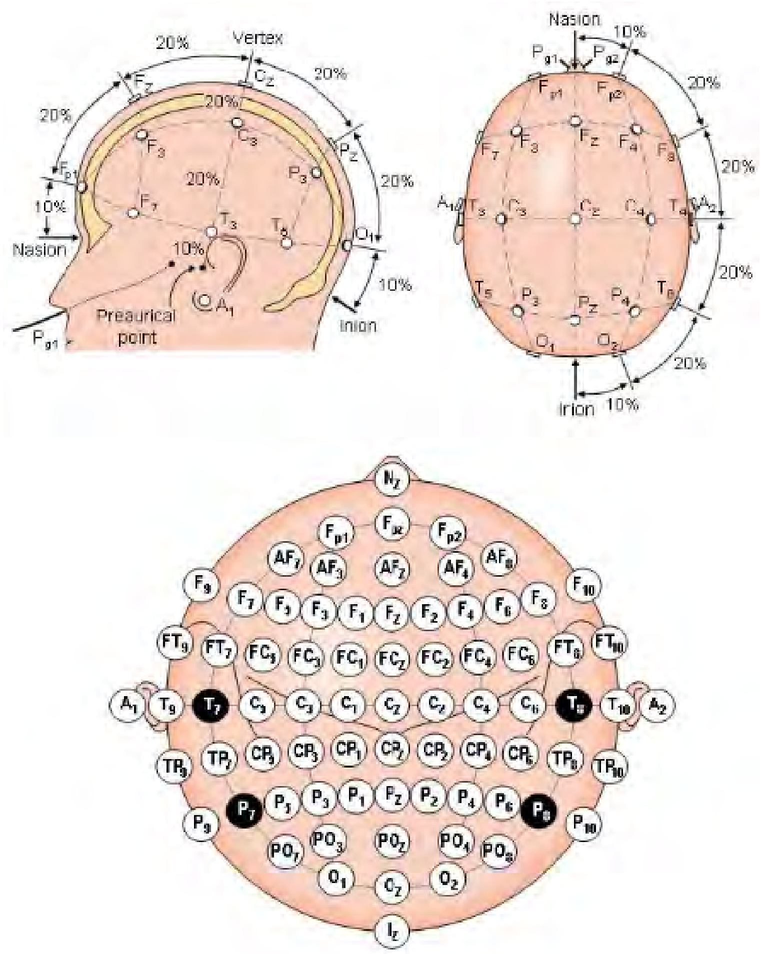


FIGURE 2.2 Measurement sites of the international 10-20 system of standardised electrodes locations (Swartz Center of Computational Neuroscience, University of California San Diego 2014).

2.1.1 HARDWARE

A typical clinical-grade hardware system with a wired EEG-headset, like the one described previously, can use up to 256 electrodes and has a high cost i.e. thousands of US dollars (Brunner et al. 2011), thus making the technology unapproachable to the general population and the creative professionals. Especially the latter were able so far to gain access and experiment with the EEG technology via dedicated collaborations with scientists and scientific labs, such in the case of the early pioneers, who will be presented in the next chapter. However, in recent years, with the accelerating advances in neuroscience and biomedical engineering research, new low-cost commercial-grade devices have been developed that have lower but comparable acquisition accuracy, better aesthetics and more easy setup (Nijboer et al. 2015). These new EEG-headsets amplify the analogue electrical signal of the brain, they convert it to digital and then they send it wirelessly to a computer via communication protocols, such as Bluetooth. Additionally, instead of the typical electrodes, they are equipped with sensors that can be either wet, using a conductive gel, or dry sensors that do not require it. The key milestones in the development of these new hardware and the most significant of which are presented below.

Neurosky

More specifically, it was Neurosky that introduced in 2007 the first, to present knowledge, wireless device for consumer use, which was also the first device with a dry sensor that did not require the application of a conductive gel, nor skin preparation (Neurosky 2007).

FIGURE 2.3 The MindWave Headset (Neurosky 2017).

Neurosky is one of the leading companies worldwide, which apart from developing their own headsets, they provide with their *ThinkGear AM* EEG sensors their partners globally. Their *MindWave* headset is compatible with Windows and Mac computers, whereas the *MindWave*

Mobile is compatible with iOS and Android mobile devices (Figure 2.3). They are powered with only one single AAA battery and they have typically a 6 to 8 hours battery life (Neurosky 2007).

Emotiv

In 2009, Emotiv launched two new wireless devices in the market, the *EPOC* and the *EEG* neuroheadsets, with 14 wet sensors plus 2 references. The sensors used in these headsets require regular hydration with the use of saline, while they are powered with a lithium battery that when fully charged provides up to 12 hours of continuous use. The headsets are as well compatible with Windows, OS, Linux, Android and iOS operating systems. At that time a key difference between the two headsets was that the first gave the users access to interpretations of their brain-activity, whereas the latter also gave them access to raw EEG data. The devices also come with two different types of licenses: the Developer Edition SDK (Software Development Kit) licence for users creating applications, which includes a development platform, APIs (Application Programming Interfaces) and detection libraries, but does not give access to raw EEG data; and the Research Edition SDK licence that gives users additional access to raw EEG data. Their accompanying software include three ’detection suites’, based on the use of ‘detection algorithms’, that map different activities and states of the user: the *Expressiv*, more recently renamed as *Facial Expressions*, mapping the facial muscle activity (‘blink’, ‘left wink’, ‘right wink’, ‘raise brow’ etc.); the *Affecti*v, renamed as *Emotional States*, that tracks the user’s ’emotional state’ (‘instantaneous excitement’, ‘long term excitement’, ‘frustration’, ‘engagement’ etc.); and the *Cognitiv*, renamed as *Mental commands* (‘push’, ‘pull’, ‘lift’, ‘drop’, ‘left’ etc.). More recently, the two initial headsets were replaced by the new *EPOC+* that incorporates all the aforementioned features, while an additional model was also launched, the *Insight*, which includes 5 semi-dry sensors (Figure 2.4). Both models are also provided with motion sensors, gyro, accelerometer and magnetometer that can be used as a pointing device (Emotiv [no date]). However, the ‘detection algorithms’ upon which the interpretation of the user’s brain activity is based, are not published, which poses issues that will be further addressed in Chapter 3.

FIGURE 2.4 The Emotiv *EPOC+* (a) and *Insight* (b) headsets (Emotiv [no date]).

MyndPlay

In 2014 MyndPlay released a new commercial-grade device, the *MyndPlay Brain-BandXL EEG Headset,* with two dry sensors, located in the prefrontal lobe (MyndPlay 2017b). The headset offers access to different interpretations of the user’s brain-activity (‘attention’, ‘meditation’, ‘mindfulness/zone’ etc.), based on Neurosky’s *ThinkGear AM* technology, as well as access to the raw EEG data (Figure 2.5). The headset includes a lithium-ion battery that when fully charged provides 6 to 10 hours of continuous use, while it is compatible with Windows, OS, Android and iOS operating systems. As in the case of the other hardware, an SDK licence is also available for developers (MyndPlay 2015).

FIGURE 2.5 The *MyndPlay Brain-BandXL EEG Headset* (MyndPlay 2015).

OpenEEG

At the same time, alongside with the aforementioned and other companies building new commercial-grade wireless interfaces, a community of developers and engineers working on do-it–yourself (DIY) open-source devices has also emerged. Such is the case of the OpenEEG project (OpenEEG project [no date]), which is a relatively well-known community amongst artists and creative practitioners. The objective of the project is to promote the development of freely available EEG devices, more specifically the *ModularEEG* and the *MonolithEEG*, aimed towards both amateurs who would like to experiment and professionals who might like to contribute, while some members have also developed relevant software, released under Creative Commons licenses.

OpenBCI

Another community that emerged more recently with the aim of democratising neurotechnology is the *OpenBCI*. They develop a series of commercial ‘bio-sensing systems’ including EEG-headsets that can be 3D-printed, acquisition boards for EEG, electrocardiographic (ECG) and electromyographic (EMG) signals that are compatible with Arduino, as well as sensors and electrodes (Figure 2.6). They also develop open-source software, compatible with Windows, Mac and Linux operating systems, supporting top programming languages, like C++, JavaScript, Python, Processing and Arduino, with SDK licences and drivers (OpenBCI 2016).

FIGURE 2.6 The OpenBCI *Ultracortex "Mark IV" EEG Headset* (OpenBCI Shop 2017).

2.1.2 SOFTWARE

The accelerating advances in neuroscience and biomedical engineering research, has also led to the development of new free and open-source software for real-time EEG recording and processing that are compatible with the new EEG-headsets. A list of the most well-known, which however is not extensive, is presented in this section.

OpenViBE

OpenViBE (Open Virtual Brain Environment) is a free and open-source multi-platform software, compatible with Windows and Linux operating systems and a great number of EEG-headsets. It was first developed in 2006 by Inria Rennes, INSERM, and Orange Labs in collaboration with AFM, CNRS, Gipsa-lab and CEA List. Currently in its 1.3.0 version, the software has been further continued through several funded projects, extensive published scientific research and a growing list of contributors and an international community of scientists, engineers and developers. The software is aimed for 'designing, testing and using' BCIs. With its capabilities of real-time signal processing algorithms, functions for machine learning and scripting, it can be used for medical, robotics, as well as multimedia applications (OpenViBE 2015). Amongst the advantages of *OpenViBE* are: its compatibility with the vast majority of the EEG-headsets currently available in the market; its friendly Graphical User Interface (GUI) that enables visual programming and allows users without advanced skills to design applications by combining configurable toolboxes (Figure 2.7); its ability to import and/or export file formats of other BCI platforms, as well as receive and send data and stimulations to other software; and that it does not rely to third party software components that require the purchase of expensive licences. Amongst its disadvantages is that the platform is not supporting Mac and Android operating systems, although according to the developers the *OpenViBE* might be able to run on unsupported systems, but there may be issues and challenges (OpenViBE 2016).

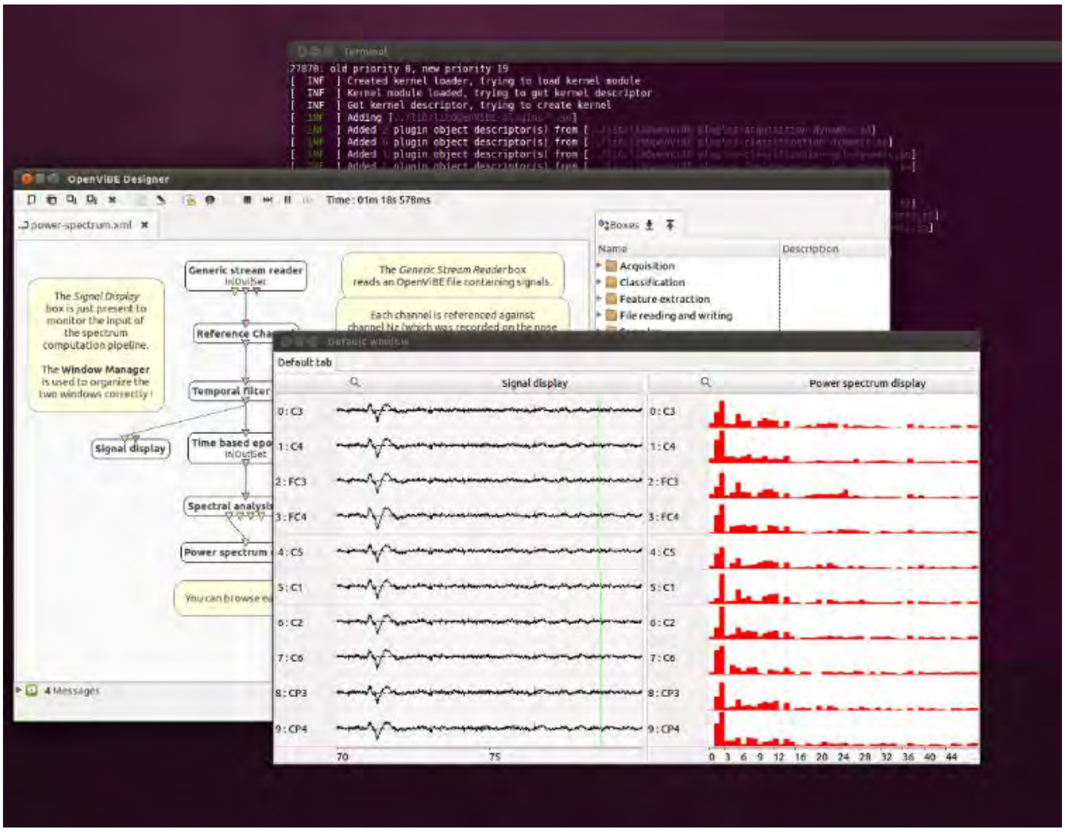


FIGURE 2.7 The *OpenViBE GUI* (OpenViBE 2015).

BCILAB

BCILAB is a free open-source research-grade toolbox for MATLAB (MathWorks 2016), but it can be deployed without the need of a MATLAB licence, only with the use of the redistributable MATLAB Compiler Runtime, while it can also be compiled as a stand-alone application (Figure 2.8). *BCILAB* is developed since 2010 for designing, testing, using and evaluating BCIs by Christian Kothe and the Swartz Center for Computational Neuroscience, University of California San Diego (2013), who have also developed EEGLAB and MoBi Lab. Its functionalities include:

(1) ‘Signal Processing’, which transform the acquired brain-signals into output signals.
(2) ‘Feature Extraction’ that interprets the output signals using algorithmic transformations.
(3) ‘Machine Learning’ that can create and apply predictive models from the acquired data.
(4) ‘BCI Paradigms’, which combine the previous features and may also support visualisation.
(5) ‘Online Plugins’ that allow the communication with other sources.
(6) ‘Framework’, which supports the plugins.

BCILAB has too a long-standing history of development, supported by a growing community. It presents similar advantages to OpenViBE, but also important differences. On the one hand its interface is designed for more advanced users in terms of programming skills, but at the same time it supports all the main operating systems, including Mac.

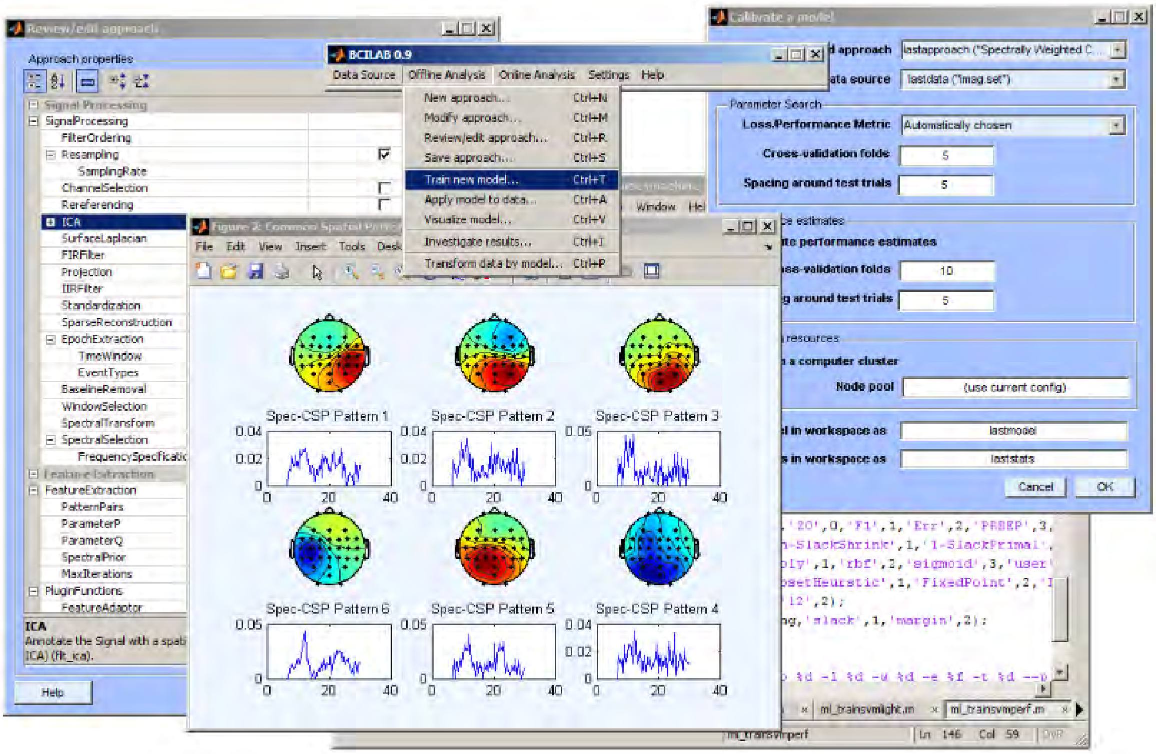


FIGURE 2.8 The *BCILAB* GUI (Swartz Center for Computational Neuroscience, University of California San Diego 2013).

BCI2000

BCI2000 is one of the oldest free and open-source software, more well-known amongst neuroscientists, developed by the Schalk Lab. It is aimed for BCI research and applications development (Schalk Lab 2017). Like in the case of the previously discussed platforms, it supports a variety of EEG-headsets and includes ready study/feedback paradigms. Additionally, it can communicate in real-time with other software, i.e. MATLAB, while it is compatible with Windows.

One key advantage of the *BCI2000* system is that, like the *OpenViBE*, it does not rely on other software and 3rd-party components, which often require the purchase of expensive licences, such in the case of MATLAB (Schalk Lab 2016). However, it is designed like BCILAB for more advanced users.

OpenBCI

As previously mentioned, the *OpenBCI* community also develops the open-source software *OpenBCI* (Figure 2.9), compatible with Windows, Mac and Linux operating systems, supporting top programming languages, like C++, JavaScript, Python, Processing and Arduino, with SDK licences and drivers (OpenBCI 2016).

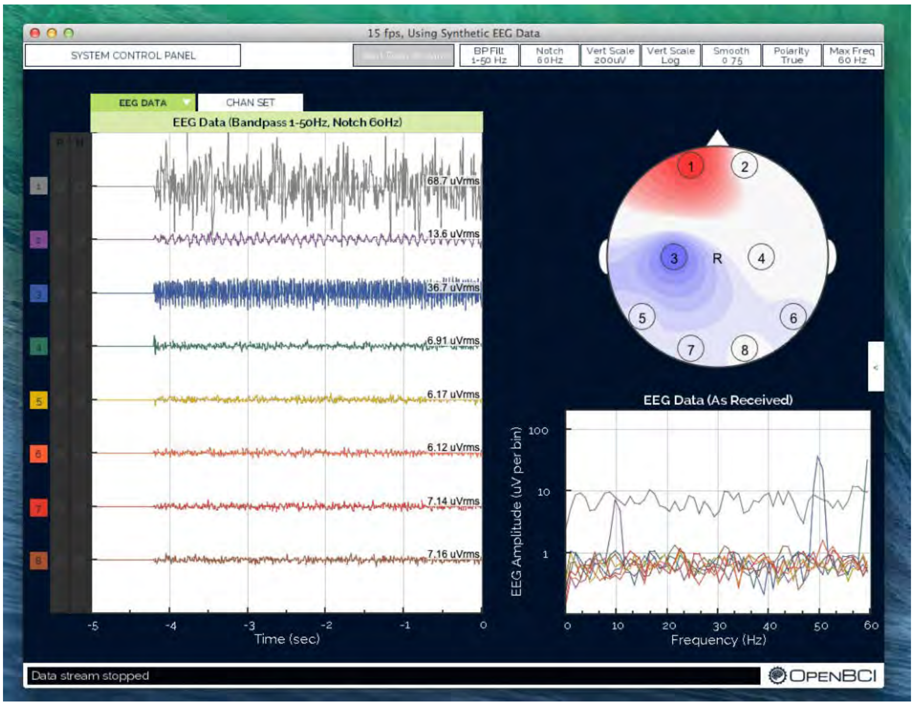


FIGURE 2.9 The *OpenBCI* GUI data stream (OpenBCI 2016).

BrainBay

Alongside the aforementioned software that are developed in laboratories and institutions over several years of funded projects, there is also a number of platforms created on the fringes of the field by communities of developers and designers. For example, *BrainBay* is developed by Chistoph Veigl and Jeremy Wilkerson, in order to work with the *OpenEEG* headsets and the flexibility of importing also data from other sources, such as a file reader or a webcam (Figure 2.9). The software has capabilities of signal acquisition and processing, together with feature extraction, used for providing audio-visual feedback and control of other devices (Veigl 2006).

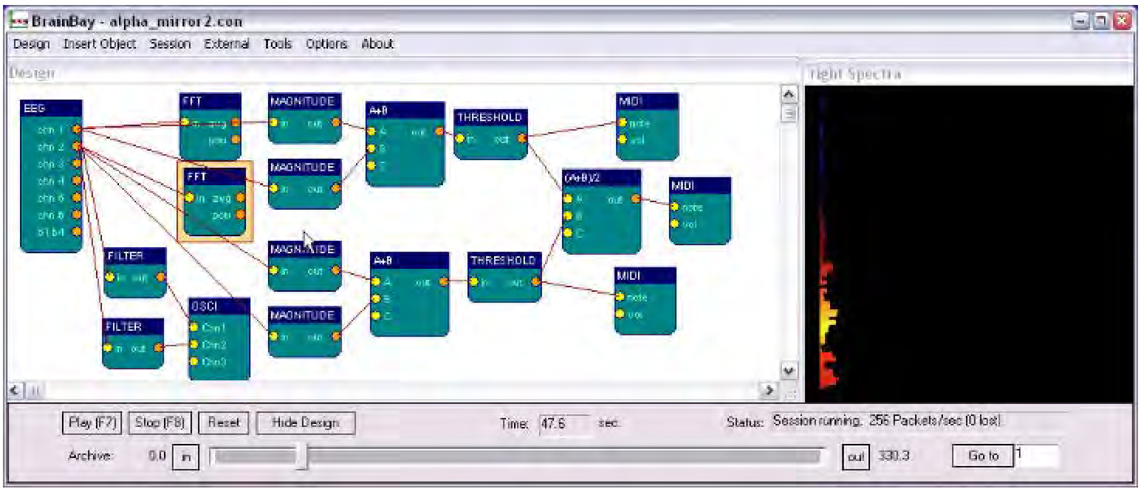


FIGURE 2.10 *BrainBay* Configuration Design Window (Veigl 2006).

2.2 MODERN BRAIN-COMPUTER INTERFACE DESIGN

The interdisciplinary field of prototyping and designing a BCI using modern methods, in order to process the acquired brain-signals, is called Modern Brain-Computer Interface Design. It combines theories and methods from the fields of Signal Processing, Machine Learning (Pattern Recognition), Computational Intelligence, Neuroscience, Statistics and Linear Algebra (Swartz Center of Computational Neuroscience, University of California San Diego 2014). The applications of the Modern BCI Design span across health purposes for patients, purposes for healthy populations in their working environment, as well as entertainment and the arts. For example, they can aid the communication of severely disabled patients that do not have control of their muscular system, i.e. in tetraplegia and locked-in syndrome, with the use of speller applications, control of wheelchairs or robotic prosthetics and the control of electrical devices in their environment. Another health application of BCIs is also the neurorehabilitation, whereas in the working environment, BCIs can be used to assess the workload and fatigue of users like drivers and operators. For entertainment purposes, the BCIs are most commonly used as control mechanisms in computer games.

However, the design and implementation of BCIs is particularly challenging as it is dependent on many factors and unknown parameters, such as the variability of the brain-activity between different people engaged with the same task under the same conditions. This variability is the result of the unique brain anatomy and the folding of the cortex of each person, which is not the same even amongst monozygotic twins. Similarly, the size and location of the functional centres of the brain can be different in each person. At the same time the positions of the BCI sensors can also be even slightly different between each user and between each different session. Moreover, our brain-activity is dynamic, which means that even with the same person performing the same task, the result can be different between different time-periods.

Other reasons that make the design and implementation of BCIs challenging include the contamination of the brain-signals with noise and non-brain artifacts. The artifacts can be either 'internally generated' or 'physiological', EMG from the neck and face muscles, electrooculographic (EOG) from the eye movements and ECG from the heart activity; and 'externally generated' or 'non-physiological', spikes from equipment, cable sway and thermal noise (Nicolas-Alonso and Gomez-Gil 2012, 1238; Swartz Center of Computational Neuroscience, University of California San Diego 2014).

Also, in the case of BCIs using EEG for acquiring the brain-signals, there are additional technical limitations. One of them is EEG's low spatial resolution, which is also further influenced by the 'head volume conduction effect' (He and Ding 2013), meaning that the recorded electrical signal is further blurred, as it passes through the different anatomical tissues of the head, before it reaches the scalp (Figure 2.11). The result of this phenomenon is that positioning the electrodes or sensors on different locations on the head cannot be easily associated with the activity of specific regions of the brain.

2.2.1 ACTIVE, REACTIVE AND PASSIVE EEG-BASED BCIS

The EEG-based BCIs are divided into three different types: the 'passive' where the user is not trying to control anything and instead the outputs are derived from the 'arbitrary brain activity' taking place 'without the purpose of voluntary control'; in contrast to 'active' BCIs that can be controlled by the user consciously i.e. by imagining a right or left arrow in order to execute a specific command; and the 'reactive' BCIs that derive their outputs from 'brain activity arising in reaction to external stimulation', for example when focusing on a flickering light on a computer screen (Zander et al. 2008). The choice of the BCI type depends in each case on the purpose of the application, the users and the conditions under which it will be used. Whereas, the measurement of the brain-activity can focus on different large-scale processes/phenomena and can be accomplished with the use of different paradigms, as it will be further discussed.

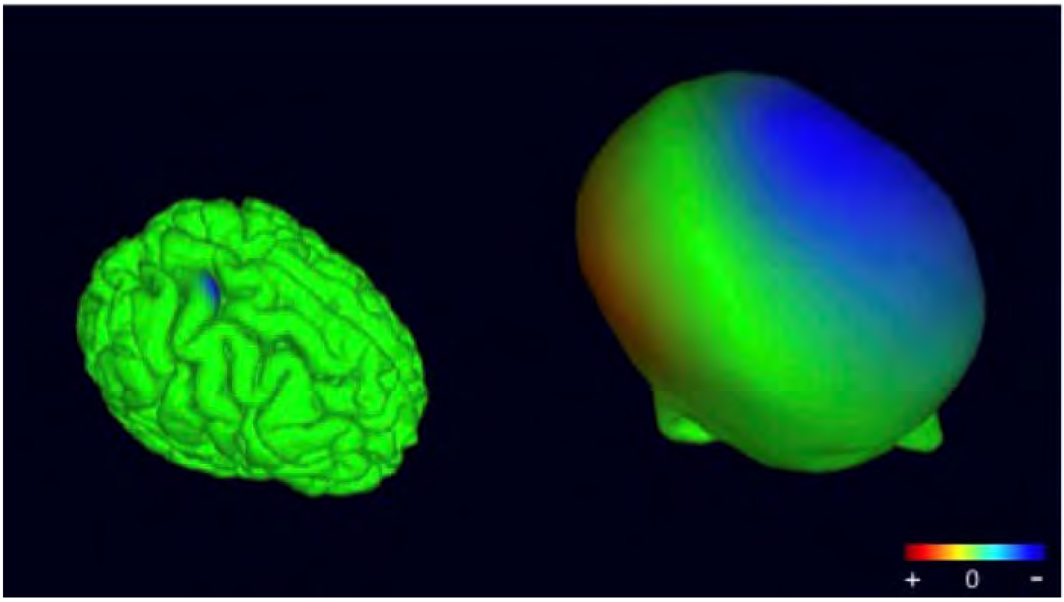


FIGURE 2.11 The projected spread of the neural activity from the source of the brain to the scalp (Swartz Center of Computational Neuroscience, University of California San Diego 2014).

2.2.2 NEURAL SIGNALS AND PARADIGMS USED BY EEG-BASED BCIS

The most important of the brain phenomena are the Oscillatory Processes and the Event-Related Potentials (ERPs). In the currently discussed study the type of the BCI used is passive with a focus on the users' Oscillatory Processes, which occur when large neural populations are not engaged with a specific task and synchronise following an oscillatory pattern. The ERPs take place following either an external event, like an audio or visual stimulus and are called 'exogenous', or following an internal event and are called 'endogenous'. The most important ERPs are presented below.

Exogenous ERPs: Visual Evoked Potential (VEP)

Both the exogenous, as well as the endogenous, ERPs are manifested as significant increase of the EEG amplitude (voltage fluctuations), result of evoked neural activity (Teplan 2002, 4). The most common exogenous ERP used in BCIs is the Visual Evoked Potential (VEP) and in particular the Steady State Visual Evoked Potential (SSVEP), which occurs after the presentation of a visual stimulus repeated at a specific steady frequency. An example is a user looking at one or more objects flickering on a screen at specific frequencies. In this case, the user's brain-activity shows an increase of the power at the frequency of the object s/he is looking at. This can be applied in order to allow the selection by the user of a particular object. The BCIs using exogenous ERPs usually do not require significant user training, but the environment and the stimuli need to be controlled (He et al. 2013 110; 130).

Endogenous ERPs: P300

The P300 is an ERP evoked by an internal event. This is manifested as a large increase of the brain-wave's amplitude occurring approximately 300 msec after the onset of the event. This response is triggered when the user is presented with two different events/stimuli (visual or auditory), one of which is less frequent than the other, which s/he needs to successfully categorise, in order to accomplish a task. An example is a screen with the letters A and B flashing, where the user is requested to count the number of times one of them is being shown. The BCIs using endogenous ERPs usually do not require user training (He et al. 2013, 110).

Event-Related Desynchronisation and Event-Related Synchronisation

When movement or motor imagery (MI) take place, decreases and increases of the brain rhythmic activity in the sensorimotor cortex also occur. These phenomena, referred as Event-Related Desynchronisation and Event-Related Synchronisation, can be used in BCIs when the user is presented with an MI task, for example by being asked to imagine a right or left arrow or hand movement (Pfurtscheller and McFarland 2012). These BCIs require significant user training.

2.3 Single- versus multi-brain BCI interaction

The vast majority of the BCIs are designed for single-users. However, a smaller but increasing number is aimed at more than one users, thus enabling a multi-brain BCI interaction. This more recent trend originally emerged for entertainment and artistic purposes. Especially in new media art, computer and serious games the use of different applications and devices for engaging multiple participants and players is highly disseminated, from the use of mobile applications, to Human-Computer Interaction (HCI) devices and after 2007, EEG-based BCIs. At the same time, in a parallel course with the BCIs' advancements and breakthroughs, in the fields of neuroscience and experimental psychology has emerged a new and increasing interest in studying the mechanisms, dynamics and processes of the interaction and synchronisation between multiple subjects and their brain activity. Hasson et al. called in 2012 'for a shift from a single-brain to a multi-brain frame of reference', arguing that 'in many cases the neural processes in one brain are coupled to the neural processes in another brain via the transmission of a signal through the environment […] leading to complex joint behaviors that could not have emerged in isolation.' (Hasson et al. 2012, 114).

2.3.1 Brain-to-brain coupling

More specifically, brain-to-brain coupling is analogised to a wireless communication system, 'in which two brains are coupled via the transmission of a physical signal (light, sound, pressure or chemical compound) through the shared physical environment. […] The coordination of behavior between the sender and receiver enables specific mechanisms for brain-to-brain coupling unavailable during interactions with the inanimate world.' (Hasson et al. 2012, 115). The authors continue explaining how the exchange of information between two individuals bears similarities to the transmission of information between two areas of a single brain. An example is the coupling and the enhancement of the signal-to-noise ratio of the frequency of the speech with the auditory cortical oscillations that have a similar frequency (Hasson et al. 2012, 115), which can also be extended and further amplified with the presence of visual information and stimuli, like watching the speaker's face and lips. Relevant studies include fMRI scanning of both speakers and listeners during natural verbal communication, which have shown that 'the speaker's activity is spatially and temporally coupled with the listener's activity'. The listener's brain activity on average mirrors the speaker's activity with a delay, but there are also areas that exhibit predictive anticipatory responses and in fact 'the greater the anticipatory speaker–listener coupling, the greater the understanding' (Stephens, Silbert and Hasson 2010, 14425). Other experiments have shown that performing and observing hand gestures and facial expressions can also result in brain-to-brain coupling (Schippers et al. 2010) and related results have been obtained with experiments that involved facial communication of affect (Anders et al. 2011). The majority of these studies investigate brain-to-brain coupling through the use of Intersubject Correlation (ISC), which is 'a measure of how similar subjects' brain activity is over time', and is also considered highly reliable, allowing 'the exploration of sensory areas involved in natural viewing of long stimulus segments i.e. >6 min.' (Jola et al. 2013).

The phenomenon and theory of brain-to-brain coupling and the multi-brain BCI interaction in general are not only innovative for the fields of neuroscience and psychology, but the potential applications in the frame of multi-brain interactive works of new media art, computer and serious games is apparent and has already attracted the attention of researchers, artists and developers alike.

2.4 SUMMARY

The past 15 years, the rapid advancements in the fields of neuroscience and biomedical engineering research have led to a phenomenal development of EEG hardware, including low-cost commercial grade, as well as free and open-source software. This has further promoted the emerging field Modern BCI Design leading to an increasing number of EEG-based BCI applications in health, psychology, education, entertainment and the arts and the democratisation of the neurosciences. The new hardware, software and applications developed by diverse communities of scientists, engineers, designers and artists across the globe enable the brain-activity of the users to communicate with and control an increasing list of outputs, including but not limited to electric wheelchairs and prosthetic robotics, computer games, mobile applications and microcontrollers. At the same time, the design and implementation of EEG-based BCIs still presents several difficulties, but also new opportunities. However, as it will be presented in the following chapter, artists have been amongst the pioneers in the field, historically designing and using EEG-based BCIs, in order to enhance their natural CNS outputs in the frame of creative and performative practices. In particular, the new wireless devices help the artists to overcome important constraints, although at the same time they also present new challenges.

[…] may you stop at Phoenician trading stations
to buy fine things,
mother of pearl and coral, amber and ebony,
sensual perfume of every kind—
as many sensual perfumes as you can;
and may you visit many Egyptian cities
to gather stores of knowledge from their scholars. […]

C. P. Cavafy's *Ithaca* 1910-1911 (Keeley & Sherrard, 1992)

3. THE USE OF SINGLE- AND MULTI-BRAIN BCIS IN MIXED-MEDIA PERFORMANCES

As demonstrated in the previous chapters, since 2007, the introduction of new commercial-grade EEG-based BCIs and wireless devices has led to a phenomenal development of applications across health, entertainment and the arts. At the same time, an increasing interest in the brain activity and interaction of multiple participants, referred to as multi-brain interaction (Hasson et al. 2012, 114), has emerged. Artists, musicians and performers have been amongst the pioneers in the design of BCI applications (Nijholt 2015, 316) and while the vast majority of their works use the brain-activity of a single participant, a survey by Anton Nijholt (Nijholt 2015, 316) presents earlier examples that involve multi-brain BCI interaction in installations, computer games and music performances, such as: the *Brainwave Drawings* (1972) for two participants by Nina Sobell; the music performance *Portable Gold and Philosophers' Stones* (*Music From the Brains In Fours*) (1972) by David Rosenboom, where the brain-activity of four performers was used as creative input; the *Alpha Garden* (1973) installation and the *Brainwave Etch-a-Sketch* (1974) drawing game by Jaqueline Humbert, both for two participants.

Nowadays, there is a new increasing number of works that involve the simultaneous interaction of more than one participants or performers with the use of EEG-based BCIs. The emergence of these applications is not coincidental. On the one hand, amongst artists and performers the notion of communicating and establishing a feeling of being connected with each other and the audience is part of their anecdotal experience. On the other hand, with the recent advancements in neurosciences and the new EEG technology they have been enabled to realise works and projects as a manifestation of their intra- and inter-subjective experiences. This is further augmented by the parallel new and increasing trend in the fields of neuroscience and experimental psychology in studying the mechanisms, dynamics and processes of the interaction and synchronisation between multiple subjects and their brain activity, such as the brain-to-brain coupling. Recent applications include the computer games *Brainball* (Hjelm and Browall 2000); *BrainPong* (Krepki et al. 2007); *Mind the Sheep!* (Gürkök et al. 2013); and *BrainArena* (Bonnet, Lotte and Lecuyer 2013). Amongst the relevant installations are: Mariko Mori's *Wave UFO* (2003), an immersive video installation (Mori, Bregenz and Schneider 2003); the *MoodMixer* (2011-2014) by Grace Leslie and Tim Mullen, an installation with visual display and 'generative music composition' of two participants' brain-activity (Mullen et al. 2015, 217); and a series of projects, like *Measuring the Magic of Mutual Gaze* (2011), *The Compatibility Racer* (2012) and *The Mutual Wave Machine* (2013), by the Marina Abramovic Institute Science Chamber and the neuroscientist Dr Suzanne Dikker (Dikker 2011). Whereas, in the field of music performances are included: the *DECONcert* (2003), where forty-eight members of the audience – the largest number to my knowledge so far - were adjusting the live music (Mann, Fung and Garten 2008); the *Multimodal Brain Orchestra* (Le Groux, Manzolli and Verschure 2010) that involves the real-time BCI interaction of four performers; *Ringing Minds* (2014) by Rosenboom, Mullen and Khalil that involved the real-time brain-activity of four members of the audience combined to a 'multi-person hyper-brain' (Mullen et al. 2015, 222); and *The Space Between Us* (2014) by Eaton, Jin, and Miranda. In the latter the brainwaves of a singer and a member of the audience are measured and processed in real-time, separately or jointly, as an attempt of bringing the 'moods of the audience and the performer closer together' (Eaton 2015) with the use of a system that 'attempts to measure the affective interactions of the users' (Eaton, Williams and Miranda 2015, 103).

However, the use of multi-brain BCIs in the field of live brain-computer mixed-media and cinema performances for both performers and members of the audience is rather new and distinct from applications like those described above. Live cinema (Willis 2009) and mixed-media performances (Auslander 1999, 36) are historically established categories in the broader field of the performing arts and bear distinct characteristics that essentially differentiate them from music performances with the addition of 'dynamical graphical representations' (Mullen et al. 2015, 212) or VJing practices[b]. A possible reason that might explain why historically the majority of the performative works with the use of BCIs are music performances, might be the fact that the audio and EEG waves bear similarities. They are both characterised by their amplitude and frequency, which possibly makes the EEG signal processing easier for musicians and composers and accordingly its transformation or mapping to sound.

This chapter involves a critical review of the use of both single- and multi-brain BCIs in performative works and works that involve the real-time participation of an audience, in order to present common key characteristics. This further leads to identifying the particular challenges of the design and implementation of multi-brain BCIs in mixed-media performances and the main research question.

3.1 PERFORMANCE ART, INTERACTION AND THE BCIS

3.1.1 KINESIOLOGY, FACIAL EXPRESSION AND NOISE

Since the first works with the use of BCIs, performers have encountered considerable limitations to their kinesiology and even their facial expression, either in cases they use wired devices and electrodes, and/or because of the contamination of the EEG-data with noise and non-brain artifacts

[b] VJing, derived from the term Video Jockey (VJ), refers to the real-time selection and possibly manipulation of videos/visuals in front of an audience, similarly to the way a Disc Jockey (DJ) is selecting and manipulating audio/music in real-time.

from the cranial and body muscles (see also Chapter 2.2). One year after the demonstration of the first BCI, Alvin Lucier collaborated with Edmon Dewan, who provided him with the necessary technical support, and presented the *Music For Solo Performer* (1965), which is considered the first real-time performance using EEG. In this work, which continues being performed until today, the performer has two electrodes attached to his forehead, while he sits almost without moving on a chair, opening and closing slowly his eyes, thus controlling the effect of the visual stimuli on his brain-activity and consequently the alpha rhythmic activity frequency band, which is associated with a brain-state of relaxation (Figure 3.1). The electrodes are connected via an amplifier to a set of speakers, who transmit the electrical signal and vibrate percussion instruments placed around the performance space (Ashley 1975).

FIGURE 3.1 Alvin Lucier performing *Music for Solo Performer* (Ashley 1975).

Another example is *INsideOUT* (2009) by Claudia Robles Angel, in which she uses an open source EEG interface from Olimex, consisting of one analogue and one digital board, connected to a computer. Two electrodes, one on her forehead and one on the back of her head, are connecting respectively the frontal lobe's activity with the sound output from the computer and the occipital lobe's activity with the video output. The sounds and images are projected on a screen and onto the performer (Figure 3.2). They are controlled by the values of the signals acquired via the electrodes and processed via the MAX/MSP software. As Alvin Lucier, so is she focusing on the recording of the Alpha band frequency, 'accentuated during relaxation' (Angel 2011, 424).

In one of her interviews, Angel mentions that with the EEG interface she could not move because it 'is so sensitive that if you move you get values [noise] from other sources' (Lopes and Chippewa 2012). Today, the new wireless devices have provided the performers with greater kinetic and expressive freedom, while in some cases they also include filters and algorithmic interpretations which can be used to some extent for the real-time processing of the acquired data. However, there are certain issues, which will be discussed more in detail in Section 3.1.4.

Figure 3.2 Claudia Robles Angel performing *INsideOUT* at the SIGGRAPH Asia2009 in Yokohama, Japan (Angel 2011, 424).

3.1.2 Rhythmic activity frequency bands and cognitive states

The limitations imposed in the performers' kinesiology and facial expression, like in the works by Alvin Lucier and Claudia Robles Angel, have further implications and result in additional performative constraints, such as the inevitable focus in the control of only the relaxation state and the associated alpha rhythmic activity frequency band. For performers that are interested in using BCIs while engaging in more active situations and states of tension, like for example in works that involve intense kinesiology and speech, the use of wireless devices is indispensable. Consequently, they are also enabled to consider all the different frequency bands, associated with a greater range of brain- and cognitive-states. The EEG-data can be further processed and differentiated according to the tasks executed and in consistency with the dramaturgical conditions of the performance. In this way the use of the BCIs as a medium in live performances is enriched. Examples of such works are presented in the following sections.

3.1.3 Spatial resolution and the head volume conduction effect

As discussed in Chapter 2, one of the EEG's technical limitations is its low spatial resolution, which is also further influenced by the 'head volume conduction effect'. As a result, it is difficult to associate the position of the electrodes or sensors on the scalp with the activity of specific regions of the brain. In neuroscience research, in order to bypass this limitation, apart from the clinical grade systems that can use up to 256 electrodes, there are methods and tools, such as invasive BCIs, the complementary use of fMRI scans, as well as complex linear algebra mathematical modelling. However, these techniques are currently not applicable to artistic performances and especially in cases where low-cost interfaces are used with limited number of electrodes/sensors, either wireless or not. For this reason, either the artists should not rely the concept of their live brain-computer mixed-media performances on the localisation of the electrodes/sensors or they should consider applying a combination of pre-performance study and on-performance use of computational processing, which however is complex and therefore challenging.

3.1.4 RAW EEG DATA VERSUS 'DETECTION SUITES'

The new low-cost wireless devices have not only given greater kinetic and expressive freedom to the performers, but with their accompanying user-friendly software, SDK licenses and a variety of connectivity solutions, they have enabled artists to establish communication with different hardware and boards like Arduino, and software like Pure Data, MAX/MSP, Processing, Ableton Live and others, creating prototypes and playful applications. This easiness is largely achieved because these devices enable the real-time raw EEG data extraction, but at the same time they also include ready-made algorithmic interpretations and filters for feature extraction. The user can view and process/map data under categorisations such as 'frustration' or 'excitement', 'meditation' or 'relaxation', 'engagement' or 'concentration', which however are differentiated amongst the different models and manufactures (see also Chapter 2.1.1).

For example, Adam John Williams with Alex Wakeman and Robert Wollner (Williams 2014) presented in 2013 a project, which uses an Emotiv EPOC headset in order to connect with and sent to a computer the participants' EEG data, converting them to:

> *[…] OpenSound Control messages, which were sent to a Mac where Max MSP used the data to adjust the rules of a generative music engine. Tempo and sync information were then packed along with the original EEG messages and transmitted to the Raspberry Pi upon which the visuals were generated.*

As it is shown in the video documentation, the software processes different inputs titled as 'Bored/Engaged', 'Excited', 'Excited LT', 'Meditation' and 'Frustration', which are associated with the Emotiv's 'detection suites' (Emotiv [no date]).

Lisa Park in her work *Eunoia* (2013), a Greek word meaning goodwill and beautiful thinking, reinterprets in a way Alvin Lucier's *Music for Solo Performer* (1965) by using Neurosky's Mindwave wireless device, monitoring her brain-wave activity and processing the EEG-data categorised in different rhythmic activity frequency bands, but also states, such as 'Attention' and 'Meditation'. These data and the corresponding values are amplified and transmitted through five speakers, positioned underneath equal number of round metal plates, filled with water, and associated according to the artist with the emotions of 'happiness', 'anger', 'sadness', 'hatred', and 'desire'. The speakers vibrate the metal plates and 'varieties of water forms' are created (Park 2013).

The use of the aforementioned ‘detection suites’ serves in the artists’ hands as ready-made tools for the creation of inspiring and imaginative works. However, on the one hand the algorithms and methodology upon which the interpretation and feature extraction of the brain’s activity is made are not published by the manufactures. On the other hand, the published neuroscience research in the field of emotion recognition via the use of EEG data is fairly new. Thus, the use of these ‘detections’ of emotional states should not necessarily be regarded as accurate and therefore the creative results may not be consistent to the artists’ original intentions.

Other examples in the direction of scientifically established use of emotion interpretation via EEG in the arts come from the field of computer music research. The Embodied AudioVisual Interaction Group (EAVI) at Goldsmiths, University of London, has developed a BCI toolkit that can be used with both clinical grade and consumer level devices, and has the ability of detecting Event Related Potentials (ERPs) used for ‘making high-level musical decisions’, like for example in *Music of the Mind* (2010) album and tour by Finn Peters and Matthew Yee-King (Grierson, Kiefer and Yee-King 2011, 110). In the *Multimodal Brain Orchestra,* a conductor chooses sounds and tempo triggered by four performers’ brain activity, two wearing BCIs using P300 ERPs and two using SSVEP (Le Groux, Manzolli and Verschure 2010, 309). The *MoodMixer* (2011-14) is an installation by Grace Leslie and Tim Mullen that generates real-time EEG-based music, combined by ‘a simultaneous visual display’ of two participants’ brain activity. Three versions of the installation have been created so far. The first involves the measurement of the raw EEG data, together with the ‘meditation’ and ‘focus’ indicators provided by the NeuroSky Mindset device (Mullen et al. 2015, 217). Whereas, the second and the third version involve the measurement of the valence and arousal levels of the participants with the use of the Mindo devices (Mullen et al. 2015, 219-220). For their performance piece, *The Space Between Us*, Eaton, Jin, and Miranda (2014) also describe the measurement and mapping of valence and arousal levels within EEG, for which there are different known methods with well documented results (Figure 3.3). Similar approaches can contribute to a new system of validation and evaluation, enabling further advancements in the field.

FIGURE 3.3 *The Space Between Us* by Joel Eaton and Weiwei Jin (Eaton 2015).

3.1.5 COHERENCE, SYNCHRONICITY AND INTERACTION WITH MULTIPLE PARTICIPANTS

As mentioned before, amongst artists and performers the notion of communicating and establishing a feeling of being connected with each other and the audience is not new, but rather part of their anecdotal experience. In the early years of the use of BCIs they started exploring the dynamic communication and collaboration of two participants through their brain-activity. Nina Sobell created a series of interactive video drawings, the *Brainwave Drawings* (1972). Her exploration was a continuation of her previous interest in engaging the participant/viewer as an actor/co-creator of the final artwork (ninasobell 2008). Jaqueline Humbert created in 1973 *Alpha Garden*, one of the first works explicitly referring to and making use of the synchronisation of two participants' brain-activity (Nijholt 2015, 317). Whereas, one year later she presented the *Brainwave Etch-a-Sketch* (1974) interactive drawing for two participants, further developing Nina Sobell's previous idea and methodology. In recent years with the advancement of neurosciences and the new EEG technology artists managed to realise works and projects as a manifestation of their inner subjective experiences and they have implemented related ideas, such as coherence and synchronisation between multiple participants or between performer/s and spectator/s.

One of the most cited works, Mariko Mori's *Wave UFO* (2003) is an immersive video installation, where computer-generated graphics are combined with the 'real-time interpretation of three participants' alpha, beta, and theta brain-waves' (Mori, Kunsthaus Bregenz and Schneider 2003, 46). Mariko Mori collaborated for the ambitious project with more than one hundred scientists, engineers, and technological consultants who contributed to the project. Amongst them was Masahiro Kahata, who provided the software for the brain-wave analysis. Mariko Mori developed the real-time visual graphics software with Silicon Studio Corporation in Tokyo. While the architect Marco Della Torre supervised the architecture and engineering of *Wave UFO*'s structure and Modelleria Angelino became the prime contractor. The brain-computer interface devices were designed by Body Media and K development and the sound was composed by Ken Ikeda. (Mori, Kunsthaus Bregenz and Schneider, 143). The participants are wearing EEG devices with three electrodes/sensors attached to their foreheads, recording the frequencies of their brains' right and left hemispheres. According to which frequency is showing higher activity, projected animated spheres on the ceiling (one for each participant's hemisphere) take a different/associated colour (red for beta band, blue for alpha and yellow for theta). At the same time is also animated each participant's brain coherence with a second pair of smaller spheres, the 'Coherence Spheres'. By coherence the artist refers to the phenomenon of synchronicity of the alpha-wave activity between the two brain's hemispheres (Mori, Kunsthaus Bregenz and Schneider, 143). When this is achieved, the 'Coherence Spheres' are joining together. If all the participants reach this state, then a circle is created, as a scientific and visualisation approach to the artist's idea of connectivity, which is rooted to the Buddhist philosophy (Figure 3.4). Coherence in Mariko Mori's work also serves as an example of a real-time interaction between the brain activity of multiple participants and the visualisation of the brain-data as a form of physicalisation, which is the process of rendering physical the abstract information through either graphical representation and visual interpretation or sonification (Tanaka 2012).

More recently, a series of projects, like *Measuring the Magic of Mutual Gaze* (2011), *The Compatibility Racer* (2012) and the *Mutual Wave Machine* (2013), by the Marina Abramovic Institute Science Chamber and the neuroscientist Dr Suzanne Dikker, explore 'moments of

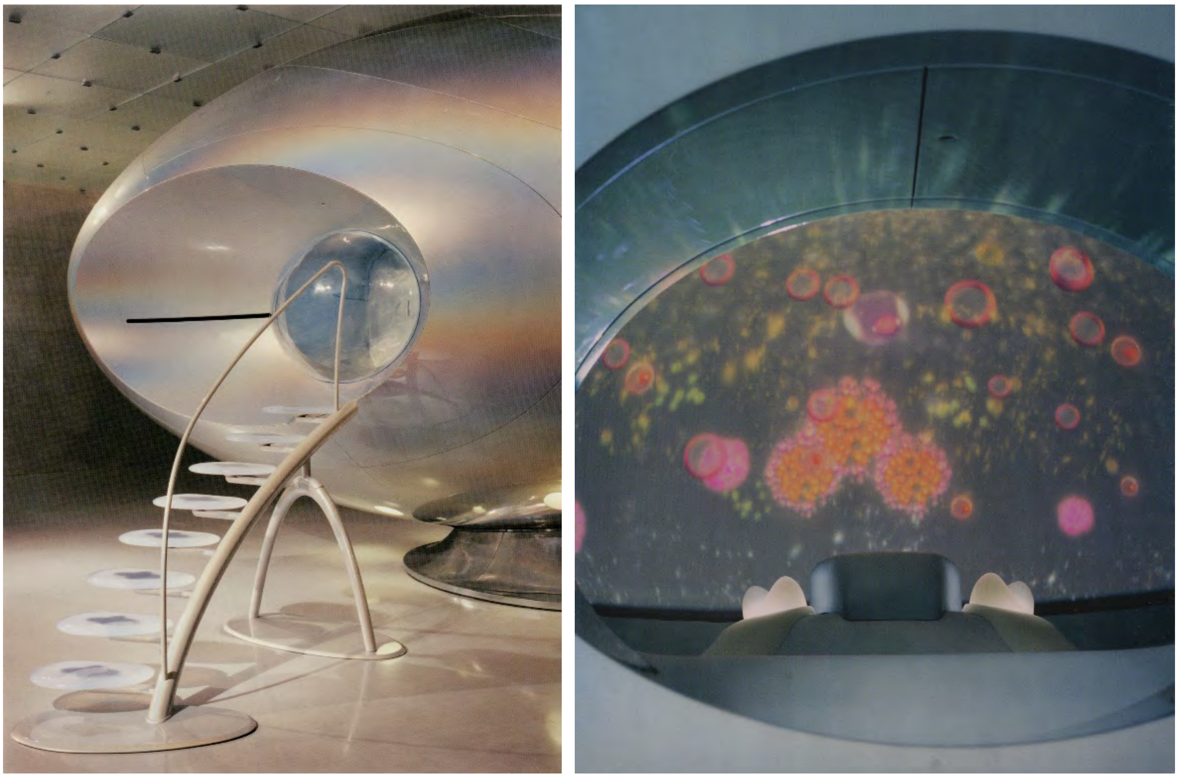


Figure 3.4 *Wave UFO* by Mariko Mori (Mori, Kunsthaus Bregenz and Schneider 2003, 29; 37).

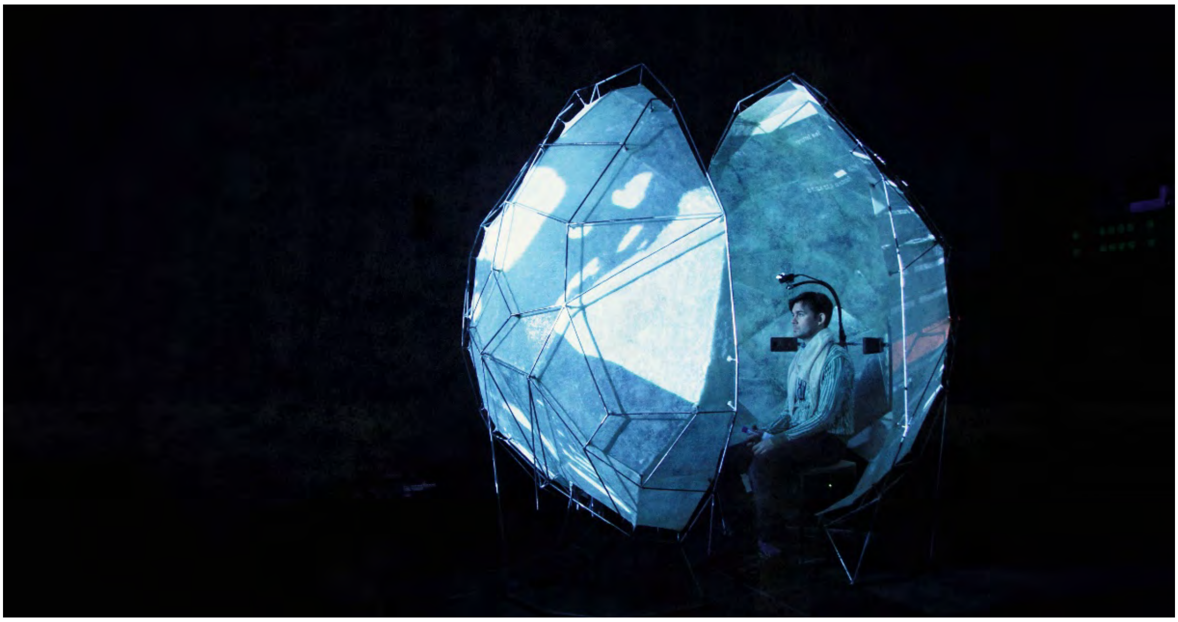


Figure 3.5 *Mutual Wave Machine* by Suzanne Dikker, Matthias Oostrik, Peter Burr, Diederik Schoorl and Matthew Patterson Curry (Dikker 2014).

synchrony’ of the brain-activity between two participants, when they interact by gazing at each other (Figure 3.5) (Dikker 2014). As Dikker explains by ‘moments of synchrony’ are meant points in time when the two participants present the same predominant brain-activity (Marina Abramovic Institute 2014). In both cases, Mariko Mori’s work and the projects by the Marina Abramovic Institute Science Chamber and Dr Suzanne Dikker, the concept of synchronisation between multiple participants is implemented by focusing in and examining the temporal EEG brain-activity within the range of either one specific frequency band and/or examining a wider spectrum.

As presented in the previous sections, in the field of live computer music performances, Eaton, Jin, and Miranda created in 2014 the piece *The Space Between Us*, where the brainwaves of a singer and a member of the audience are measured and processed in real-time separately or jointly, as an attempt of bringing the ‘moods of the audience and the performer closer together’ (Eaton 2015). In this case the phenomena investigated are the levels of valence and arousal within the EEG brain-activity (Eaton, Jin and Miranda 2014). The same year Rosenboom, Mullen and Khalil, presented the *Ringing Minds* (2014), introducing a new concept of the ‘hyper-brain’ as ‘the collective brain responses’ of four audience members interacting with the music. The performance refers to the idea of the participant/listener as performer/co-creator (Mullen at al. 2015, 201; 222), also found in Nina Sobell’s work. Previously in 2003, the *DECONcert* performance engaged forty-eight members of the audience adjusting the live music (Mann, Fung and Garten 2008)

Applications from the field of computer games can also provide us with relevant examples and inform us on specific methodologies implemented. There are different approaches in the implementation of BCIs in games, such as the use of neurofeedback, visually evoked potentials, and motor imagery, while the BCI itself is not always the central game mechanic. The majority of the games are designed for the interaction of one player’s brain activity. However, a smaller number, the ‘multi-brain games’ (Nijholt and Gürkök 2013), involve the interaction of two or more players’ brain-activity, not necessarily at the same time, while they are most commonly designed for multi-brain competition and less often for multi-brain collaboration. Whereas, brain-to-brain coupling and synchronisation seems to be promoted more in conditions of collaboration, than in conditions of competition. A game of this kind, designed for research purposes, is *Mind the Sheep!* (MTS!), which allows ‘both BCI and non-BCI play’ with the use of an EEG cap, and it is designed for a single-user, but also multi-users either collaborating or competing. The players use BCI/s in order to select and move dogs that help them fence the sheep in, while they can collaborate through visual, vocal and gestural communication (Nijholt and Gürkök 2013).

Another similar game is *BrainArena*, a football game for two players with two BCIs. The users ‘can score goals on the left or right of the screen by simply imagining left or right hand movements’. They can play either by competing against each other or by collaborating, in which case their brain activities are combined (Figure 3.6). The results of the experiments conducted for the evaluation of the performance and the user experience, have interestingly suggested that the multi-user conditions can be ‘operational, effective, and more engaging’ for the players, and even more, some of them showed significantly improved performance comparing to the single-user condition (Bonnet, Lotte and Lecuyer 2013, 185).

Observations like these can open a dialogue with behavioural studies, which can further advance the field. For example, Bahrami et al. studied collective decision making between different observers. Their results showed that for 'two observers of nearly equal sensitivity' collective decision making was more efficient than a single decision making process, 'provided that they were given the opportunity to communicate freely, even in the absence of any feedback about decision outcomes.' However, for observers with very different sensitivities the collaborative outcome was worse than the single decision making process (Bahrami et al. 2010, 1081).

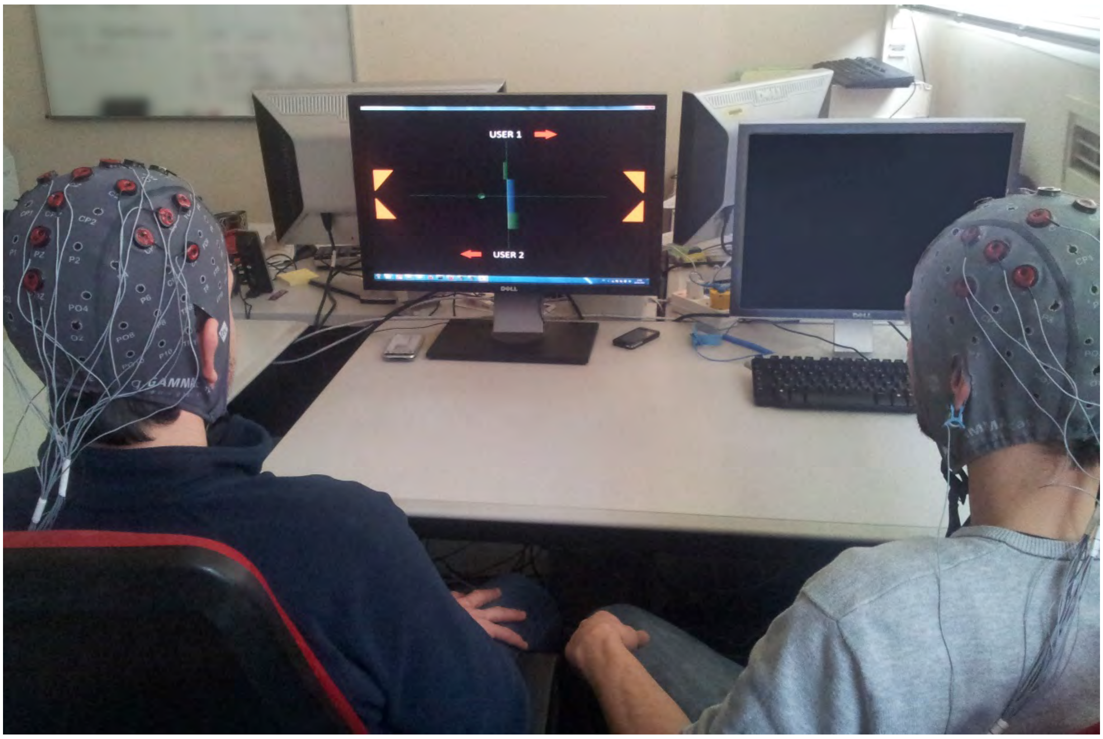


FIGURE 3.6 Two users playing *BrainArena* in a competitive trial (Bonnet, Lotte and Lecuyer 2013, 190).

Another example of brain-to-brain communication and synchronisation, applied in a computer game, is the first direct Brain-to-Brain Interface (BBI) between two humans, demonstrated by Rao et al. (2014). The interface, which is non-invasive, is designed to detect motor imagery in the EEG signals recorded from one participant (the 'sender'), which are then transmitted over the internet and delivered to the motor cortex of a second participant (the 'receiver') with the use of Transcranial Magnetic Stimulation (TMS). The BBI is used in order for the participants to corporate and achieve a desired goal in a computer game, which was to 'defend a city […] from enemy rockets fired by a pirate ship' with the use of a cannon (Figure 3.7). More specifically, the 'sender' was able to see the game on a computer screen, but could not control the cannon. No input device was provided, but the participant could communicate the intent to fire by imagining right hand movement. Through the recording of his/her EEG signals a cursor was controlled. When the cursor hit 'fire', a signal was transmitted from his computer over the internet, to the computer connected to the TMS machine, which was then sending a pulse to the 'receiver'. The 'receiver' could not see the game, but the stimulation he/she received was causing a quick movement of the right hand, enabling him/her to press a touchpad, in order to fire the cannon. The two participants were remotely located and had no communication with each other, apart from the BBI (Rao et al. 2014).

Recently, MyndPlay released the game 'Focus Pocus' (Figure 3.8), described by the company as an 'Interactive attention and brain development training game for children' (MyndPlay 2017a), and is

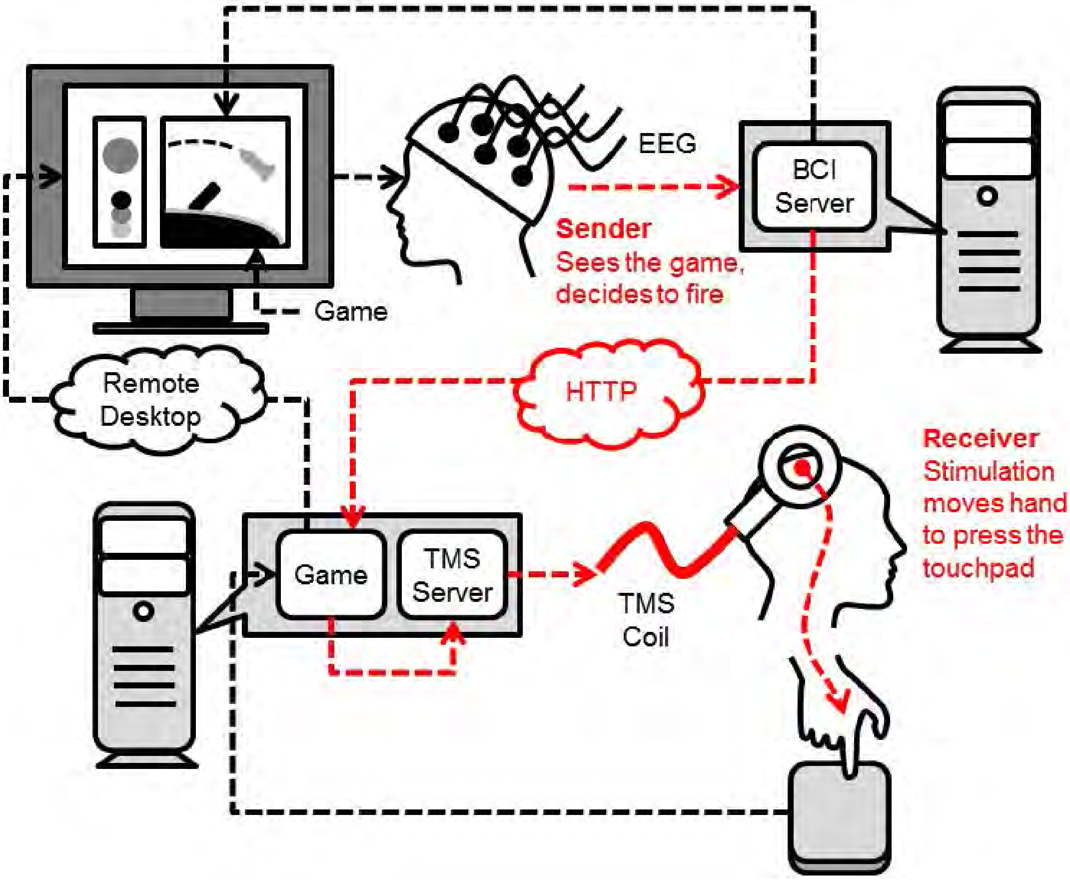


FIGURE 3.7 Schematic diagram of the BBI set-up (Rao et al. 2014, 18).

FIGURE 3.8 The *Focus Pocus* game by MyndPlay (2017a).

designed for educational purposes as well as a supplementary treatment method for Attention Deficit Hyperactivity Disorder (ADHD). The game can be played by both a single-player, as well as multiple players.

3.2 The challenges of the use of multi-brain BCIs in mixed-media performances

Today, the new wireless EEG-based devices provide the performers with greater kinetic and expressive freedom, especially when compared to wired systems and electrodes used by artists and pioneers like Alvin Lucier (*Music For Solo Performer* 1965), Claudia Robles Angel (*INsideOUT* 2009) and others. At the same time, they also offer a variety of connectivity solutions. They enable the computational and creative processing of a wide range of brain- and cognitive-states, according to the tasks executed, in consistency with the dramaturgical conditions and the creative concept of the performance. However, the design and implementation of multi-brain BCIs in the context of mixed-media performances is linked to a series of neuroscientific, computational, creative, performative and experimental challenges (Table 3.1).

Table 3.1 The challenges of the design and implementation of multi-brain BCIs in mixed-media performances.

Neuroscientific
• *Type of sensors* • *Unique brain anatomy of different participants wearing the devices* • *Location of the sensors during each performance* • *EEG low spatial resolution* • *Ratio of noise and non-brain artifacts to the actual brain signal*
Computational
• *Application design for non-desk-bound computer user* • *Limited Bluetooth physical range* • *Raw EEG data versus 'detection suites'* • *Independent and joint real-time multi-brain interaction and visualisation for more than two participants*
Creative and Performative
• *Performer/s' cognitive load* • *Meaningful BCI system design for performer/s and audience alike* • *Liveness* • *Technoformalism*
Experimental
• *Recruitment of participants* • *Coordination of study during a public event*

3.2.1 Neuroscientific challenges

Although EEG is a very effective technique for measuring changes in the brain-activity with accuracy of milliseconds, one of its technical limitations is the low spatial resolution, as compared to other brain imaging techniques, like fMRI (functional Magnetic Resonance Imaging), meaning that it has low accuracy in identifying the precise region of the brain being activated.

Additionally, the design and implementation of the EEG-based BCIs presents particular difficulties and is dependent on many factors and unknown parameters, presented in the previous chapter, such as the unique brain anatomy of the different participants wearing the devices during each performance, or the type of sensors used. Other unknown parameters include the location of the sensors, which might be differentiated even slightly during each performance, and the ratio of noise and non-brain artifacts to the actual brain signal being recorded. The artifacts can be either 'internally generated' or 'physiological' - EMG from the neck and face muscles, EOG from the eye movements and ECG from the heart activity; and 'externally generated' or 'non-physiological' - spikes from equipment, cable sway and thermal noise (Nicolas-Alonso and Gomez-Gil 2012, 1238; Swartz Center of Computational Neuroscience, University of California San Diego 2014).

3.2.2 COMPUTATIONAL CHALLENGES

As Heitlinger and Bryan-Kinns (2013, 111) point out, the Human-Computer Interaction research has mainly focused on 'users' abilities to complete tasks at desk-bound computers'. This is still evident also in the field of BCIs and the application development across games, interactive and performance art. Often this is necessary, such as in cases where SSVEP paradigms are used, for which users need to focus their attention at visual stimuli flickering at a constant frequency on a screen, for periods of several seconds that can be repeated multiple times. Similar conditions are also encountered in live computer music performances where the performers are limited by the music tasks they need to accomplish. However, for the brain-computer interaction of performers engaging with more intense body movement and making more active use of the performance space, like actors/actresses and dancers, the design of the BCI application needs to be liberated from 'desk-bound' constraints.

At the same time, the use of the performance space itself is also limited due to the available transmission protocols, such as Bluetooth, which is very common amongst the wireless BCI devices (Lee et al. 2013, 221) and has typically a physical range of 10m.

The new low-cost headsets that are used by an increasing number of artists creating interactive works have proven to be reliable for the real-time raw EEG data extraction (see also Section 3.1.4). At the same time, they also include ready-made algorithmic interpretations, filters and 'detection suites' which indicate the user's affective states, such as 'meditation' or 'relaxation', 'engagement' or 'concentration', which vary amongst the different devices and manufactures. However, the algorithms and methodology upon which the interpretation and feature extraction of the brain's activity is made are not published by the manufactures and therefore their reliability is not equally verified. Towards this direction new research is trying to understand the correlates of individual functions, such as the attention regulation, and compare them to published literature (van der Wal and Irrmischer 2015, 192).

Moreover, multi-brain applications designed for simultaneous real-time interaction of both performers and members of the audience in a staged environment, like in mixed-media performances, are rather new and have involved so far up to two interacting brains. What kind of methods need to be developed and what tools to be used in order to visualise, both independently as well as jointly, the real-time brain-activity of multiple participants under these conditions?

3.2.3 CREATIVE AND PERFORMATIVE CHALLENGES

The use of interactive technology in staged works presents major creative and performative challenges, especially when audience members become participants and co-creators. This occurs as the aim is to achieve 'a comprehensive dramaturgy' with 'a high level of narrative, aesthetic, emotional and intellectual quality'. While, at the same time a great emphasis is placed 'on the temporal parameter' of the interaction, which needs to be highly coordinated comparing to interactive installations that in most cases can be activated whenever the visitor wants (Lindinger et al. 2013, 121).

In the case of BCIs, the different systems are categorised as 'active', 're-active' and 'passive', according to their interaction design and the tasks involved (see also Chapter 2.2.1). The passive derive their outputs from 'arbitrary brain activity without the purpose of voluntary control', in contrast to 'active' BCIs where the outputs are derived from brain activity 'consciously controlled by the user', while the 'reactive' BCIs derive their outputs from 'brain activity arising in reaction to external stimulation' (Zander et al. 2008). At the same time, one of the first creative challenges that the performer/s might face during a mixed-media performance that involves different tasks is the cognitive load. For example, if the performer/s need to dance, act and/or sing, it is highly difficult to execute at the same time mental tasks, such in the case of active or re-active BCIs.

Additionally, if we would like to involve both the performer/s' as well as the participating members' of the audience real-time brain-interaction, then we would need to approach the BCI design in a way that addresses the dramaturgical, narrative and participatory level, in order to induce 'feelings of immersion, engagement and enjoyment' (Lindinger et al. 2013, 122).

Moreover, in real-time audio-visual and mixed-media performances, from experimental underground acts to multi dollar music concerts touring around the world in big arenas, liveness is a key element and challenge. In the case of performers using laptops and operating software, the demonstration of liveness to the audience can be approached in various ways. The Erasers (2013) for example, transform the stage into an audio-visual laboratory, where the creative process and the different techniques they use to produce moving images and sound, as well as the final outcome, are immediately visible to the audience. Other performers use two projections, with one of them showing their computers' desktops and the other one showing the visual output/result. A similar approach is also live coding, a programming practice disseminated in contemporary music improvisational performances. In the case of using BCIs in real-time audio and visual performances, how could liveness be presented to the audience, and more specifically the real-time interpretation of the EEG activity in the creative process? In the field of live brain-computer mixed-media performances, the members of PULSE4ART group, awarded in *Errors Allowed Mediterranea 16 Young Artists Biennial* (2013) for their project *ALPHA* (Pulse 4 Arts and Oullier 2014), have mentioned that in the future they will engage the audience (and thus increase the element of liveness) by having them wear the headsets and contributing their EEG data to the performance, much like the way it was realised in their previous project. *ALPHA* was presented as an improvisation-based performance with live music, live visuals and the brain-activity of two dancers, wearing two EPOC headsets, extracted and mapped real-time to projected moving images (Association Bjcem 2013). In a similar direction, Lisa Park, in her demo video for her performance *Eudaimonia*, named after the Greek word meaning bliss, presents the idea of an installation with the collaboration of eight to ten participants wearing portable BCI devices. As in her 2013 performance, discussed in Section 3.1.4, the brain-activity of the participants are physicalised as sound-waves, played by speakers placed underneath a shallow pool of water, vibrating and creating 'corresponding ripples and droplets' on the surface (Park 2014).

Last but not least, as it is known from the history of arts when a new medium is introduced, the first works are commonly oriented around the capabilities and the qualities of the medium itself. The use of BCIs in interactive art has not been an exception. However, a negative manifestation of this tendency is technoformalism, the fetishising of the technology (Heitlinger and Bryan-Kinns 2013, 112), when the artists' focus on the medium is made at the expense of the artistic concept and the underpinning ideas of the creative process. In a way this moment in history presents similarities with the first years of the development of computer art. A. Michael Noll, an early pioneer in the use of digital computers in the visual arts, whose research includes work in the effects of media on interpersonal communication, three-dimensional computer graphics, human-machine tactile communication, speech signal processing, and aesthetics (Noll 2016), has prophesised the communication of artists with computers via an EEG. He has also pointed out the aesthetic problem of early computer art (Noll 1970, 11):

> *The computer has only been used to copy aesthetic effects easily obtained with the use of conventional media […] The use of computers in the arts has yet to produce anything approaching entirely new aesthetic experiences […].*

In the case of the use of BCIs how could this be avoided and how can the specific technologies serve the purpose of the creative concept?

3.2.4 EXPERIMENTAL CHALLENGES

When EEG studies are conducted in a lab environment there is greater flexibility and freedom compared to studies attempted in a public space and moreover under the tight conditions of a mixed-media performance. In a lab experiment the allocation of a time that is suitable for the research purposes and convenient for the participants is easier and can expand during a longer period. While in a performance setting the study needs to be organised according to the event and venue logistics. Additionally, a lab environment is a more informal and private space comparing to a public performance venue, where apart from the researcher/s and the participants, other spectators are also present, a fact that increases considerably the psychological pressure for a successful process. Moreover, conducting an EEG study within the frame of a public mixed-media performance, involves many additional elements that need to be coordinated and precisely synchronised, like for example live video projections with live electronics and the real-time acquisition and processing of the participants' data.

3.3 SUMMARY

There is no doubt that the new wireless devices are not only the future, but already the present in the field of live brain-computer mixed-media performances. Artists are not only enabled with the new EEG technologies to use their own brain in their creative practices in the most direct way made so far possible, but they are also given a new freedom of access, interpretation, communication, interaction, and the ability to investigate new performative patterns.

The presented and discussed artists and their work (Table 3.2) is part of a continuously increasing number of imaginative applications, creative and playful ideas that have emerged within only a few years. The new wireless devices help performers to overcome the so far dominant constraints, providing them with greater kinetic and expressive freedom, but at the same time they also present new challenges. By taking into account both the advantages and disadvantages, the opportunities and limitations of the technology, in comparison with the current scientific research and methodologies, artists can enrich their practices in a meaningful and consistent to the medium way. They will be able to contribute to the advancement of the field and the creation of a greater and more validated area of investigation in discourse with other relevant practices.

From the presented challenges of the design and implementation of multi-brain BCIs in mixed-media performances also derives the main question of the currently discussed research:

> *What might be an effective model for the simultaneous multi-brain interaction of performers and audiences using EEG-based BCIs in the context of live cinema and mixed-media performances?*

Accordingly, I present in Chapter 4 *Enheduanna – A Manifesto of Falling*, the first demonstration of a live brain-computer cinema performance, as a complete combination of creative and scientific solutions, in the frame of the use of BCIs in performances that involve audience participation and interaction with a performer (Nijholt and Poel 2016, 81). This new work enables for the first time, to my present knowledge, the simultaneous real-time interaction with the use of EEG of more than two participants, including both a performer as well as members of the audience in the context of a mixed-media performance.

Table 3.2 A survey of performative and interactive artworks with the use of single- and multi-brain BCIs.

Year & Artist	Artwork & Description	Performer/s with BCI	Audience with BCI
1965: A. Lucier	*Music For Solo Performer:* **music performance**, the first known real-time performance using EEG (Ashley 1975).	One performer	-
1972: D. Rosenboom	*Portable Gold and Philosophers' Stones* (*Music From the Brains In Fours*): early **music performance** for multiple participants (Nijholt 2015).	Four performers	-
1972: N. Sobell	*Brainwave Drawings:* early **interactive video drawings** exploring the dynamic communication and collaboration of two participants as actors/co-creators of the final artwork (ninasobell 2008).	-	Two participants
1973: J. Humbert	*Alpha Garden:* early **installation**, one of the first works explicitly referring to and making use of the synchronisation of two participants' brain-activity (Nijholt 2015).	-	Two participants
1974: J. Humbert	*Brainwave Etch-a-Sketch:* early **interactive drawing** for two participants (Nijholt 2015).	-	Two participants
2003: M. Mori	*Wave UFO:* immersive **video-installation** for multiple participants' alpha, beta, and theta brain-activity and coherence (Mori, Kunsthaus Bregenz and Schneider 2003).	-	Three participants
2003: S. Mann, J. Fung and A. Garten	*DECONcert:* **music performance** with the largest known number of audience adjusting the live music (Mann, Fung and Garten 2008).	-	Forty-eight audience
2009: C. R. Angel	*INsideOUT:* **mixed-media performance** with the use of an open source EEG interface (Angel 2011).	One performer	-
2010: F. Peters and M. Yee-King	*Music of the Mind:* **music performance** using ERPs for 'making high-level musical decisions' (Grierson, Kiefer and Yee-King 2011).	One performer	-
2010: S. Le Groux, J. Manzolli and P. F.M. Verschure	*Multimodal Brain Orchestra:* **music performance**, where a conductor chooses sounds and tempo triggered by four performers' brain activity, two wearing P300 and two using SSVEP BCIs (Le Groux, Manzolli and Verschure 2010).	Four performers	-

(continued)

Table 3.2 (continued)

Year & Artist	Artwork & Description	Performer/s with BCI	Audience with BCI
2011: M. Abramovic, S. Dikker and M. Oostrik	*Measuring the Magic of Mutual Gaze:* **installation** exploring 'moments of synchrony' of participants gazing at each other (Dikker 2014).	-	Two participants
2011-14: G. Leslie and T. Mullen	*MoodMixer:* **installation** with visual display and 'generative music composition' for multiple participants. The latest versions measure the EEG valence and arousal levels (Mullen et al. 2015).	-	Two participants
2012: L. Silbert, J. Silbert, S. Dikker, M. Oostrik, O. Hess and A. Parkes	*The Compatibility Racer:* **installation** exploring 'moments of synchrony' of participants gazing at each other (Dikker 2014).	-	Two participants
2013: S. Dikker, M. Oostrik, P. Burr, D. Schoorl and M. P. Curry	*The Mutual Wave Machine:* **installation** exploring 'moments of synchrony' of participants gazing at each other (Dikker 2014).	-	Two participants
2013: L. Park	*Eunoia:* **music performance** where the EEG data are amplified and transmitted through five speakers, creating 'varieties of water forms' inside metal plates (Park 2013).	One performer	-
2013: PULSE4ART	*ALPHA:* **mixed-media performance** with the brain-activity of two dancers, mapped real-time to projected moving images (Association Bjcem 2013).	Two performers	-
2013: A. J. Williams, A. Wakeman and R. Wollner	*Untitled:* **installation** with generative music engine, where the rules are adjusted by the EEG data (Williams 2014).	-	One participant
2014: J. Eaton, W. Jin, and E. Miranda	*The Space Between Us:* **music performance** for a performer and an audience member with the use of a system that measures the valence and arousal of the users (Eaton, Williams and Miranda 2015, 103).	One performer	One audience
2014: D. Rosenboom, T. Mullen and A. Khalil	*Ringing Minds:* **music performance** with the use of a 'hyper-brain' of four audience members interacting with the music as performers/co-creators (Mullen at al. 2015).	-	Four audience
2015: P. Zioga and A. Katsinavaki	*Enheduanna – A Manifesto of Falling:* first **live brain-computer cinema performance** for more than two participants, including both performer/s and audience member/s (Zioga et al. 2016).	One performer	Two audience

[…] Keep Ithaca always in your mind.
Arriving there is what you are destined for.
But do not hurry the journey at all.
Better if it lasts for years,
so you are old by the time you reach the island,
wealthy with all you have gained on the way,
not expecting Ithaca to make you rich. […]

C. P. Cavafy's *Ithaca* 1910-1911 (Keeley & Sherrard, 1992)

4. *'ENHEDUANNA – A MANIFESTO OF FALLING'* *LIVE BRAIN-COMPUTER CINEMA PERFORMANCE*

In the previous chapter I presented a critical review of the use of single- and multi-brain BCIs in performative works that involve the real-time participation of an audience. The common key characteristics were identified, together with the particular challenges of the design and implementation of multi-brain EEG-based BCIs in mixed-media performances. Based on these, the main question of the currently discussed research is to identify an effective model for the simultaneous multi-brain interaction of performers and audiences using such systems in the context of live cinema and mixed-media performances.

In order to address this question, scientific and creative practice-based methodologies were combined and *'Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance* was realised as a complete combination of creative and research solutions and as the research case study, reviewed and approved by the Glasgow School of Art Research Ethics Committee. In this chapter, after the description and aims outlined in Section 4.1, the cognitive approach that was followed is explained in Section 4.2, whereas Section 4.3 presents the scientific methodologies followed and the new passive multi-brain EEG-based BCI system that was implemented. Finally, Section 4.4 presents the creative concept and the methodologies that were used, focusing more specifically in directing and live cinema, interactive storytelling, the narrative structure and the live visuals.

4.1 DESCRIPTION AND AIMS

Enheduanna – A Manifesto of Falling (2015) is a live brain-computer cinema performance, a new interactive performative work that combines live, mediatised representations, more specifically live cinema, and the use of BCIs. The project involves a multidisciplinary team. The key collaborators of the project include myself, as the director, designer of the Brain-Computer Interface system, live visuals and BCI performer; the actress and writer of the inter-text Anastasia Katsinavaki; the composer and live electronics performer Minas Borboudakis; the director of photography Eleni

Onasoglou; the MAX MSP Jitter programmer Alexander Horowitz; Ines Bento Coelho as the choreographer; the costumes designer Ioli Michalopoulou; the software engineer Bruce Robertson; Hanan Makki as the graphic designer; Jack McCombe and Alexandra Gabrielle responsible for the video documentation; Shannon Bolen for the sound recording and Catherine M. Weir for the photo documentation.

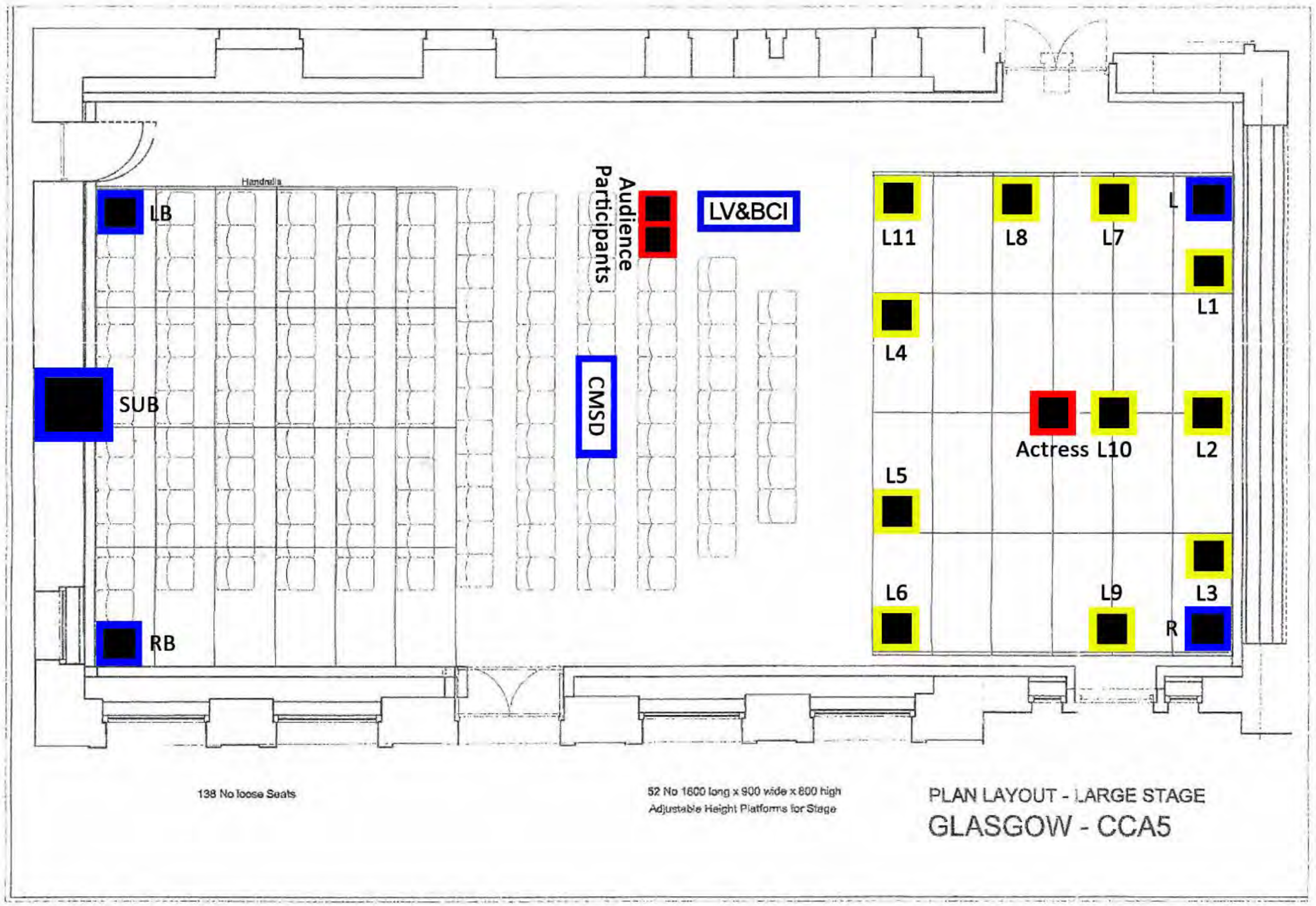
The performance is an artistic research project, which aims to investigate in practice the challenges of the design and implementation of multi-brain BCIs in mixed-media performances, as demonstrated in Chapter 3, and develop accordingly a combination of creative and research solutions. It involves a large production team of professionals, performers and public audiences in a theatre space. The concept of the performance is based on the following elements: my aesthetic, visual and dramaturgical vision as the director; the thematic idea and the inter-text written by the actress; as well as the design and implementation of a new passive multi-brain EEG-based BCI System. More specifically, the work, with an approximate duration of 50 minutes, involves the live act of three performers - myself as the live visuals (live video projections) and BCI performer, the live electronics and music performer, and the actress - and the participation of two members of the audience, with the use of the passive multi-brain EEG-based BCI system. The real-time brain-activity of the actress and the audience members control the live video projections and the atmosphere of the theatrical stage, which functions as an allegory of the social stage. The premiere took place at the Theatre space of CCA: Centre for Contemporary Arts, Glasgow, UK, from 29 to 31 July 2015 (CCA 2015) involving different audience and participants each day (Figure 4.1).

The space configuration had a total capacity of 138 spectators. The technical specifications of the space (Figure 4.2) included: a stage with an approximate width of 710cm, 540cm depth and 60cm height; a video projection screen with approximate dimensions of 370cm x 400cm; an HD video projector; and a 4.1 sound system with two active loudspeakers located at the back of the stage, two more at the far end of the space together with one active sub bass unit.

The thematic idea of the performance explores the life and work of the historical figure of Enheduanna (ca. 2285-2250 B.C.E.), an Akkadian Princess, the first documented High Priestess of the deity of the Moon Nanna in the city of Ur (present-day Iraq), who is regarded as possibly the first known author and poet in the history of human civilisation, regardless of gender (Center for Digital Discourse and Culture, Virginia Tech University 1999). In her most known work, T*he Exaltation of Inanna* (Hadji 1988), Enheduanna describes the political conditions under which she was removed from high office and sent into exile. She speaks about the ‘city’, power, crisis, falling and the need for rehabilitation. Her poetry is used as a starting point for a conversation with the work of contemporary writers, Theodor W. Adorno et al. (1950), Maya Angelou (1995), Jean Laplanche and Jean-Bertrand Pontalis (1988), Pavlina Pampoudis (1989), Virginia Woolf (2002) and Marguerite Yourcenar (1974), that investigate the notions of citizenry, personal and social illness, within the present-day international, social and political context of democracy. The premiere was performed in English, French and Greek with English supertitles (CCA 2015).

This new work enables for the first time the simultaneous real-time interaction with the use of EEG of more than two participants, including both a performer as well as members of the audience in the context of a mixed-media performance.

FIGURE 4.1 '*Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance* promotional poster.



<u>Lights</u>
L1, L2... L11: Light 1, Light 2... Light 11

<u>Audio</u>
L: Left speaker
R: Right speaker
LB: Left-back speaker
RB: Right-back speaker
SUB: Subwoofer
CMSD: Computerised Mixing Sound Desk for live electronics performer

<u>Live Visuals</u>
LV&BCI: Live Visuals and BCI performer

FIGURE 4.2 Technical and lighting design for '*Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance* at CCA: Centre for Contemporary Arts Glasgow, 30-31 July 2015.

4.2 The cognitive approach

As I mentioned in Chapter 3, if we would like to combine the performer's and the audience participants' real-time brain-activity, we need to approach the BCI design in a way that addresses the dramaturgical, narrative and participatory level of the work. In *Enheduanna – A Manifesto of Falling* the actress' performance involves speaking, singing, dancing and intense body movement, sometimes even simultaneously, as it is common in similar staged works. This results to a very important challenge: the cognitive load she is facing and because of which it is not feasible for her to execute at the same time mental tasks such as those used for the control of 're-active' and 'active' BCIs i.e. focusing her attention at visual stimuli on a screen for periods of several seconds and repeated multiple times or trying to imagine different movements (motor imagery). For this reason, the cognitive approach in the design of the performance was focused on the 'arbitrary brain activity without the purpose of voluntary control' (Zander et al. 2008) and a passive BCI system was developed for both the performer, as well as for the audience participants. This is a feasible solution for the actress' cognitive load, but it also presents two opportunities. It allows us to directly compare the brain-activity of the performer and the audience. It also enables us to study and compare the experience and engagement of the audience in a real-life context, which is multi-dimensional and bears analogies to free viewing of films, extensively studied in the interdisciplinary field of neurocinematics, which is investigating the effect of films on the spectators' brain activity, searching for similarities in their spatiotemporal responses (Hasson et al. 2008, 1). This way a double aim is pursued: the development of a multi-brain EEG-based BCI system, which will enable the use of the brain activity of a performer and members of the audience as a creative tool, but also as a tool for investigating the passive multi-brain interaction between them.

4.3 The passive multi-brain EEG-based BCI system

The design of the passive multi-brain EEG-based BCI system is based on a model of interactions between the performer/s and the audience in the context of live brain-computer mixed-media performances (Figure 4.3). The model demonstrates the collective participation and co-creation of the mediatized elements of the performance.

Furthermore, the passive multi-brain EEG-based BCI system consists of the following parts (Figure 4.4): the performer and the audience participants; the data acquisition; the real-time EEG data processing and feature extraction; and the MAX MSP Jitter programming.

4.3.1 Participants

The participants of the study included the actress, who performed in all three events - the dress rehearsal, the premiere and the second public performance, and six members of the audience, two for each event. The audience participants were recruited in the close geographical proximity. The inclusion criteria were general adult population, aged 18-65 years old, both female and male. The exclusion criteria were not to suffer from a neurological deficit and not to be receiving psychiatric or neurological medication. The participants were asked to avoid the consumption of coffee, tea, high caffeine drinks, cigarettes and alcohol, as well as the recreational use of drugs for at least twelve hours prior to the study, as these substances can affect the brain's electrical activity and

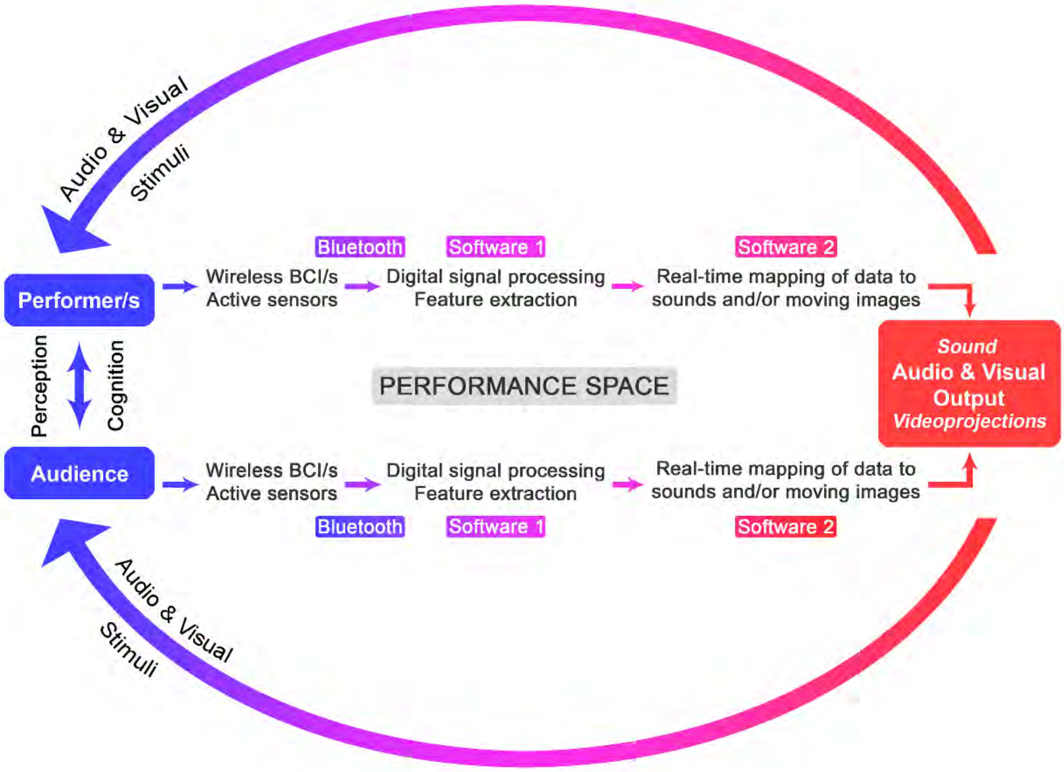


FIGURE 4.3 A model of interactions between the performer/s and the audience in live brain-computer mixed-media performances.

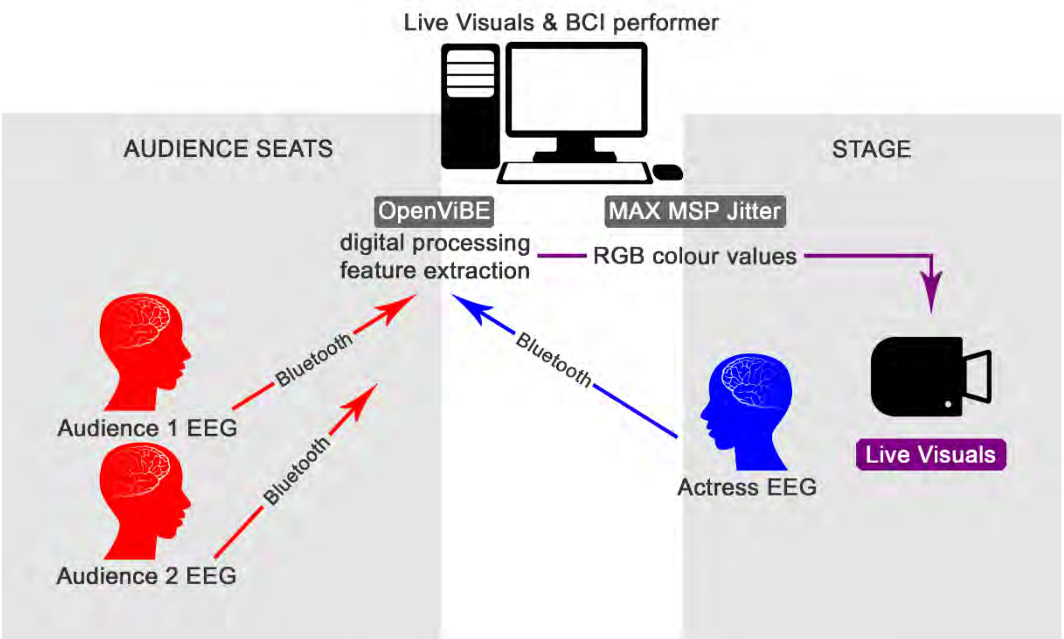


FIGURE 4.4 The passive multi-brain EEG-based BCI system. (Images of human heads originally designed by Freepik).

therefore the EEG recordings. They were asked to arrive at the space one hour before the performance, when the venue was closed for the public. This gave sufficient quite time to discuss any additional questions they might have, provide their informed consent, answer a preliminary brief questionnaire and start the preparation (Figure 4.5). Following the opening of the space to the public, they were asked to watch the performance like any other spectator and in the end to complete a final brief questionnaire (see Appendix A.1). The recruitment and the preparation of the actress followed a similar process, inclusion and exclusion criteria, similar informed consent and questionnaires (see Appendix A.2).

FIGURE 4.5 The live visuals and BCI performer preparing two audience participants prior to the performance at CCA: Centre for Contemporary Arts Glasgow, 30-31 July 2015. Photography by Catherine M. Weir.

As argued in Chapter 3, when EEG studies are conducted in a lab environment there is greater flexibility and freedom comparing to studies attempted in a public space and moreover under the tight conditions of a mixed-media performance. In the case of *Enheduanna – A Manifesto of Falling* the process described here, which includes informing the participants and answering their questions a few days prior to the study and also allowing for an hour without the presence of other spectators, has been adequate and helped to minimise the psychological pressure to both the participants as well as the researcher.

The audience participants were seated side by side together with a technical assistant, who was present in order to help them during the performance if they had a request or in the case they would have liked to withdraw. They were positioned facing the stage, at the left end of the third row, near the director and the MAX MSP Jitter programmer, but also within the standard 10m range of the Bluetooth connection with the main computer, where the EEG data were collected and processed (see 'Live Visuals' in Figure 4.2). At the same time, they had an excellent view of the entire performance and the video projections, while both the audience members as well as the actress were free from 'desk-bound' constraints.

4.3.2 EEG DATA ACQUISITION

The second part of the system involves the use of commercial grade EEG-based wireless devices. More specifically, the participants are wearing the *MyndPlay Brain-BandXL EEG Headset*, presented in Chapter 2, which was also used during the design phase of the system, in order to ensure that important parameters remain the same.

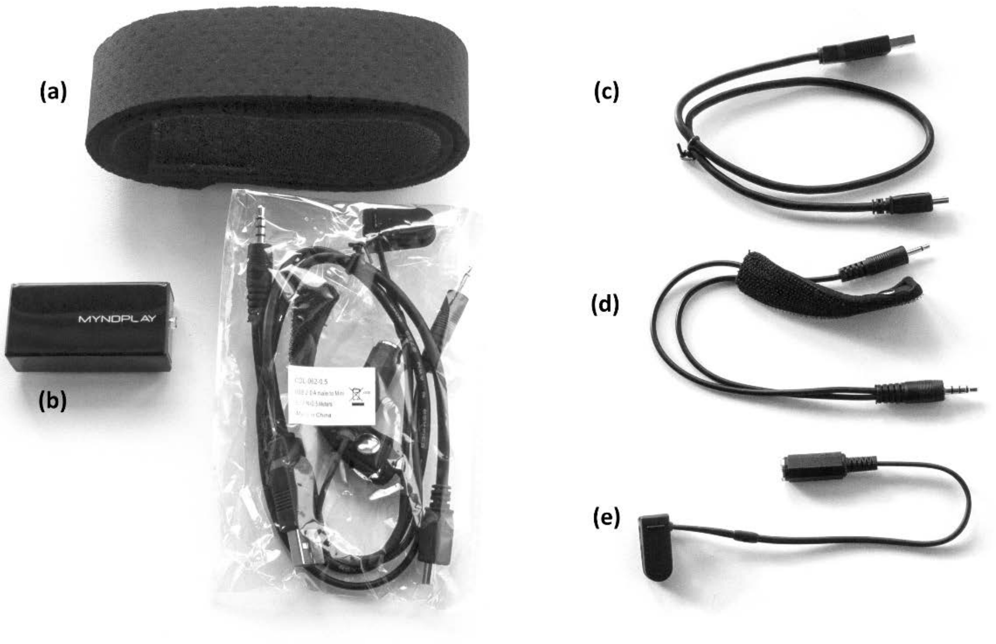


FIGURE 4.6 The components of the MyndPlay BrainBandXL EEG Headset: (a) the headband on which the rest of the components are attached; (b) the unit that transmits via Bluetooth the EEG data to the computer; (c) the USB cable for charging the unit; (d) the two dry sensors attached to a soft material similar to the one used for the headband; and (e) the ear clip with the grounding electrode for the ear lobe.

The headset has two dry sensors with one active, located in the prefrontal lobe (Fp1) (MyndPlay 2015). The components of the device are presented in Figure 4.6: the headband on which the rest of the components are attached, the unit that transmits via Bluetooth the EEG data to the computer, the USB cable for charging the unit, the two dry sensors attached to a soft material similar to the one used for the headband, and the ear clip with the grounding electrode for the ear lobe. The choice of the specific device was based on the following criteria:

(1) Low cost – feasible for works that involve multiple participants.
(2) Easy to wear design – crucial for the time constraints of a public event.
(3) Lightweight – convenient for use over prolonged periods such as during a performance.
(4) Aesthetically neutral - easier integration with the scenography and other elements such as the costumes.
(5) Dry sensors – same as [1].

(6) Position of the sensors on the prefrontal lobe – broadly associated with cognitive control.

The three devices (the actress' and the two audience participants') are always switched on and connected to the main computer one after another and in the same order, so that to ensure that they are always assigned the same COM (Communication) ports[c]. The raw EEG data are acquired and transmitted wirelessly to the main computer via Bluetooth at a sampling frequency of 512Hz with 32 sample count per sent block[d].

4.3.3 Real-time EEG data processing

In the third part of the system the real-time digital processing of the raw EEG data from each participant and device is performed with the OpenViBE software (Renard et al. 2010; see also Chapter 2). The two main components of the software include the 'Acquisition Server' (lbonnet 2011a), which receives the data from the EEG headset and the 'Designer' (lbonnet 2011b), an authoring tool with plugins and 'box algorithms' that can be flexibly combined and configured, allowing the user to design the preferred signal processing and data visualisation. However, the software does not include automatic functions that enable the simultaneous acquisition, processing and recording of data from multiple EEG headsets. In the case of the currently discussed system, this is achieved by configuring multiple 'Acquisition Servers' sending their data to corresponding 'Acquisition Clients' (Renard 2015) within the same Designer scenario (Figure 4.7). In this way, not only the simultaneous real-time multi-brain interaction of more than two participants becomes possible, but also the synchronisation with the live video projections is enabled, as I will demonstrate further along.

The processing continues by selecting the appropriate EEG channel with the 'Channel Selector' box (Mahe 2014) and by using algorithms that follow the frequency analysis method, a custom-based feature extraction is designed. Taking into consideration the challenges presented in Chapter 3, such as the unique brain anatomy of the different participants wearing the devices, the location of the sensors, which might be differentiated even slightly during each performance, but also the EEG's low spatial resolution, the methodology focuses on the oscillatory processes of the brain activity, that is the characteristics of the EEG frequency bands in time. The model is dynamic, meaning that the output is depending/changing according to time and it is also causal, meaning that the output depends only on the parameters in specific time and is not able to look/predict into the future (Swartz Center of Computational Neuroscience, University of California San Diego 2014). As it is demonstrated in Figure 4.7, with the use of temporal band-pass filters, the 4-40Hz frequencies that are meaningful in the conditions of the performance, are selected and separated (see 'EEG frequency separation'). More specifically, the frequency bands that are processed include the theta (4-8Hz), associated with deep relaxation but also emotional stress, the alpha (8-13Hz), associated with relaxed but awake state, the beta (13-25Hz) and the lower gamma (25-40Hz) that occur during intense mental activity and tension (Thakor and Sherman 2013, 261). The <4Hz

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[c] A COM port is a physical or virtual serial port interface on a PC, through which data is transmitted from different hardware to the PC.

[d] 512Hz with 32 samples per sent block results in one block of signal sent every 32/512 = 0.0625 seconds.

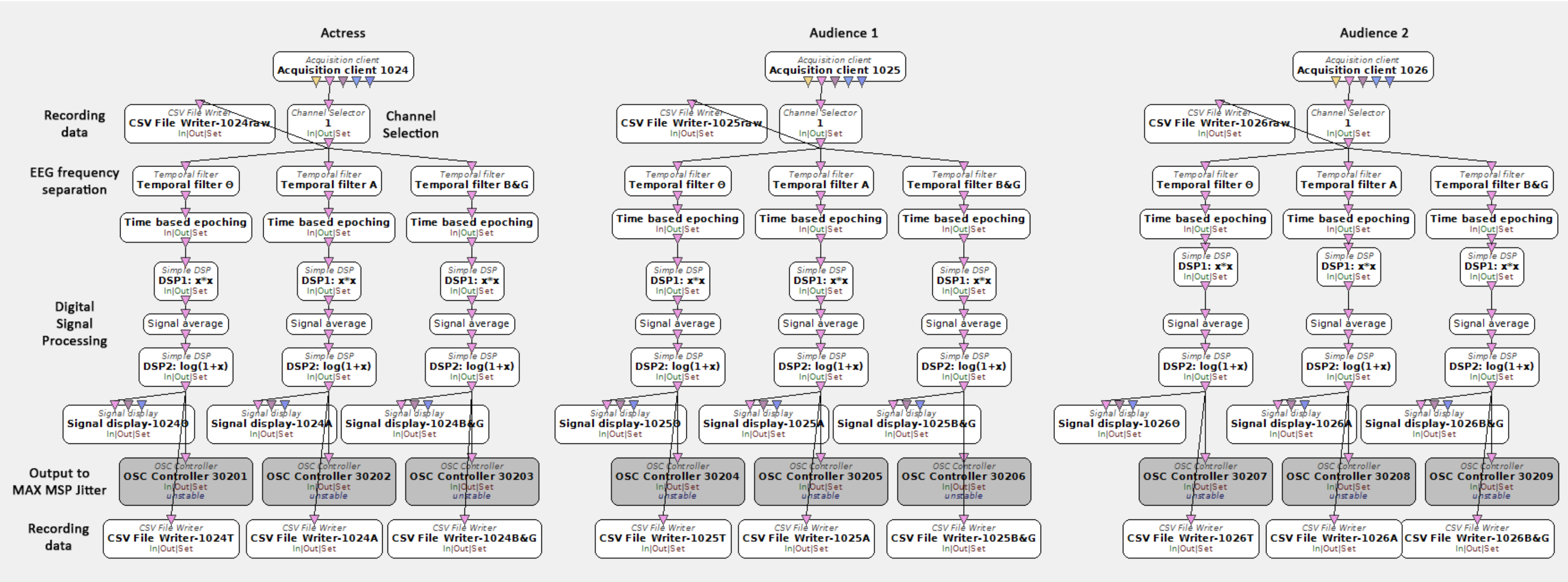


FIGURE 4.7 The OpenViBe Designer scenario for '*Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance*.

frequency, which corresponds to the delta band, and is associated with deep sleep, is rejected, in order to suppress low pass noise, EOG and ECG artifacts (artifacts deriving from the movements of the eyes and the cardiac muscle respectively). Also the 40Hz and above frequencies are rejected, in order to suppress EMG artifacts from the body muscle movements, high pass and line noise from electrical devices in the proximity of the performer and the participating spectator/s. This way the ratio of actual brain signal to the noise and non-brain artifacts being recorded is improved. The digital signal processing continuous by applying time based epoching, which generates blocks of signal with a configurable duration and interval (Renard 2016); followed by squaring ('DSP1'), averaging ('Signal average') and then computing the log(1+x) ('DSP2'), in order to extract the logarithmic power of each selected frequency band. Both the raw as well as the processed EEG data of each participant are being recorded as CSV files ('Recording data'), in order to be analysed off line after the performance. At the same time, signal display boxes are used to visually monitor the process in real-time and promptly identify any issues. The final objective of the signal processing and feature extraction is to send the generated values to the MAX MSP Jitter software. Since its initial development, OpenViBE has included various well-documented tools for streaming data and stimulations to external applications, such as the Virtual Reality Peripheral Network (VRPN) and the LabStreamingLayer (LSL) protocols, the Python and Matlab boxes and others. However, the use of these tools for sending data to hardware and software using the Open Sound Control (OSC) protocol, like the MAX MSP Jitter software, is not a one-step communication process and can present complexities and difficulties. The particular challenge in the design of the currently discussed system was successfully addressed with the use of a new, at the time, toolbox, the OSC Controller (Caglayan 2015), which sends the data as UDP (User Datagram Protocol) messages to the external applications.

4.3.4 MAX MSP JITTER PROGRAMMING

The fourth part of the system involves the MAX MSP Jitter programming. The main features include the processed EEG values of each participant, imported as OSC messages with the use of separate 'User Datagram Protocol (UDP) receivers' (Cycling 2016) in the first 'p inputs' subpatch (Figure 4.8), where they are scaled to RGB colour values from 0 to 255. More specifically, the processed data from the 13-40Hz frequency (beta and lower gamma) are mapped to the red value, the data from the 8-13Hz (alpha) band are mapped to the green value and from the 4-8Hz (theta) to the blue value. A second 'p averages' subpatch is designed in order to combine the values as averages used in specific parts of the performance, as it will be explained in more detail in Section 4.4.

From these two subpatches the resulting RGB values of each participant and their averages are imported into the main patch (Figure 4.9). There, the programming allows the user to select manually through the 'SELECT MAIN FEED' function either of the participants' processed signal and RGB values, individually ('perf' for performer, 'aud1' for audience participant 1, 'aud 2' for audience participant 2) or jointly ('average'), depending on the stage of the performance. Especially regarding the joint selection, the patch is programmed in order to allow additionally the real-time manual selection of different combinations through the 'AVERAGE INPUT' function. All the different selections then feed into a 'swatch' (max objects database 2015). The 'swatch' provides 2-dimensional RGB colour selection and display and combines in real-time the values creating a constantly changing single colour. The higher the incoming OSC message value of any given processed frequency, the higher the respective RGB value becomes and the more the final

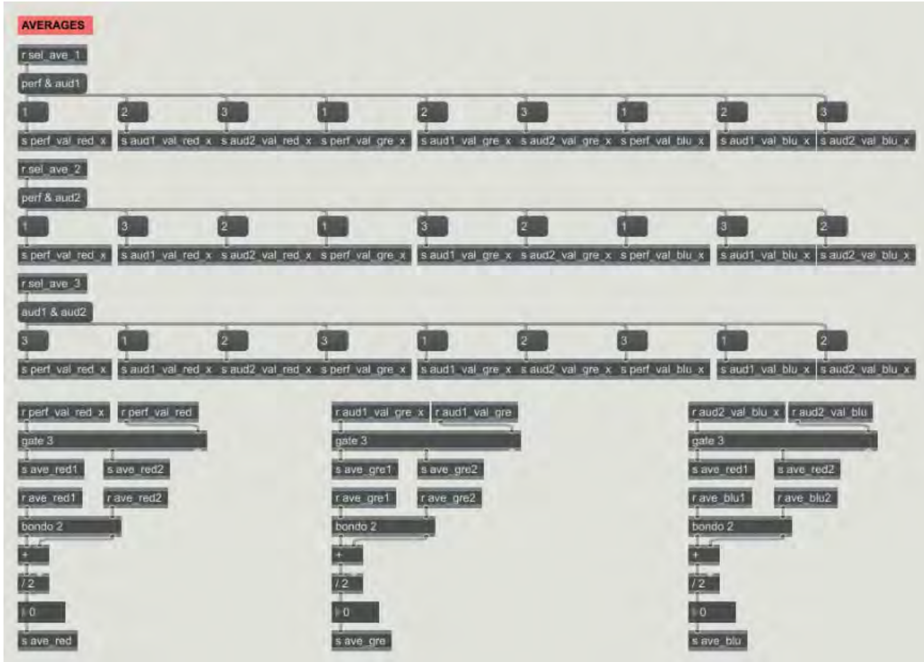


FIGURE 4.8 The MAX MSP Jitter subpatches for '*Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance*: 'p inputs' (left) and 'p averages' (right).

FIGURE 4.9 The MAX MSP Jitter patch for '*Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance*.

FIGURE 4.10 Stills from the pre-rendered black and white video files for '*Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance*.

colour shifts towards that shade. The generated colour is then applied as a filter, with a manually controlled opacity ('CONTROL OPACITY' function) of maximum 50%, to pre-rendered black and white video files reproduced in real-time (Figure 4.10). Additionally, the programming of the main patch enables the split of the filter in two equal vertical parts with the 'SELECT LEFT GLUE INPUT' and the 'SELECT RIGHT GLUE INPUT' functions, controlled by two different inputs/processed signals respectively, including a 'CONTROL CROSSFADE' function, allowing also for progressive blending. The resulting video stream is projected on a screen. Its chromatic variations not only correspond to a unique real-time combination of the three selected brain activity frequencies of multiple participants, but also serve as visualisation of their predominant cognitive states, both independently as well as jointly.

4.4 THE CREATIVE CONCEPT, METHODS AND PROCESSES

I started by presenting the cognitive approach and the passive multi-brain EEG-based BCI system, leaving the creative concept, methods and processes for the current section. However, these three directions have influenced each other and were co-designed during the entire preparation phase of the project. Also, the use of the BCI system has influenced almost every aspect of the creative production, such as the choreography, the scenography and even the lighting and the costumes design (Figure 4.11). Nevertheless, for the purposes of this dissertation I will focus on directing and live cinema, the interactive storytelling and narrative structure, and the live visuals.

FIGURE 4.11 Designs of the actress' costume for '*Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance* by Ioli Michalopoulou.

4.4.1 CREATIVE CONCEPT

The conceptualisation phase of the performance commenced in 2013, following *The Shelter* (2011-2012) video-installation and in parallel with the subsequent works *Where Am I at Home?* (2013) and *HOME network* (2013-2014) (see also Chapter 1.1.1). The common key elements and notions that were further developed include: the civic participation and interaction in a theatrical, which is also a public, setting; the sense of belonging in terms of our multi-cultural social environment and as a contemporary political question; and illness as a transformative personal experience projecting to a shared/collective sphere. These have been reflected first on the choice of the authors and the texts and subsequently on the narrative structure and interactive storytelling. On the one hand, the historical figure of the Akkadian Princess and High Priestess Enheduanna (ca. 2285-2250 B.C.E.) who lived in the city of Ur, in the present-day war-torn Iraq, has its own semiotic perspective. On the other hand, she is the first author and poet we know of that reveals her identity, including her gender (Center for Digital Discourse and Culture, Virginia Tech University 1999). At the same time, although she lived in pre-democratic times, in her most known work, T*he Exaltation of Inanna* (Hadji 1988), Enheduanna describes the political conditions under which she was removed from high office and sent into exile, speaking about the 'city', power, crisis, falling and the need for rehabilitation.

Nevertheless, her poetry is not used to create a historical work/portrait, but rather as a starting point for a conversation with the work of contemporary writers, reaching to the present-day international social and political scenery. In the context of power and its abuse, *The Authoritarian Personality* by Theodor W. Adorno et al. (1950) presents an extended social psychology study conducted after the World War II, which looked into identifying personality traits that can be linked to fascism and for this purpose introduced a questionnaire, the 'F [Fascist] scale'. Although the study has been criticised and today is considered out-dated, the 'F scale' includes a series of questions that can still be thought-provoking for the contemporary citizen. As a parallel discussion, *The language of psychoanalysis* by Jean Laplanche and Jean-Bertrand Pontalis (1988) presents the role of the identification in the development of the personality. In the context of crisis and falling, the *Feux* [Fires] by Marguerite Yourcenar (1974) speak about a profound inner torment and *O Enikos* [The Tenant] by Pavlina Pampoudis (1989) refers to mourning, the exile and time. The need of solace and rehabilitation in the work of Enheduanna is brought together with Virginia Woolf's essay *On Being Ill*, originally published in 1926, which addresses illness as a transformative power, common to us all. In the performance, the crisis, the falling and the personal illness are projected to a social sphere and by that they lead to a comment about our common origins and destination, expressed through the poem *A Brave and Startling Truth* by Maya Angelou (1995), at the beginning and at the end, as a prologue and epilogue.

At the same time, the concept of *Enheduanna – A Manifesto of Falling* as Live Brain-Computer Cinema Performance is developed according to the theoretical underpinnings established by previous relevant works and the gap/challenges that have been identified in the field. The brain-activity of the performer and the audience members is visualised as a creative medium; as a form of physicalisation, which is the process of rendering physical the abstract information of data through either graphical representation and visual interpretation or sonification (Tanaka 2012); and as demonstration of liveness that previous artists in the field, like the PULSE4ART group, have tried to address (see also Chapter 3.2.3) and will be further analysed in the following section. The idea of the viewer/participant as co-creator, found in the works of Nina Sobell, Rosenboom, Mullen and Khalil (see also Chapter 3.1.5), is explored. Whereas, the performance also investigates the correlation (synchronisation) of the participants' brain-activity, a concept found originally in Jaqueline Humbert's work and later installations by Mariko Mori, Suzanne Dikker and others (see also Chapter 3.1.5).

4.4.2 DIRECTING AND LIVE CINEMA

Following the conceptualisation phase, the performance was developed based on a series of directing choices and the use of live cinema as its cornerstone. As previously explained, a live brain-computer cinema performance is an event that combines live, mediatised representations, more specifically live cinema, and the use of BCIs. In particular, live cinema is defined as '[...] real-time mixing of images and sound for an audience, where […] the artist's role becomes performative and the audience's role becomes participatory.' (Willis 2009, 11). In the case of *Enheduanna – A Manifesto of Falling*, there are three performers, myself as the live visuals and BCI performer, the actress and the live electronics performer. The actress' activity and the participatory role of the audience members are enhanced and characterised by the use of their visualised real-time brain-activity as a physical expansion of the creative process, as an act of co-creating and co-authoring, and as an embodied form of improvisation, which is mapped in real-time to the live visuals. At the same time, I have a significantly different role than those usually encountered in a theatre play. I am the director, video artist and BCI performer on stage, a multi-orchestrator facilitating and mediating the interaction of the actress and the audience participants. Additional elements borrowed by the practices of live cinema include the use of non-linear narration and storytelling approach through the fragmentation of the image, the frame and the text.

Moreover, one of my preliminary directing preoccupations has been to avoid technoformalism and create a work not just orientated towards an entertaining, 'pleasurable, playful or skilful' result and interaction, but aiming to a 'meaning-making' of historical and socio-political themes (Heitlinger and Bryan-Kinns 2013, 113). The goal is to bring together the thematic idea of the life of Enheduanna with the passive brain-interaction of the actress and the audience as two complementary elements. This has been achieved in the conceptual as well as the aesthetic level.

A conceptual and dramaturgical non-linear dialogue is created between: the poetry of Enheduanna (Hadji 1988) who speaks about power, crisis, falling and citizenry; the work of the contemporary writers that investigate socio-political themes; and the passive brain-interaction of the participants as an allegory of the passive citizenry and its role in the present-day context of democracy.

In the aesthetic level, my basic directing strategy is to create multiple levels of storytelling and interaction. The texts in the three languages of the original literature references, Greek, English and French, are either performed live by the actress or her pre-recorded voice is reproduced together with the live electronics. This symbolically creates the effect of three personalities: the live narrator and two other female commentators, perceived as either external or as two other sides of her consciousness. The basic directing strategy also involves associating the different aspects of the real-time brain-activity of the participants to the colour of the live visuals. However, the visualisation is not uniform throughout the performance. It presents variations that follow the interactive storytelling pattern and the narrative structure presented in the following section.

4.4.3 INTERACTIVE STORYTELLING AND NARRATIVE STRUCTURE

As Ranciere (2007, 279) argues:

> *Spectatorship is not the passivity has to be turned into activity. It is our normal situation. We learn and teach, we act and know as spectators who link what they see with what they have seen and told, done and dreamed […] We do need to acknowledge that every spectator is already an actor in his own story and that every actor is in turn the spectator of the same kind of story.*

The interactive storytelling and the narrative structure in *Enheduanna – A Manifesto of Falling* consists of two parts introduced to the audience with vignettes projected during the live visuals (Figure 4.12 and Figure 4.13): in part 1, titled 'Me', the interaction is based solely on the actress' brain-activity (Figure 4.14), while in part 2, titled 'You/We', it is based first on either of the two audience members' brain-activity (Figure 4.15) and then on the combination of the actress and one of the audience members (Figure 4.16 and Figure 4.17).

The two parts of the performance are further divided into five scenes. The first three correspond to part 1 and the last two to part 2: scene 1 'Me Transmitting Signals' with an approximate duration of 13min 14sec (Figure 4.14; see also Accompanying Material/Film from beginning to 13min 25sec approximately); scene 2 'Me Rising' with an approximate duration of 8min 42sec (Figure 4.14; see also Accompanying Material/Film from 13min 25sec to 22min 05sec approximately); scene 3 'Me Falling' with approximate duration of 10min 14sec (Figure 4.14; see also Accompanying Material/Film from 22min 05sec to 32min 16sec approximately); scene 4 'You Measuring the F-Scale' with approximate duration of 5min 00sec (Figure 4.15; see also Accompanying Material/Film from 32min 16sec to 37min 55sec approximately); and scene 5 'We' with approximate duration of 9min and 43sec (Figure 4.16 and Figure 4.17; see also Accompanying Material/Film from 37min 55sec to 47min 35sec approximately).

In part 1 we are introduced and immersed in the story of Enheduanna in a more traditional theatrical manner, with the actress being perceived by the audience as a third person (she) (Dixon 2007, 561). Starting with a prologue referring to the beginning of times and our voyage in a universal setting (Angelou 1995), the performer emerges as an undefined mass, takes the form of a statue, gradually becoming human and then feminine, while *The Exaltation of Inanna* (Hadji 1988) unfolds. In the process, her story reaches a climax of power, which is violently interrupted at the end of scene 2, whereas scene 3 represents a state of crisis, mourning and inner torment. In part 2 we witness her transformation to becoming a second person (you), when the audience members are addressed (Dixon 2007, 561). This transformation/transition is promoted with the use of different theatrical elements. The actress is present performing throughout part 1, but at the end of scene 3 she leaves the stage. The lights fade out and two soft spots above the two audience participants are turned on throughout scene 4 and the first half of scene 5. This way the performance becomes a cinematic experience, while the use of light underlines the control of the live visuals by the audience's brain activity (Figure 4.15). At the same time, they are confronted with the 'F scale' (Adorno et al. 1950) and a series of provocative questions (see also Section 4.4.1), projected on the screen during scene 4, calls the audience to reflect upon and leads to the second climax of the performance, which is again violently interrupted. At the beginning of scene 5, the actress reappears on stage addressing directly the audience (Figure 4.16) and citing fragments from *On Being Ill* (Woolf 2002), while their real-time brain-interaction gradually merges and their averaged values control the colour filter applied to the live video stream (Figure 4.17).

This way, the narrative and dramaturgical structure fulfils the directing vision and aim of bringing together the thematic idea of the performance with the use of the interaction technology in a coherent and comprehensive manner. It associates the real-time brain-activity of the participants to the colour of the live visuals within a consistent storytelling process and by this it also serves as an evidence of liveness.

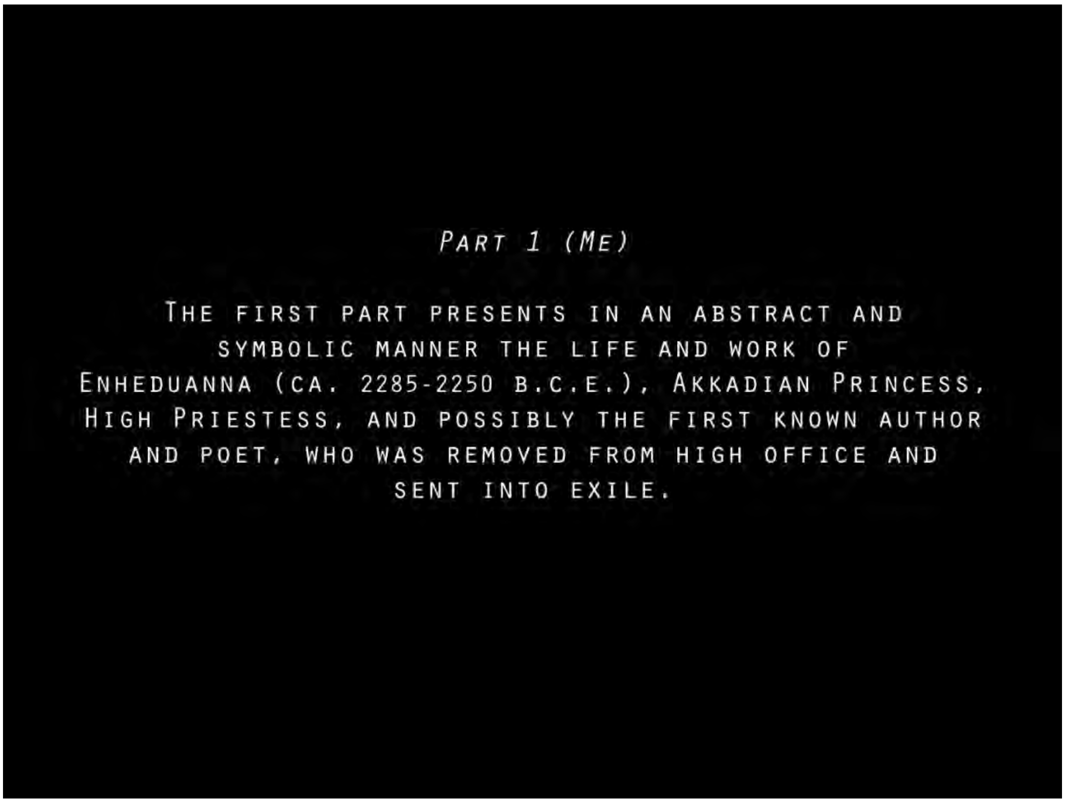


FIGURE 4.12 Vignette introducing part 1 'Me' of *'Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance*.

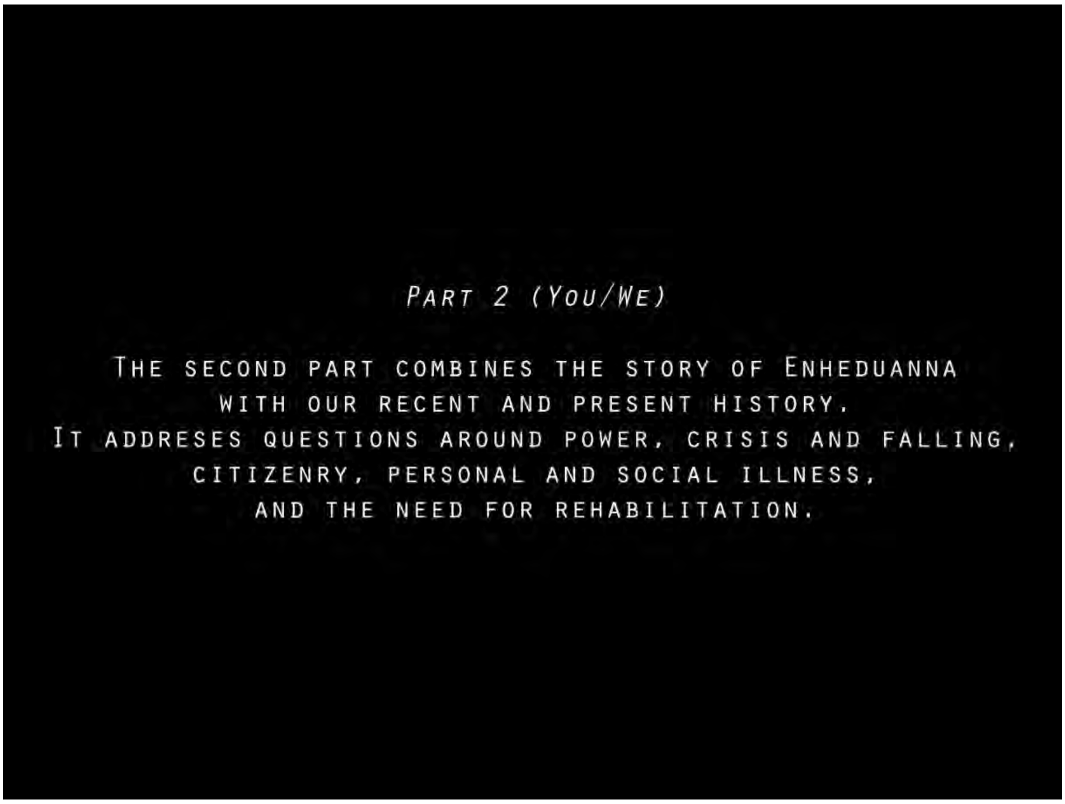


FIGURE 4.13 Vignette introducing part 2 'You/We' of *'Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance*.

Figure 4.14 Part 1 'Me' of *'Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance* at CCA: Centre for Contemporary Arts Glasgow, 30-31 July 2015. Photography by Catherine M. Weir.

FIGURE 4.15 Part 2 ‘You/We’, Scene 4 ‘You Measuring the F-Scale’ of *‘Enheduanna – A Manifesto of Falling’ Live Brain-Computer Cinema Performance* at CCA: Centre for Contemporary Arts Glasgow, 30-31 July 2015. Photography by Catherine M. Weir.

FIGURE 4.16 Part 2 'You/We', first half of scene 5 'We' of '*Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance* at CCA: Centre for Contemporary Arts Glasgow, 30-31 July 2015. Photography by Catherine M. Weir.

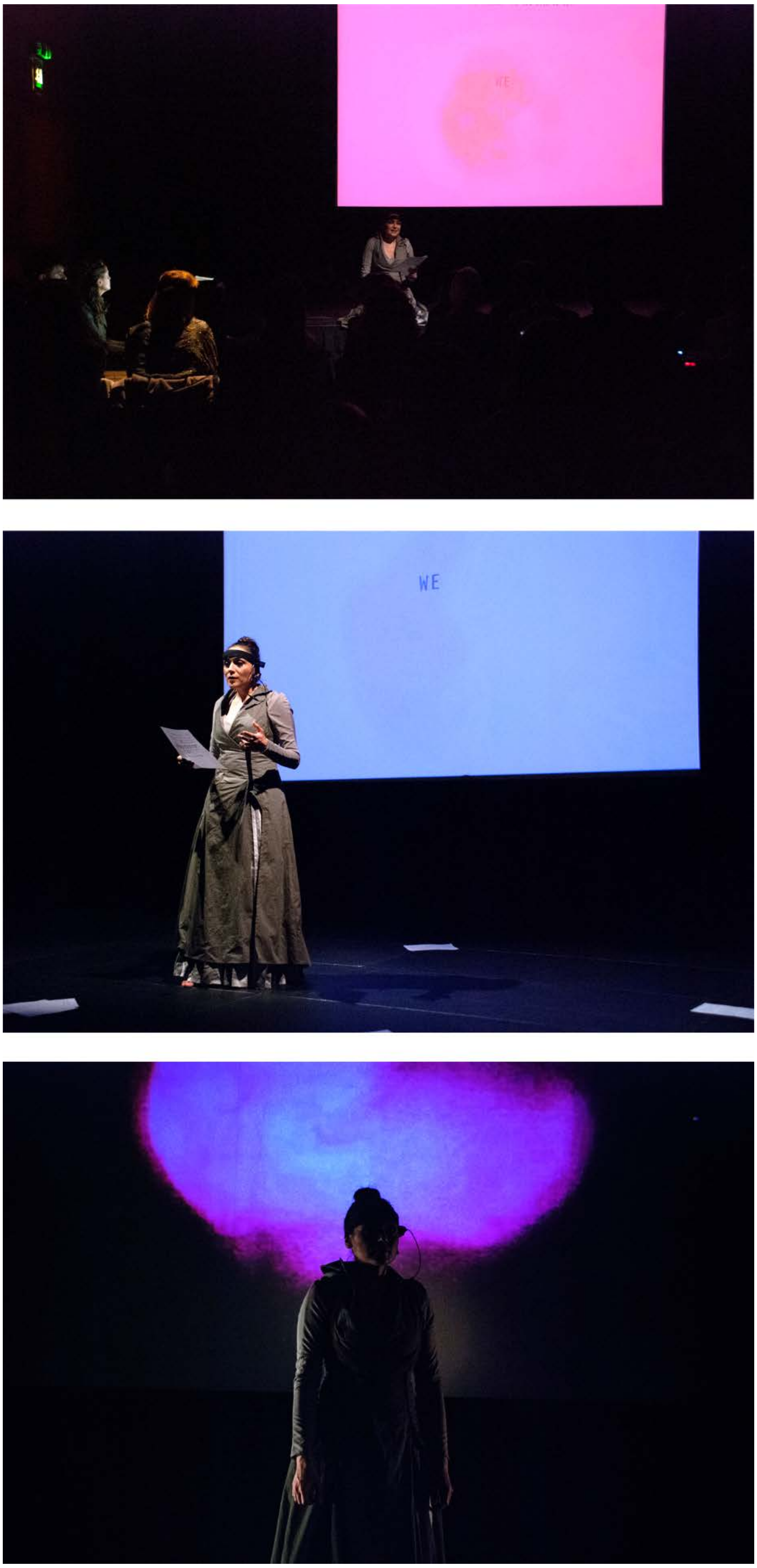


FIGURE 4.17 Part 2 'You/We', second half of scene 5 'We' of *'Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance* at CCA: Centre for Contemporary Arts Glasgow, 30-31 July 2015. Photography by Catherine M. Weir.

4.4.4 LIVE VISUALS

As I mentioned previously, the live visuals are performed with the MAX MSP Jitter software and consist of two main components: the pre-rendered black and white .wmv video files (Figure 4.10) and the RGB colour filter generated by the processing and mapping of the participants' EEG data. The video shootings took place on location in Athens, Greece, while the editing and post-production was made with the Adobe After Effects (Adobe 2016).

Regarding the generation of the colour filter, the choice of mapping the selected EEG frequency bands to the specific RGB colours, as described in Section 4.3.4, is based on the historically established in the western world cultural associations of specific colours with certain emotions. The blue colour is controlled by the theta frequency band, which is associated with deep relaxation; the green by the alpha band, associated with a relaxed but awake state; and the red colour is controlled by the beta and lower gamma frequency bands that occur during intense mental activity and tension. This way the transition of the participants from relaxed to more alert cognitive states is visualised in the colour scale of the live visuals as a shift from colder to warmer tints. Taking into account that all the other production elements are in black, white and grey shades, including the costumes and the lighting design, the generated RGB colour filter not only creates the atmosphere of the visuals, but also of the theatrical stage. It becomes a real-time feedback of the cognitive state of the participants and sets the emotional direction for the overall performance.

Furthermore, the configuration of the live-visuals with the MAX MSP Jitter software is not an entirely automated process. In consistency with the interactive storytelling and narrative structure, certain features are subject to manual control (Figure 4.9):

(1) Selection of processed brain-activity for the generation of the RGB colour filter – the actress' in scene 1, 2 and 3; one of the audience participants in scene 4; the actress' and one of the audience participants' in scene 5, separately and then averaged.
(2) Selection and triggering of video files and corresponding scenes – performed in coordination with the live electronics performer who functions as a conductor, leading the initiation of the different scenes and the synchronisation between the audio and the visuals.
(3) The RGB colour filter saturation level – i.e. decreasing in cases that the level is high for a prolonged period of time thus becoming unpleasant for the audience or increasing when the level is low therefore creating a non-visible result.
(4) The RGB colour filter opacity level - 0% during the video vignettes and increased up to 50% during the main scenes. This allows the video vignettes to function as aesthetically neutral intervals orienting the audience in regards to the narrative structure and the brain-activity interaction.
(5) The RGB colour filter split in two equal parts – at the beginning of scene 5, the filter on the right half of the screen maps the actress' brain-activity (marked as 'Me') and on the left maps one of the audience member's activity (marked as 'You') (Figure 4.16). Towards the middle of the scene, the two parts merge and the filter is averaged (marked as 'We') (Figure 4.17). This way not only their respective cognitive state, but also a real-time comparison between them, is visualised, enriching the interactive storytelling and reinforcing the audience perception of liveness.

4.5 SUMMARY

‘*Enheduanna – A Manifesto of Falling’ Live Brain-Computer Cinema Performance* was realised as a complete combination of scientific and creative practice-based methodologies, in order to address the main question of the presently discussed research. The demonstrations of the performance enabled the collection of valuable data: qualitative through the completion of the participants’ questionnaires and quantitative through the recording of the participants’ EEG data, the analysis of which will be presented in Chapter 5. Additionally, the performances and the implementation of the passive EEG-based BCI system within the real-life conditions of a public event made additional observations possible that cannot be simulated in the environment of a lab or a studio. These too will be presented in the next chapter, together with a discussion that sheds new light not only on the use of multi-brain EEG-based BCIs in the context of mixed-media performances, but also in comparison to important studies and dominant positions on the cognitive experience and engagement of the spectators during performative works and free viewing of films.

[…] Ithaca gave you the marvelous journey.
Without her you would not have set out.
She has nothing left to give you now. […]

C. P. Cavafy's *Ithaca* 1910-1911 (Keeley & Sherrard, 1992)

5. *ENHEDUANNA – A MANIFESTO OF FALLING*: DATA ANALYSIS AND DISCUSSION

In the previous chapter I presented the scientific and creative practice-based methodologies that were followed in order to answer the main research enquiry and *'Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance*, the case study of the currently discussed research.

The performance was realised as a complete combination of scientific and creative solutions to the challenges of the use of multi-brain BCIs in mixed-media performances (Section 5.1) that also enabled the collection of valuable data. More specifically, this chapter presents the observations made during the public events; the participants' demographic data (Section 5.2); followed by the analysis of the participants' behavioural data (Section 5.3); and the analysis of the participants' EEG data; together with the statistical methods used (Section 5.4). The aforementioned lead and inform a critical discussion of the results, presented in Section 5.5, in comparison with important studies and dominant positions on the cognitive experience and engagement of spectators during live performative works and free viewing of films.

5.1 THE SOLUTIONS TO THE CHALLENGES OF THE USE OF MULTI-BRAIN BCIS IN MIXED-MEDIA PERFORMANCES

As mentioned before, *'Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance* was realised as a complete combination of creative and scientific solutions to the challenges of the design and implementation of multi-brain BCIs in mixed-media performances, which are summarised in Table 5.1. These well-documented solutions can function as general guidelines; however, I expect that other artists might also investigate individualised approaches, customised and consistent to the specific context of their performances.

5.1.1 OBSERVATIONS FROM THE PERFORMANCES

The demonstrations of the performance were very well received by the audiences and provided valuable feedback from the participants, the analysis of which is presented further along in this chapter. Pre- and post-performance questionnaires were completed, while the participants' raw

Table 5.1 *'Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance*: the solutions to the challenges of the design and implementation of multi-brain BCIs in mixed-media performances.

Neuroscientific
• *Type of sensors* Use of identical headsets and sensors from the design phase to the implementation (4.3.2).
• *Unique brain anatomy of different participants wearing the devices* • *Location of the sensors during each performance* • *EEG low spatial resolution* Digital processing focus on the oscillatory processes (4.3.3).
• *Ratio of noise and non-brain artifacts to the actual brain signal* Use of band-pass filters combination for rejecting artifacts, low and high pass noise (4.3.3).
Computational
• *Application design for non-desk-bound computer user* • *Limited Bluetooth physical range* Arrangement of space with BCI performer positioned between audience participants and stage (4.3.1).
• *Raw EEG data versus 'detection suites'* Use of processing software for custom-based feature extraction (4.3.3).
• *Independent and join real-time multi-brain interaction and visualisation for more than two participants* Configuration of multiple acquisition servers & clients (4.3.3). Mapping of EEG data to RGB colour values (4.3.4) separately, jointly split & averaged (4.4.3).
Creative and Performative
• *Performer/s' cognitive load* Focus on passive 'arbitrary brain activity without the purpose of voluntary control' (4.3.3).
• *Meaningful BCI system design for performer/s and audience alike* Design of BCI system for direct comparison of participants' brain-activity & offline comparison to free viewing of films (4.2).
• *Liveness* Mapping of participants' brain-activity to the narrative and dramaturgical structure (4.4.2). Application of RGB colour filter separately, jointly split (actress versus audience participants) & averaged (4.4.3).
• *Technoformalism* Conceptual and aesthetic combination of creative direction and interaction technology (4.4.1).
Experimental
• *Recruitment of participants* • *Coordination of study during a public event* Recruitment introductions prior to study. Preparation without the presence of public (4.3.1). Processing software for simultaneous receiving, processing and recording of the EEG data and synchronisation with the live mediatised material (4.3.3).

EEG data were also collected, the quantitative and statistical analysis of which most interestingly revealed a correlation with their answers to the questionnaires. The first demonstrations also gave the opportunity to observe in real-life conditions challenges that have not been predicted before and at the same time to consider the direction of future work.

In the computational level, one of the first issues was that the BCI devices would connect successfully via the Bluetooth to the computer, only if they were assigned in each session the same COM Ports. In order to ensure this, they had to be switched on and connected, one after another and in the same order. This was especially crucial, since the current version of the OpenViBE driver is searching for devices assigned to COM Ports 1-16, so a headset with a greater value is not being recognised. This issue has also been reported with the Neurosky *MindSet* and *MindWave* headsets (OpenViBE 2016). Another experienced computational issue was the noticeable disconnections of the actress' headset. By trying different devices, it was verified that this was not occurring due to hardware malfunctioning. Also, since the actress was always within a distance of 10m, it is assumed that it was also not a problem related to the physical range of the Bluetooth. Nevertheless, this requires further investigation including experimenting with different communication protocols.

As presented in the previous chapter, the actress, like the audience participants, was asked to avoid the consumption of coffee, tea, high caffeine drinks, cigarettes and alcohol, as well as the recreational use of drugs for at least twelve hours prior to the study, as these substances can affect the brain's electrical activity and therefore the EEG recordings. Caffeine for example can cause a significant increase of the EEG waves' amplitude (Dixit, Vaney and Tandon 2006), but as the mean serum caffeine half-life in healthy subjects is five to six hours (Statland and Demas 1980), a twelve-hour window allows sufficient time in order to eliminate any possible effects. However, depriving the actress of the consumption of any high caffeine drink twelve hours before each performance and for three consecutive days, was one of the difficulties in the experimental level that had not been predicted. As she explained, for performers that even consume moderate amounts of caffeine, like her, that is one to two cups of coffee per day, it is common practice to drink a cup one hour before the performance in order to feel fresh and energised. In the case of *Enheduanna – A Manifesto of Falling*, in order to help the actress perform at a high level and at the same time implement the experimental conditions, a programme of rehearsals was realised that started one month earlier and during which she gradually reduced the caffeine consumption. However, this might not always be feasible and therefore needs to be reconsidered.

5.2 PARTICIPANTS' DEMOGRAPHIC DATA

The participants of the study included one performer and six members of the audience, two for each performance (see also Chapter 4.3.1). Alongside their demographic data, the participants were asked to complete the 'Edinburgh Handedness Inventory' (Oldfield 1971), in order to determine whether they are right- or left-handed, as this can indicate differences in the underlying mechanisms of the neural processes (see Appendix A.1.1 and Appendix A.2.1).

TABLE 5.2 Individual demographic data for the audience participants: f = female, m = male; d = Danish, e = English, r = Romanian, s = Spanish; r = right-handed.

Audience participant	Sex	Age	Mother tongue	Handedness
1	m	28	s	r
2	m	28	s	r
3	f	43	e	r
4	m	33	e	r
5	f	25	d	r
6	f	30	r	r

The performer participant was an ambidextrous, 36 years old female, whose mother tongue is Greek. The six audience participants included (Table 5.2 and Table 5.3): three right-handed females, with a mean age of 32.67 years and range 25 to 43 years; and three right-handed males, with a mean age of 29.67 years and range 28 to 33 years. Regarding their mother tongues, one audience participant has stated Danish, two English, one Romanian and two Spanish. Whereas no audience participants stated French and Greek as their mother tongues, which were two out of the three languages in which the work was performed, while the third one was English.

TABLE 5.3 Overall demographic data for the audience participants.

Audience participants		Female	Male	Total
Number		3	3	6 (100%)
Age	**Mean**	32.67	29.67	31.17
	Median	30.00	28.00	29.00
Mother tongue	**Danish**	1	0	1 (16.67%)
	English	1	1	2 (33.33%)
	French	0	0	0 (0%)
	Greek	0	0	0 (0%)
	Romanian	1	0	1 (16.67%)
	Spanish	0	2	2 (33.33%)
Handedness	**Right**	3	3	6 (100%)
	Ambidextrous	0	0	0 (0%)
	Left	0	0	0 (0%)

5.3 ANALYSIS AND RESULTS OF PARTICIPANTS' BEHAVIOURAL DATA

The collected data from the pre- and post-performance questionnaires aimed to reveal:

(1) whether the participants had a prior knowledge or experience using a Brain-Computer Interface device (Table 5.4) that could possibly influence their participation in the study;
(2) whether the participants were able to identify when and how their brain-activity was controlling the live video projections (Table 5.4); and
(3) what were the most special elements of the performance (Table 5.5).

More specifically, in the frame of the pre-performance preliminary questionnaires (see Appendix A.1.2 and Appendix A.2.2) the participants were asked: *Do you have a prior knowledge or experience of using a Brain-Computer Interface device? If yes, please give more information i.e. the type/model or device used, the mental tasks performed etc.* The majority of the audience participants (83.33%) replied that they had no prior experience. One audience participant (16.67%) replied that he previously tried out for a few minutes a similar device, as part of a demo presented in a conference, but he didn't know anything about the device. Whereas, the performer participant replied that her only prior experience has been wearing the BCI device during the rehearsals of the currently discussed study (Table 5.4). Therefore, it is concluded that the participants' prior knowledge did not influence their participation in the study and their responses to the post-performance experience questionnaires.

Additionally, the participants were asked after the performance: *Did you think/understand that your brain-activity was interacting with the audio and videos during the performance? If yes, when? And how?* As described in Chapter 4.4.3, in each one of the three events, the brain-activity of both the audience participants was being recorded and processed, but one of them was manually selected in order to generate the RGB colour filter during scene 4 and scene 5. Additionally, the brain-activity of the performer participant was generating the RGB colour filter during scene 1 to 3 and then jointly with the audience during scene 5. Based on this, the answers of the participants can be categorised as true positive, true negative, false positive and false negative. As demonstrated more specifically in Table 5.4, the majority of the audience participants (66.67%) were able to successfully identify whether their brain-activity was interacting with the live visuals (true positive answers) or not (true negative answers). Whereas, one audience participant gave a false positive answer (16.67%) and one was not able to determine (16.67%). The performer participant was 66.67% successful in identifying that her brain-activity was interacting with the live visuals (true positive answers), compared to 33.33% of false positive answers.

In the frame of the post-performance questionnaires (see Appendix A.1.3 and Appendix A.2.3) the participants were asked what they did during the study, in order to verify that they followed the instructions for participation in the study (Table 5.5). All the audience participants replied that they watched the performance and the actress replied that she performed, as expected. Additionally, two audience participants reported that they were concentrating on reading the supertitles. The participants were also asked whether they used any specific strategy related to mental task, in order to identify any particular factor that might have influenced their cognitive state during the study (Table 5.5). The majority, the actress in all three events and four out of the six audience participants, did not report any specific strategy. Interestingly, two of the audience participants mentioned that they were consciously staying engaged, one that was focusing especially in part 2 'You' and one that was imagining pleasant activities. None of these though are considered to have any particular influence in their cognitive states during the study.

TABLE 5.4 Quantitative analysis of participants' answers to pre- and post-performance questions.

Performer participant	BCI Knowledge[1]			BCI Interaction Awareness[2]				
	No	Not significant	Yes	True positive	True negative	False positive	False negative	N/A
1st event	0	1	0	0	0	1	0	0
2nd event	0	1	0	1	0	0	0	0
3rd event	0	1	0	1	0	0	0	0
Total	**0 (0%)**	**3 (100%)**	**0 (0%)**	**2 (66.67%)**	**0 (0%)**	**1 (33.33%)**	**0 (0%)**	**0 (0%)**

Audience participants	BCI Knowledge[1]			BCI Interaction Awareness[2]				
	No	Not significant	Yes	True positive	True negative	False positive	False negative	N/A
Female	3	0	0	2	0	1	0	0
Male	2	1	0	1	1	0	0	1
Total	**5 (83.33%)**	**1 (16.67%)**	**0 (0%)**	**3 (50%)**	**1 (16.67%)**	**1 (16.67%)**	**0 (0%)**	**1 (16.67%)**

[1] *Do you have a prior knowledge or experience of using a Brain-Computer Interface device? If yes, please give more information i.e. the type/model or device used, the mental tasks performed etc.*

[2] *Did you think/understand that your brain-activity was interacting with the audio and videos during the performance? If yes, when? And how?*

Another post-performance question that offered valuable insight and feedback was whether there was something in the performance that made a special impression to the participants. Apart from the experience as a whole for both the actress, as well as the audience, the most highlighted elements also include the live visuals and the colours, part 2 'You/We' of the performance, the use of different languages and the 'moving' texts. Other elements include the feeling of being 'connected' through the colours and the sounds and the physical control of the performer.

Additionally, the participants that were able to successfully identify that their brain-activity was interacting with the live video projections (Table 5.4) in the questions *If yes, when? And How?*, they highlighted as main factors the changing colours of the visuals, part 2 'You/We' and the explanatory vignettes. Other factors include the use of lights, whereas the actress reported that she was able to understand that her brain-activity was interacting with the video projections when she was not focusing on acting and was able to pay more attention to the environment.

Table 5.5 Descriptive analysis of participants' answers to post-performance questions.

	Performer participant (total events 3)	**Audience participants** (total part. 6)
Task (*What did you do during the study?*)	**Number of events/answer**	**Number of part./answer**
Watching the performance		6
Performing	3	
Concentrating in order to read the supertitles		2
Mental Strategy (*Did you use any specific strategy related to mental tasks*?)		
No specific strategy	3	4
Consciously staying engaged		2
Focusing especially in part 2 'You'		1
Imagining pleasant activities		1
Special Impression (*Was there anything special in the performance for you?*)		
The whole experience / The whole performance	2	1
The relation of the acting experience to the colours of the visuals as an acting environment / The visuals and the changing colours	1	2
Part 2 'You/We' of the performance		2
The different languages of the texts		2
The 'moving' texts		2
Feeling 'connected' through the colours of the visuals and the sounds		1
The physical control of the performer		1
Significant BCI Interaction Awareness Factors (*When and how did you think/understand that your brain-activity was interacting?*)		
The changing colours of the visuals	1	3
Part 2 'You/We' of the performance		3
The explanatory texts in the visuals		2
The use of lights		1
When not focusing on acting and paying attention to the environment	1	

5.4 RESULTS OF PARTICIPANTS' EEG DATA ANALYSIS AND STATISTICAL METHODS

The participants' raw EEG data were also collected, the quantitative and statistical analysis of which most interestingly revealed a correlation with their answers to the questionnaires. The raw EEG data from all participants were processed offline in the MATLAB R2016b software (MathWorks 2016) with the EEGLAB 13.6.5b interactive toolbox (Swartz Center of Computational Neuroscience, University of California San Diego 2016) and the IBM SPSS software (IBM [no date]). During the process a series of challenges and issues have been encountered, mainly due to the particularly long recorded datasets and their resulting increased size. The first challenge was the required increased computational power in order to perform the analysis. In order to address this, the datasets were down-sampled from 512Hz to 256Hz rate. Nevertheless, this did not have an effect in the quality of the analysis, since according to Nyquist theorem a sufficient sampling rate is equal to 2 times of the highest frequency of the data (Baraniuk 2007), which in the case of the currently discussed study is 40Hz. Following the down-sampling, the datasets were filtered using a windowed sinc Finite Impulse Response (FIR) filter, with cutoff frequency 4-40Hz, bandpass filter type blackman window type and transition bandwidth 1 (Smith 1997). Additionally, all the recorded data from all three events included a time-period at the beginning prior to the performance. These initial data were removed and saved, then used in the analysis as the participants' brain-activity baseline, in order to compare it with their brain-activity during the performance.

Following the processing of the datasets, group studies were created in order to plot and analyse in comparison:

(1) the 4-40Hz Signal Potential (μV) of each audience participant in the Time domain (ms) during the baseline, the overall performance, part 1 'Me' (scenes 1-3), part 2 'You/We' scene 4 and part 2 'You/We' scene 5 (Figure 5.1 and Appendix B.1.1);
(2) the Power Spectral Density for the 4-40Hz frequency range of each audience participant during the baseline, the overall performance, part 1 'Me' (scenes 1-3), part 2 'You/We' scene 4 and part 2 'You/We' scene 5 (Figure 5.2, Figure 5.3 and Figure 5.4);
(3) the Power Spectral Density for the 4-40Hz frequency range of the performer participant during the baseline and the overall performance (Figure 5.5). The recorded EEG data from the first and the third performance had to be excluded, due to the repetitive disconnections that occurred in the transmission of the data from the BCI device to the computer. For similar reasons the scenes 1-3, 4 and 5 were not examined individually from the overall performance, as in the case of the audience participants.

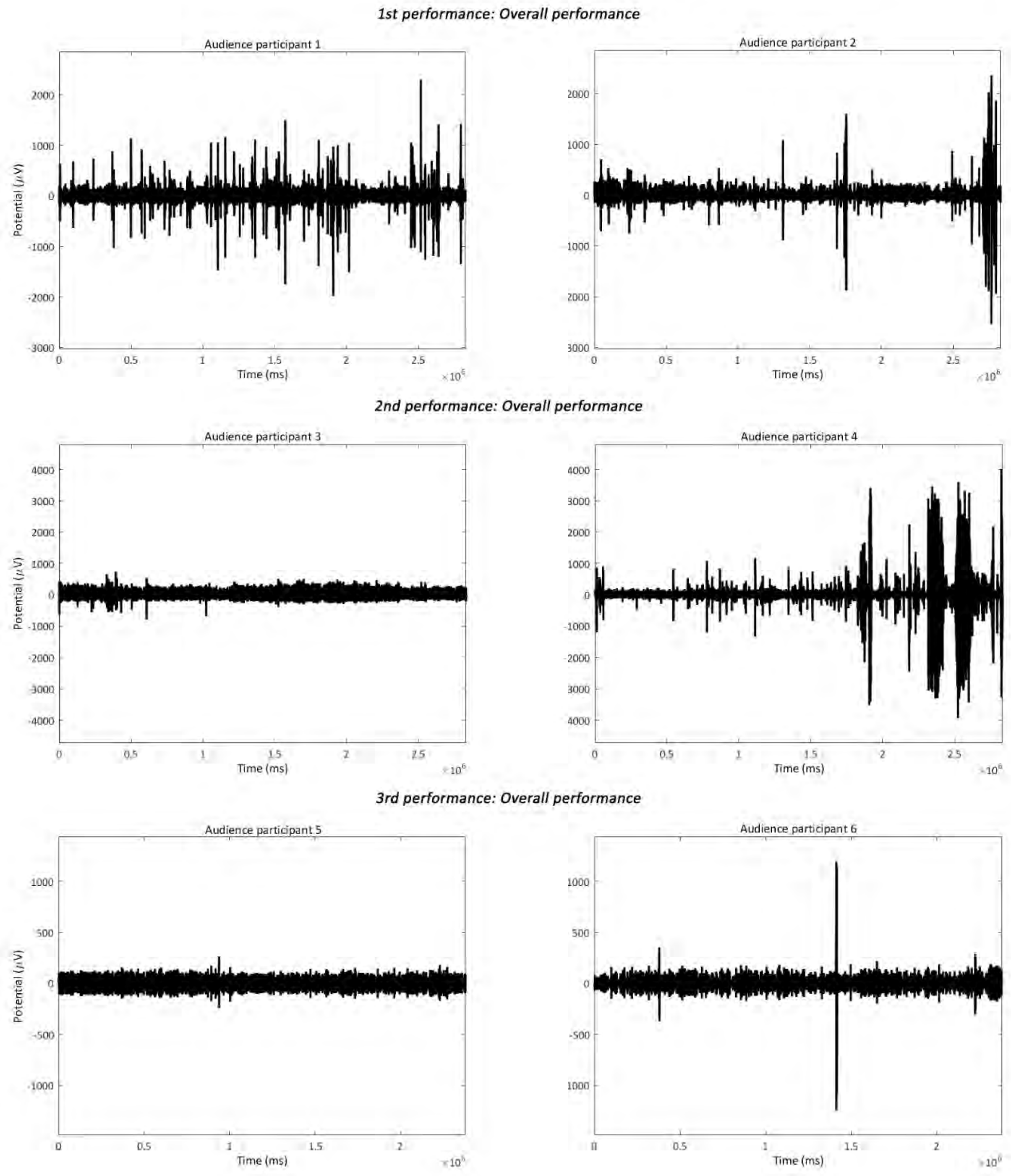
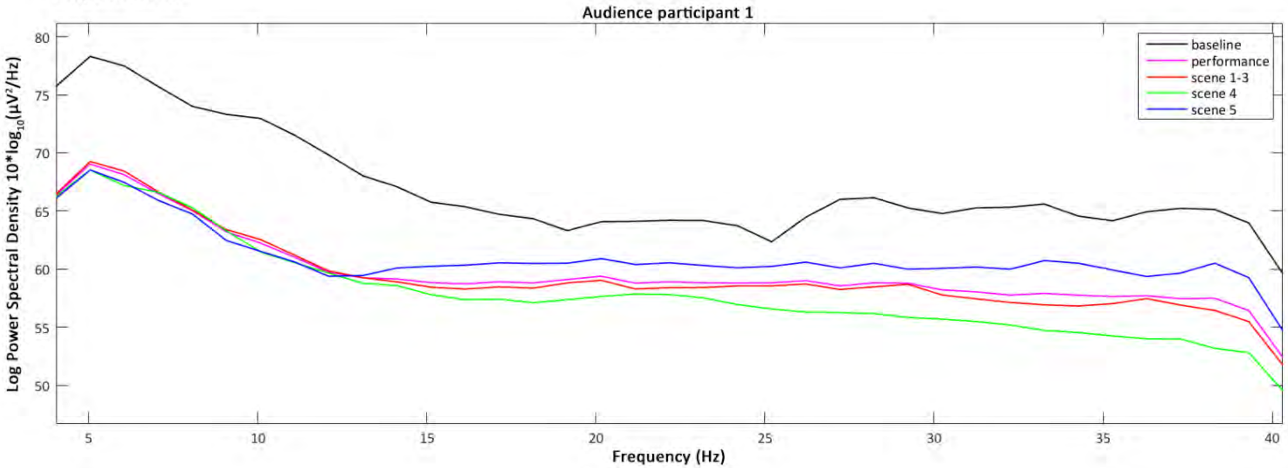
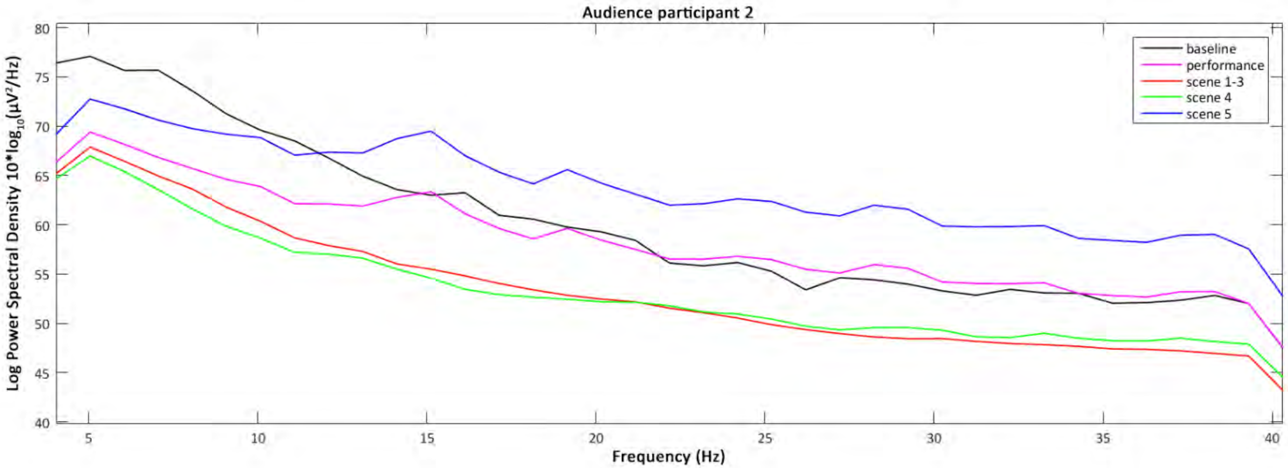


FIGURE 5.1 The plotted 4-40Hz Signal Potential (μV) in the Time domain (ms) of the audience participants during the overall performance of each performance.

1st performance





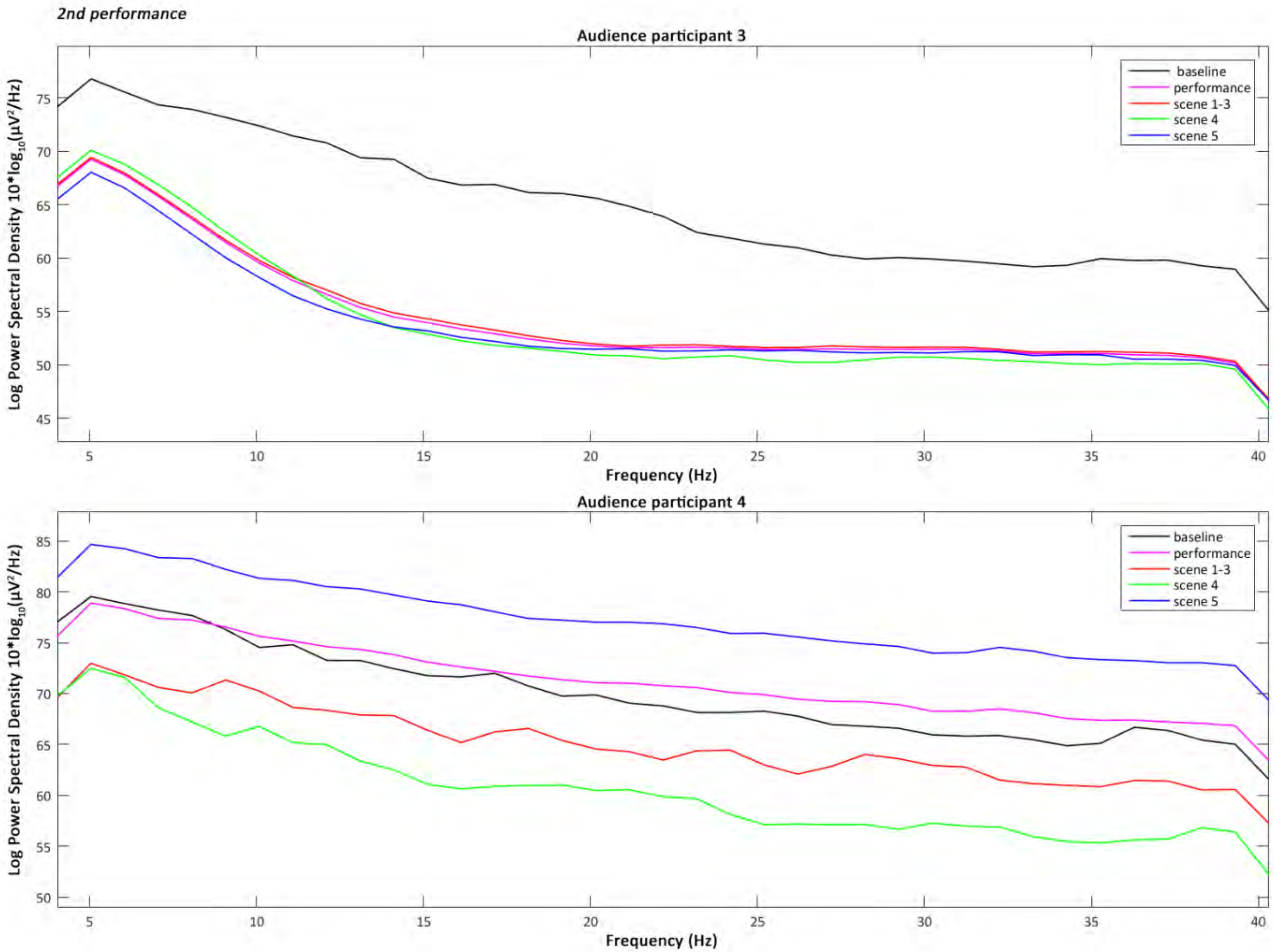


FIGURE 5.2 The plotted Power Spectral Density for the 4-40Hz frequency range of the audience participants 3 and 4 during the baseline, the overall performance, scenes 1-3, scene 4 and scene 5 of the second performance.

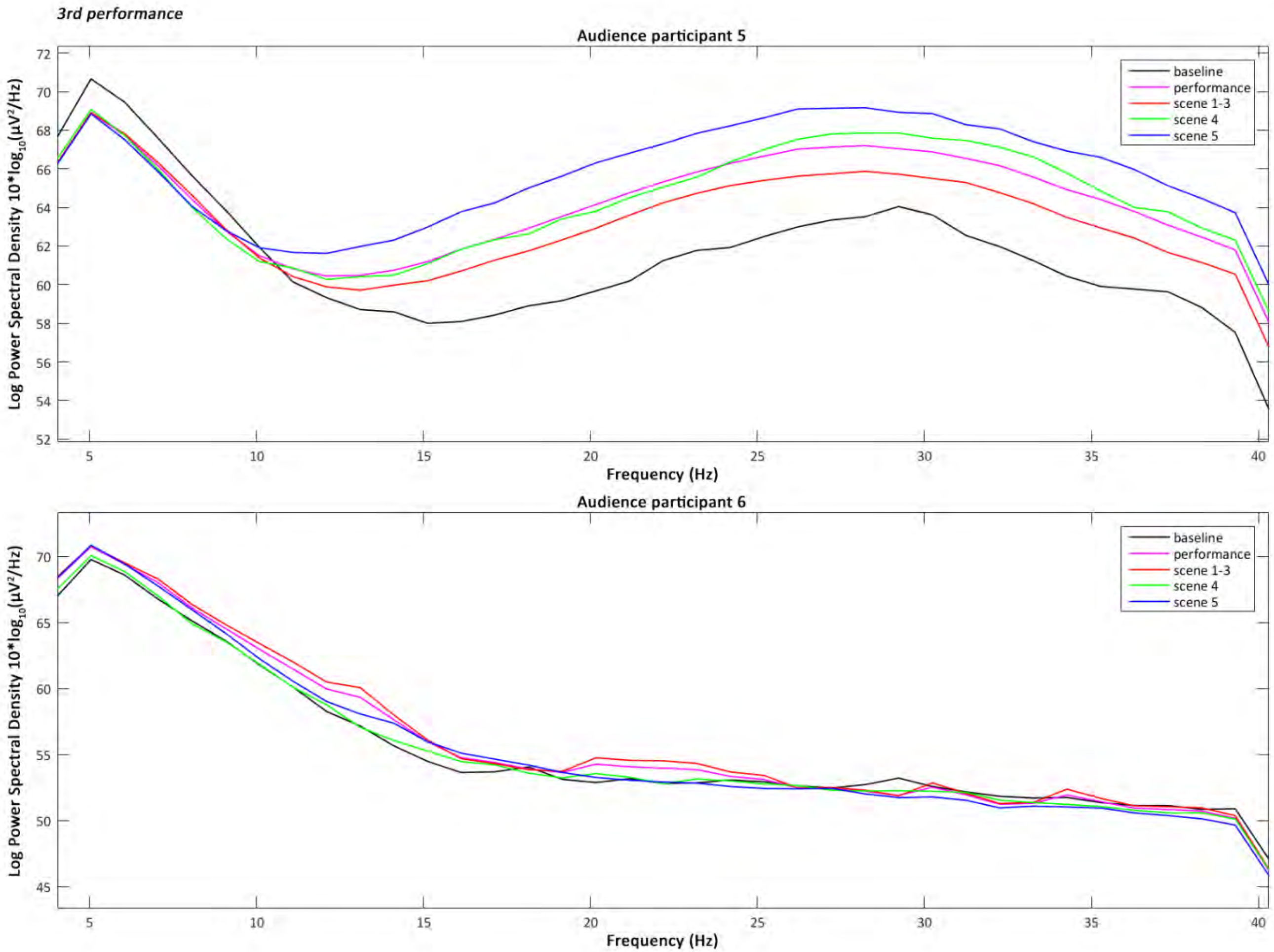


FIGURE 5.3 The plotted Power Spectral Density for the 4-40Hz frequency range of the audience participants 5 and 6 during the baseline, the overall performance, scenes 1-3, scene 4 and scene 5 of the third performance.

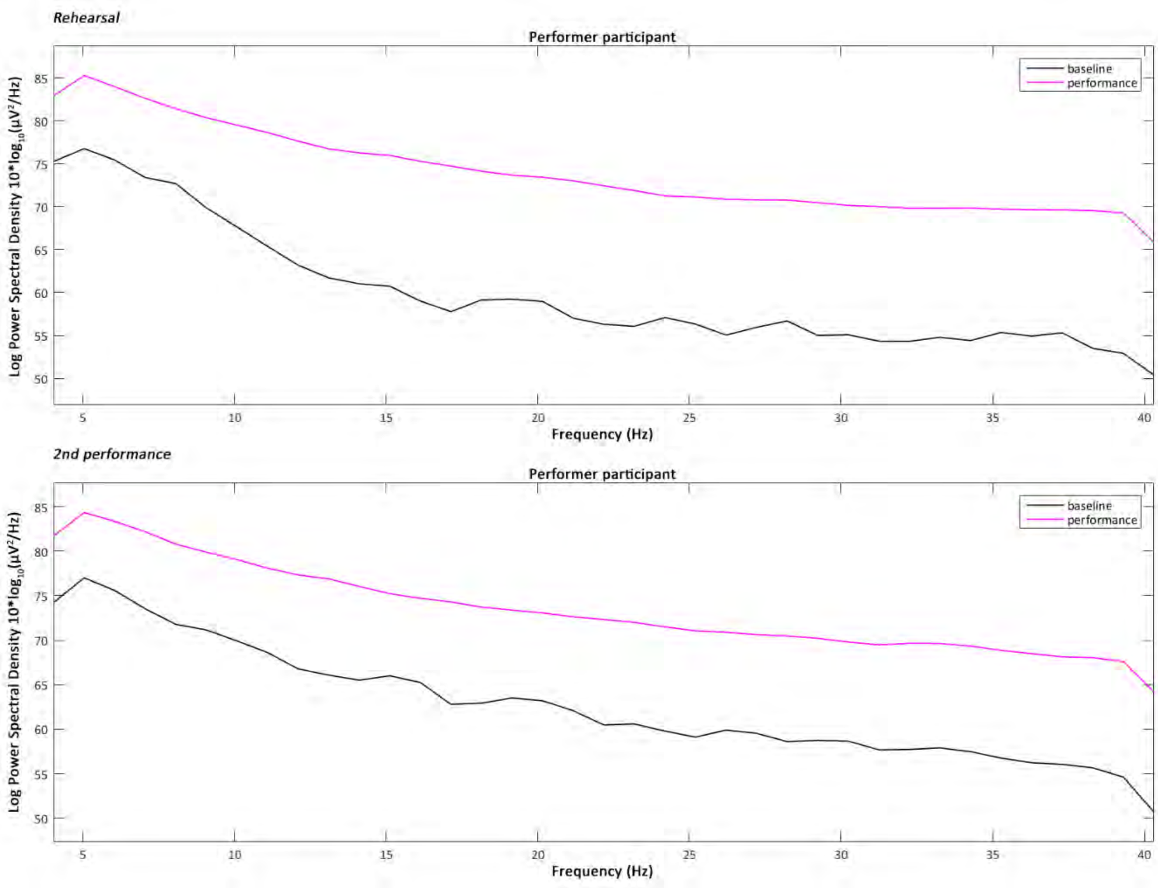


FIGURE 5.4 The Power Spectral Density for the 4-40Hz frequency range of the performer participant during the baseline and the overall performance of one rehearsal and the second performance.

5.4.1 AUDIENCE PARTICIPANTS' ANALYSIS AND RESULTS

Power Spectral Density intra-subject variability

Although the EEGLAB interactive toolbox offers automatic functions for calculating a range of statistics for the plotted data, these did not seem to reliably work in the case of the currently discussed study and for this reason manual calculations were performed. More specifically, the datapoints' values from each individual plot were extracted and the statistical analysis was performed in combination with the Microsoft Excel, MATLAB R2016b and IBM SPSS software.

The analysis, and more specifically the intra-subject variability, of the Power Spectral Density of the audience participants across all performances has shown that their Alpha power (8-13Hz) tended in most cases to decrease during the performance compared to the baseline (pre-performance time-period) and mostly during the scene 4 of part 2 'You/We' (Table 5.6 and Appendix B.1.2). The decrease of the Alpha power has been associated by previous research (O'Connell et al. 2009) with the increase of the cognitive function of attention. Therefore, the results of the audience participants indicate that not only were they more attentive, as expected, during the performance compared to the baseline period, but particularly during part 2 'You/We'. This is when the actress left the stage (scene 4), two soft spots above the two audience participants were turned on and

Table 5.6 Intra-subject variability of the audience participants' Alpha (8-13Hz) Log Power Spectral Density 10*log10(μV2/Hz): b = baseline.

Frequency		Audience participant 1				1st performance		Audience participant 2			
		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5	Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Alpha	8.06	74.00	65.03	65.08	65.28	64.74	73.58	65.71	63.62	61.61	69.75
	9.07	73.31	63.20	63.40	63.30	62.46	71.24	64.60	61.78	59.84	69.18
	10.08	72.96	62.25	62.55	61.49	61.53	69.59	63.88	60.36	58.64	68.84
	11.09	71.52	61.02	61.21	60.56	60.62	68.51	62.14	58.68	57.21	67.06
	12.09	69.82	59.73	59.85	59.66	59.39	66.77	62.12	57.89	57.02	67.36
Mean		72.32	62.25	62.42	62.06	61.75	69.94	63.69	60.47	58.86	68.44
(scene-b)/b %			-16.19%	-15.87%	-16.54%	-17.13%		-9.81%	-15.67%	-18.81%	-2.19%
Frequency		**Audience participant 3**				**2nd performance**		**Audience participant 4**			
Alpha	8.06	73.92	63.65	63.82	64.77	62.23	77.68	77.22	70.07	67.21	83.27
	9.07	73.17	61.46	61.67	62.44	60.03	76.29	76.53	71.33	65.83	82.21
	10.08	72.37	59.54	59.78	60.27	58.18	74.53	75.63	70.25	66.77	81.32
	11.09	71.43	57.89	58.19	58.32	56.47	74.80	75.16	68.64	65.18	81.12
	12.09	70.78	56.61	57.01	56.20	55.25	73.27	74.61	68.36	64.98	80.51
Mean		72.33	59.83	60.09	60.40	58.43	75.31	75.83	69.73	65.99	81.69
(scene-b)/b %			-20.90%	-20.37%	-19.76%	-23.79%		0.68%	-8.01%	-14.12%	7.80%
Frequency		**Audience participant 5**				**3rd performance**		**Audience participant 6**			
Alpha	8.06	65.64	64.41	64.63	64.01	64.06	65.11	66.10	66.36	64.89	65.96
	9.07	63.86	62.80	62.87	62.40	62.81	63.60	64.53	64.84	63.55	64.17
	10.08	61.94	61.50	61.39	61.20	61.91	61.79	62.97	63.41	61.84	62.25
	11.09	60.14	60.82	60.42	60.86	61.67	60.11	61.47	62.01	60.09	60.55
	12.09	59.33	60.44	59.89	60.27	61.62	58.25	59.96	60.48	58.76	59.01
Mean		62.18	61.99	61.84	61.75	62.41	61.77	63.01	63.42	61.83	62.39
(scene-b)/b %			-0.30%	-0.56%	-0.70%	0.37%		1.96%	2.59%	0.09%	0.99%

their brain-activities were interacting with the video projections, whereas later on (scene 5) the actress reappeared on stage, addressing directly the audience, while their real-time brain-interaction gradually merged and their averaged values were controlling the colour filter applied to the live visuals. (see also Chapter 4.4.2).

The intra-subject variability of the Power Spectral Density of the audience participants across all performances has also shown that their Lower Gamma power (25-40Hz) tended in most cases to increase during scene 5 of part 2 'You/We' of the performance, especially compared to the overall performance (Table 5.7, Table 5.8, Table 5.9 and Appendix B.1.2). The increase of the Lower Gamma power has been associated by previous research with increased emotional engagement (Müller et al. 1999) and emotional facial information processing (Balconi and Lucchiari 2008). Therefore, the results of the audience participants indicate that they were more emotionally engaged during scene 5 of part 2 'You/We', when, as mentioned before, the performer was addressing directly the audience citing 'moving' fragments from *On Being Ill* by Virginia Woolf (2002), while their brain-activity was jointly interacting with the video projections (see also Chapters 4.1 and 4.4.2).

Furthermore, a one-way Analysis of Variance (ANOVA) with repeated measures and Bonferroni post hoc test was performed, in order to compare the mean variability of each frequency band between the baseline period, the overall performance, scenes 1-3, scene 4 and scene 5, for each audience participant. A one-way ANOVA is the statistical method of choice, when the aim is to compare groups of three or more means at the same time and identify whether they differ significantly (Lowry 1999). Whereas, post hoc tests and pairwise comparisons are used to determine which means differ the most. The analysis confirmed that there were significant between the means differences in the Alpha Power Spectral Density [$F(4, 20)=3.422$ and $p<0.05$], with a greater decrease occurring during scene 4 compared to the baseline period. The analysis also confirmed that there were significant between the means differences in the Lower Gamma Power Spectral Density [$F(4, 20)=2.899$ and $p<0.05$] with a significant increase during scene 5 compared to the overall performance (see Appendix B.1.3).

Table 5.7 Intra-subject variability of the audience participants' Lower Gamma (25-40Hz) Log Power Spectral Density 10*log10(µV2/Hz) during the 1st performance: b = baseline; p = overall performance.

Frequency		Audience participant 1					1st performance	Audience participant 2			
		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5	Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Lower Gamma	25.20	62.35	58.82	58.57	56.58	60.24	55.28	56.47	49.87	50.44	62.37
	26.20	64.47	59.02	58.73	56.31	60.60	53.41	55.48	49.37	49.71	61.27
	27.21	66.00	58.56	58.25	56.27	60.11	54.63	55.11	48.97	49.35	60.91
	28.22	66.14	58.82	58.48	56.18	60.51	54.43	55.96	48.63	49.57	61.99
	29.23	65.27	58.79	58.70	55.84	60.00	53.99	55.59	48.45	49.57	61.57
	30.24	64.78	58.22	57.78	55.70	60.07	53.30	54.20	48.46	49.31	59.87
	31.24	65.27	58.05	57.45	55.50	60.19	52.86	54.06	48.18	48.64	59.79
	32.25	65.33	57.77	57.13	55.20	59.99	53.46	54.04	47.96	48.57	59.82
	33.26	65.60	57.92	56.93	54.73	60.74	53.09	54.11	47.84	49.00	59.92
	34.27	64.56	57.76	56.84	54.54	60.51	53.06	53.05	47.67	48.49	58.63
	35.28	64.16	57.64	57.03	54.26	59.93	52.05	52.83	47.41	48.24	58.41
	36.28	64.94	57.71	57.47	54.01	59.37	52.11	52.67	47.37	48.22	58.22
	37.29	65.23	57.46	56.91	54.00	59.66	52.35	53.22	47.22	48.50	58.94
	38.30	65.14	57.50	56.46	53.19	60.52	52.84	53.23	46.96	48.16	59.03
	39.31	63.97	56.44	55.49	52.82	59.27	52.01	52.01	46.69	47.90	57.55
Mean		64.88	58.03	57.48	55.01	60.11	53.26	54.14	48.07	48.91	59.89
(scene-p)/p %				-0.96%	-5.50%	3.46%			-12.62%	-10.68%	9.60%
(scene-b)/b %			-11.80%	-12.88%	-17.95%	-7.93%		1.62%	-10.79%	-8.88%	11.07%

TABLE 5.8 Intra-subject variability of the audience participants' Lower Gamma (25-40Hz) Log Power Spectral Density 10*log10(µV2/Hz) during the 2nd performance: b = baseline; p = overall performance.

Frequency		Audience participant 3		2nd performance					Audience participant 4		
		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5	Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Lower Gamma	25.20	61.31	51.46	51.64	50.47	51.32	68.27	69.89	62.99	57.12	75.93
	26.20	60.96	51.45	51.64	50.24	51.37	67.79	69.45	62.09	57.18	75.56
	27.21	60.28	51.52	51.78	50.24	51.22	66.96	69.24	62.84	57.11	75.18
	28.22	59.91	51.45	51.68	50.48	51.12	66.79	69.20	64.02	57.12	74.88
	29.23	60.05	51.46	51.65	50.74	51.16	66.59	68.92	63.60	56.67	74.63
	30.24	59.91	51.46	51.67	50.73	51.12	65.95	68.27	62.93	57.27	73.98
	31.24	59.71	51.47	51.65	50.61	51.25	65.82	68.26	62.76	56.98	74.02
	32.25	59.45	51.31	51.46	50.42	51.22	65.87	68.49	61.50	56.89	74.54
	33.26	59.19	51.05	51.20	50.31	50.88	65.46	68.12	61.14	55.94	74.17
	34.27	59.32	51.07	51.22	50.14	50.96	64.87	67.55	60.98	55.46	73.53
	35.28	59.95	51.07	51.25	50.01	50.94	65.12	67.37	60.85	55.33	73.34
	36.28	59.78	50.95	51.18	50.15	50.54	66.69	67.39	61.46	55.62	73.24
	37.29	59.81	50.89	51.11	50.09	50.54	66.37	67.21	61.41	55.70	73.03
	38.30	59.28	50.69	50.84	50.14	50.44	65.44	67.07	60.53	56.82	73.03
	39.31	58.95	50.18	50.33	49.60	49.95	65.02	66.84	60.57	56.40	72.75
Mean		59.86	51.16	51.35	50.29	50.93	66.20	68.22	61.98	56.51	74.12
(scene-p)/p %				0.37%	-1.74%	-0.45%			-10.07%	-20.73%	7.96%
(scene-b)/b %			-16.99%	-16.56%	-19.02%	-17.52%		2.96%	-6.81%	-17.15%	10.69%

TABLE 5.9 Intra-subject variability of the audience participants' Lower Gamma (25-40Hz) Log Power Spectral Density 10*log10(µV2/Hz) during the 3rd performance: b = baseline; p = overall performance.

Frequency		Audience participant 5		3rd performance					Audience participant 6		
		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5	Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Lower Gamma	25.20	62.49	66.66	65.40	67.00	68.64	52.93	53.10	53.40	52.75	52.42
	26.20	62.99	67.02	65.62	67.53	69.10	52.63	52.46	52.46	52.64	52.39
	27.21	63.34	67.13	65.74	67.80	69.13	52.45	52.46	52.50	52.29	52.43
	28.22	63.52	67.20	65.87	67.85	69.16	52.71	52.21	52.29	52.23	52.01
	29.23	64.04	67.04	65.72	67.85	68.92	53.21	51.88	51.87	52.25	51.73
	30.24	63.61	66.88	65.50	67.58	68.86	52.57	52.52	52.84	52.21	51.78
	31.24	62.55	66.54	65.29	67.47	68.28	52.16	51.94	52.05	52.12	51.52
	32.25	61.97	66.16	64.76	67.12	68.07	51.83	51.23	51.27	51.54	50.95
	33.26	61.24	65.57	64.19	66.62	67.40	51.70	51.29	51.37	51.35	51.08
	34.27	60.43	64.92	63.48	65.78	66.92	51.74	51.92	52.37	51.21	51.02
	35.28	59.91	64.41	62.94	64.85	66.59	51.35	51.42	51.67	51.06	50.94
	36.28	59.77	63.79	62.41	64.00	65.96	51.14	50.93	51.11	50.76	50.57
	37.29	59.63	63.08	61.66	63.78	65.12	51.13	50.82	51.04	50.58	50.36
	38.30	58.82	62.46	61.15	62.93	64.47	50.83	50.71	50.95	50.58	50.13
	39.31	57.53	61.80	60.54	62.30	63.73	50.88	50.16	50.36	50.10	49.65
Mean		61.46	65.38	64.02	66.03	67.36	51.95	51.67	51.84	51.58	51.27
(scene-p)/p %				-2.12%	0.99%	2.94%			0.32%	-0.18%	-0.79%
(scene-b)/b %			6.00%	4.00%	6.93%	8.76%		-0.54%	-0.22%	-0.72%	-1.33%

Inter-subject time-frequency correlation analysis

Additionally, an inter-subject 4-40Hz time-frequency correlation analysis was performed between the audience participants of each performance. As also explained at the beginning of this section, during the processing and analysis of the data a series of challenges have been encountered. In the case of the correlation analysis the process was not possible to be completed inside the IBM SPSS software due to particular large amount - up to 725,505 – datapoints. In order to overcome this problem, the datapoints' values from each individual plot were extracted and the MATLAB R2016b software was used in order to calculate the Spearman's rank correlation coefficient. The results showed that in all three performances, the correlation, ρ (rho) value, between the audience participants was greater and significant ($p<0.05$) or highly significant ($p<0.001$) during scene 4 of part 2 'You/We' when also their attention was increased (Table 5.10).

TABLE 5.10 Inter-subject time-frequency correlation analysis for the audience participants' 4-40Hz.

Event	Overall perform.		Scene 1-3		Scene 4		Scene 5	
	ρ (rho)	p value	ρ (rho)	p value	ρ (rho)	p value	ρ (rho)	p value
1st perf.	0.002	<0.05	0.007	<0.001	-0.015	<0.001	-0.002	0.401
2nd perf.	0.008	<0.001	0.003	0.058	0.024	<0.001	0.016	<0.001
3rd perf.	0.001	0.289	-0.001	0.513	-0.009	<0.05	0.002	0.426

5.4.2 PERFORMER PARTICIPANT'S ANALYSIS AND RESULTS

Power Spectral Density intra-subject variability

As in the case of the audience participants' data processing and analysis, the available automatic functions of the EEGLAB interactive toolbox for calculating a range of statistics did not seem to reliably work also with the performer participant's plotted data and for this reason manual calculations were performed. Similarly, the datapoints' values from each individual plot were extracted and the statistical analysis was performed in combination with the Microsoft Excel, MATLAB R2016b and IBM SPSS software. Also as mentioned previously, the EEG data from the first and the third performance had to be excluded, due to the repetitive disconnections that occurred in the transmission of the data from the BCI device to the computer. For similar reasons the scenes 1-3, 4 and 5 were not examined individually from the overall performance, as in the case of the audience participants. However, recordings were obtained during the performer's rehearsals and these were used in the analysis.

The analysis of the intra-subject variability of the 4-40Hz Power Spectral Density of the performer participant during one rehearsal and the second performance has shown that the Theta power (4-8Hz) and Lower Gamma power (25-40Hz) tended to increase significantly during the overall performance compared to the baseline period (Table 5.11 and Appendix B.1.2). The increase of the Theta power, and more specifically over frontal brain areas, has been associated by previous research with memory encoding (Klimesch 1999), the active maintenance and recall of working memory representations and the increase of 'memory load in a working memory task' (Jensen and Tesche 2002, 1395). At the same time, Gamma power has also been associated by previous research with directed attention and maintenance of working memory (Howard et al. 2003; Jensen, Kaiser and Lachaux 2007).

Table 5.11 Intra-subject variability of the performer participant's Theta (4-8Hz) and Lower Gamma (25-40Hz) Log Power Spectral Density 10*log10(μV2/Hz) during a rehearsal and the 2nd performance: b = baseline; p = overall performance.

Frequency		Rehearsal		2nd performance	
		Baseline	Overall perf.	Baseline	Overall perf.
Theta	4.03	75.25	82.91	74.23	81.70
	5.04	76.76	85.26	77.01	84.34
	6.05	75.42	83.97	75.58	83.35
	7.06	73.38	82.60	73.52	82.18
Mean		75.20	83.68	75.08	82.89
(scene-b)/b %		11.28%		10.40%	
Frequency		Rehearsal		2nd performance	
		Baseline	Overall perf.	Baseline	Overall perf.
Lower Gamma	25.20	56.33	71.13	59.11	71.05
	26.20	55.05	70.85	59.89	70.89
	27.21	55.95	70.78	59.53	70.63
	28.22	56.69	70.76	58.60	70.46
	29.23	55.01	70.47	58.74	70.22
	30.24	55.08	70.13	58.66	69.78
	31.24	54.34	70.01	57.67	69.48
	32.25	54.32	69.80	57.72	69.65
	33.26	54.79	69.82	57.89	69.62
	34.27	54.41	69.84	57.47	69.34
	35.28	55.35	69.70	56.75	68.85
	36.28	54.92	69.64	56.23	68.49
	37.29	55.31	69.62	56.05	68.12
	38.30	53.49	69.54	55.65	68.04
	39.31	52.91	69.27	54.61	67.59
Mean		54.93	70.09	57.64	69.48
(scene-b)/b %		27.60%		20.55%	

5.5 Discussion

The analysis of the participants' data, presented in this chapter and the comparison of the results most interestingly reveal a correlation between their answers to the questionnaires and the EEG data. More specifically, the majority of the audience participants and the performer participant across the majority of the events were able to successfully identify whether their brain-activity was interacting with the live visuals or not, and highlighted as main factors the changing colours of the visuals, part 2 'You/We' of the performance, the explanatory vignettes and the dramaturgical use of lights. At the same time, apart from the experience as a whole, the most highlighted elements that made a special impression to them include again the live visuals and the colours, part 2 'You/We' of the performance, the use of different languages and also the 'moving' texts.

These results are further reinforced in comparison with the intra-subject variability of the EEG Power Spectral Density of the audience participants across all performances, confirmed also by a one-way ANOVA analysis. One the one hand, it has shown that their Alpha power (8-13Hz) tended to decrease and therefore were more attentive during scene 4 of part 2 'You/We', when their brain-activity was interacting with the video projections without the presence of the actress. On the other hand, it has also shown that their Lower Gamma power (25-40Hz) tended to increase during scene 5 of part 2 'You/We', which means that they were more emotionally engaged, while they were processing the actress' emotional facial information, when she was directly addressing them and citing 'moving' texts. Additionally, the inter-subject 4-40Hz time-frequency correlation analysis showed that the correlation between the audience participants was greater and significant or highly significant during scene 4 of part 2 'You/We'.

Furthermore, the evidenced relationship between the participants' BCI interaction awareness, the elements of special impression to them and their cognitive state during scene 4 and 5 of part 2 'You/We' can be compared to findings from studies that investigate the effect of films on the spectators' brain activity, searching for similarities in their spatiotemporal responses (Hasson et al. 2008, 1), as previously mentioned in Chapter 4. For example, in a study by Dmochowski et al. (2012, 1), the results revealed peak inter-subject correlation of neural activity during arousing moments of a film, which according to the authors 'reflects attention- and emotion-modulated cortical processing'. In a similar investigation in a real-life context by Jola, Pollick and Grosbras (2011, 379), the audience participants' cortical excitability was measured while watching 'a dress rehearsal of a commercial production of Sleeping Beauty, lasting 2.5 hours, performed by the Scottish Ballet'. By cortical excitability the authors refer to the motor empathy of the participant's while watching the performance of the dancers. As they observed, the participants' responses 'were strongly individual' and their 'cortical excitability decreased with time', which could be due to different reasons, such as the long duration of the play, but nevertheless highlights the importance of the use time in a dance performance. Following this thread, I argue that the results of the currently discussed study, more in particular the increase of the factors associated with the audience participants' attention, emotional engagement and facial processing during the last two scenes of the performance, serve as a strong evidence of the importance of the directing strategy, dramaturgy and narrative structure. These methods and strategies can make effective use of the performance time and lead the audience's perception and cognitive state during the different stages of the work.

Last but not least, the analysis of the intra-subject variability of the 4-40Hz Power Spectral Density of the performer participant has shown that the Theta power (4-8Hz) and Lower Gamma power (25-40Hz) tended to increase significantly during the overall performance compared to the baseline period, which is consistent with the recall of working memory representations and the increase of memory load.

[…] And if you find her poor, Ithaca won't have fooled you.
Wise as you will have become, so full of experience,
you will have understood by then what these Ithacas mean.

C. P. Cavafy's *Ithaca* 1910-1911 (Keeley & Sherrard, 1992)

6. CONCLUSIONS AND FUTURE WORK

As cliché it might sound, a Ph.D. research is a long and life-changing journey, unique to every researcher/voyager, with all sorts of joys and struggles that life itself can bring, and with the goal of reaching a special place, *Ithaca* – also known as 'original contribution to knowledge'. There are many ways to approach a Ph.D. research subject and travel throughout your journey, especially when this is highly interdisciplinary. However, the choice should be made in consistency with the research study's aims, according to the specific allocated time period and also the provision of resources. This is how I have approached the currently discussed study, from the initial contextualisation, to the design, implementation and analysis of the results. I focused on and combined scientific and creative practice-based methodologies, in order to identify a series of characteristics and challenges of the use of multi-brain BCIs in mixed-media performances that spring from the fields of art, neuroscience and biomedical engineering, and address the main research question.

More specifically, in the previous chapters I have presented the development of the BCIs hardware, software and different modes of interaction with a particular focus on the new wireless interfaces, the free and open-source technologies (Chapter 2). I examined the use of single- and multi-brain BCIs in performative works and works that involve the real-time participation of an audience, presenting the key characteristics and identifying the particular challenges of the design and implementation of multi-brain BCIs in mixed-media performances leading to the main research question (Chapter 3). I presented *'Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance* as the research case study and a complete combination of creative and scientific solutions to the main research question (Chapter 4). And I also discussed the analysis of the behavioural and EEG data collected from the participants, together with observations made during the public events (Chapter 5).

In this chapter, I summarise the currently discussed study by addressing the outcomes that answer the main research question and consist original contributions to knowledge in correspondence with the initial research aims (Section 6.1). I present the challenges and limitations encountered (Section 6.2). I also discuss the emerging new trends in the field (Section 6.3), while I present my future work together with final reflections (Section 6.4).

6.1 CONTRIBUTIONS

As presented in Chapters 1 and 3, the main research question of the currently discussed study is:

What might be an effective model for the simultaneous multi-brain interaction of performers and audiences using EEG-based BCIs in the context of live cinema and mixed-media performances?

In order to identify how the main research question has been addressed and what contributions have been made in the frame of this study, the research aims previously discussed in Chapter 1 are presented in the subsections below, alongside with clarification on how they have been fulfilled and in which chapters they are presented in detail.

6.1.1 Review of BCI hardware, software and modes of interaction

The review was presented in detail in Chapter 2. The aim has been to present the impact of the accelerating advances in neuroscience, biomedical and computer engineering in the development of new low-cost commercial-grade EEG-based BCI devices that has led to a phenomenal emergence of applications. Particular focus was given on the new wireless devices that not only made the technology approachable to artists, but also offered new freedoms in the context of performative works. Alongside has been presented a selection of relevant free and open-source software that are disseminated amongst scientists, engineers and artists and are used in creative applications. Additionally, the modes of BCI interaction are explained, as these determine the possibilities and difficulties of the design and implementation of BCI applications.

Although, there are published reviews presenting the technical characteristics and performance of the new BCI hardware in detail, the material presented in Chapter 2 can function for the reader as a comprehensive overview of the current state-of-the-art technology and science in the field and a valuable guide in understanding the fundamental principles in the BCI interaction.

6.1.2 Review of the use of single- and multi-brain BCIs in mixed-media performances

The review was presented in detail in Chapter 3. The aim has been to critically review the use of single- and multi-brain BCIs in performative works and works that involve the real-time participation of an audience with a double goal and result: to present the common key characteristics; and to identify the particular challenges of the design and implementation of multi-brain BCIs in mixed-media performances leading to the main research question.

As published contributions (Zioga et al. 2014; Zioga et al. 2016; see Relevant Contributing Work), the resulting material outlines for the first time the interdisciplinary common grounds and approaches in the field, examining previous and current practices in comparison with the scientific and engineering tools and methodologies. Moreover, the presented challenges not only identify the missing knowledge in the area of interest, but also set the frame of a new type of performative work defined as *live brain-computer cinema performance*.

6.1.3 A new passive EEG-based BCI system for simultaneous multi-brain BCI interaction

The new system was presented in detail in Chapter 4. Following the cognitive approach deriving from the identified challenges of the design and implementation of multi-brain BCIs in mixed-media performances, the aim has been to design a passive multi-brain EEG-based BCI system that would enable the simultaneous real-time interaction of more than two participants, including both performers and members of the audience.

Although this published contribution (Zioga et al. 2015; Zioga et al. 2016; see Relevant Contributing Work) is based on the use of off-the-shelf hardware and software, nevertheless it has been approached in an original way combining custom-made real-time digital signal processing, mathematics and visual programming for the control of the live video projections. The result is a bespoke system that not only answers the main research question, but also provides the user/BCI performer with valuable freedoms and manual control, in order to promptly adjust and respond to different possible situations arising during a live mixed-media performance. Additionally, the system has the potential of further development, as I will discuss in detail in Section 6.4.

6.1.4 THE LIVE BRAIN-COMPUTER CINEMA PERFORMANCE AS A NEW FORMAT OF INTERACTIVE PERFORMATIVE WORK

The live brain-computer cinema performance was presented in detail in Chapters 4 and 5.1. The aim has been to create a research case study as a practice-based investigation of the identified challenges and as a complete combination of creative and scientific solutions to the main research question. The result was the presentation of *Enheduanna – A Manifesto of Falling*, as a new format of interactive performative work that combines live cinema and the use of BCIs.

This publicly presented and published new work (Zioga et al. 2015; Zioga and Katsinavaki 2015; Zioga et al. 2016; see Relevant Contributing Work) consists a most important contribution of the currently discussed study, as it enabled for the first time the simultaneous real-time interaction with the use of EEG of more than two participants, including both a performer as well as members of the audience in the context of a mixed-media performance (see also Chapter 3.3 and Table 3.2). Together with the new passive multi-brain EEG-based BCI system, it provides the future artists and researchers with a set of guidelines, presented in detail in Chapter 5.1, which they can use also in order to investigate individualised approaches. While at the same time, its systematic documentation has allowed of valuable observations that can further fuel future discussions. The realisation of the performance itself, followed the theoretical underpinnings developed in previous relevant works. The brain-activity of the performer and the audience members was visualised using scientifically established methodologies. While its combination with the use of the texts, within a consistent interactive storytelling and narrative structure, effectively demonstrated liveness, as proven by the results of the participants' behavioural data (see also Chapter 5.3), and addressed technoformalism. The idea of the viewer/participant as co-creator was further developed in conjunction with the role of the live visuals and BCI performer. Whereas, the investigation of the correlation (synchronisation), and other indicators of the participants' brain-activity, was implemented as a neuroscientific experiment in a real-life context, discussed in the following section. Additionally, the performance involved a large multinational and multidisciplinary team and attracted the support from non-profit, as well as commercial bodies, while the public demonstrations were very well received by the audiences. It is worth re-mentioning here that as the analysis of the collected data showed, the majority of the participants found that the performance was a special experience as a whole, which is in the same line with previous research that underlines the contemporary motivation of the audiences to 'get involved, to become an active part of a creative whole, give their input as fresh stimulus to professional performers, control the digital environment or decide on dramaturgical content' (Lindinger et al. 2013, 121).

6.1.5 A NEUROSCIENTIFIC EXPERIMENT IN A REAL-LIFE CONTEXT AND THE IMPORTANCE OF DIRECTING STRATEGY IN LIVE PERFORMANCES

The performance, a neuroscientific experiment in a real-life context, has been presented in detail in Chapter 5 and the Appendices. Apart from the new passive multi-brain EEG-based BCI system and the live brain-computer cinema performance as a new type of interactive performative work that answer the main research question, the case study also provided the opportunity of collecting both behavioural as well as EEG data from the participants.

This contribution is of particular usefulness not only to artists, but also to neuroscientists and biomedical engineers. As explained in Chapter 3, in recent years in the fields of neuroscience and experimental psychology has emerged a new and increasing interest in studying the mechanisms, dynamics and processes of the interaction between multiple subjects and their brain-activity and even more in a real-life context, away from the lab. Although until recently the majority of the scientific research was realised by presenting to the participants small fragments of audio-visual material and employing event-related designs, it is now acknowledged that in natural settings the brain-activity is rather continuous and transient (Dmochowski et al. 2012, 1). For this reason, the need of studies in real-life contexts, like free viewing of films and live performances has been identified. As in the study by Jola, Pollick and Grosbras (2011), also mentioned in Chapter 5, the currently discussed live brain-computer cinema performance makes a claim about live experiences and experiments outside the laboratory and contribute on new hypotheses about the effects of the length of time, but also the role of the directing strategy, dramaturgy and narrative structure on the audience's perception, cognitive state and engagement. For the above reasons, the currently discussed study also serves as evidence that interdisciplinary research not only can contribute to the advancement of the different fields involved, but can also result in new observations, not possible to be made in isolation.

6.2 LIMITATIONS

At the beginning of this chapter I mentioned that the choice of the methodological approach of my Ph.D. research and subsequently the design and implementation of the study has been consistent to the initial study's aims, the specific allocated time period and also the provision of resources. These already constitute a series of constraints to begin with. However, it is common that during the course of a research additional limitations and challenges might be encountered that can cause significant disruptiveness and even delays, but they can also inform the context of the research and become successful opportunities. The most important factors that have been manifested as either limitations and/or challenges during the course of the currently discussed study are summarised and presented below.

6.2.1 LIMITED HARDWARE AND SOFTWARE RESOURCES

Although the first BCI was demonstrated in the 1970s, only the past 15 years has the field started witnessing a research and development boom which also led to the introduction of the first low-cost wireless devices (see also Chapter 1). As a result, the relevant resources and even academic expertise are internationally still rather dispersed. Whereas when I embarked on the currently discussed study, I soon realised that there were limited opportunities of working with and testing different hardware and software and even identifying locally fellow researchers with prior experience on the specific technologies. It is logical that a ready-made provision of resources would have enabled a faster progress and in certain cases avoiding 'reinventing the wheel'. However, the particular limitation became an opportunity for reviewing the currently available technologies, with a particular focus on low-cost devices and open-source and free applications, as also stated in Section 6.1.1. As a result, this enabled me to successfully choose the appropriate tools for the study and in the process secure the in-kind support by MyndPlay, which provided me with additional devices for the public events and the future continuation of the research.

6.2.2 THE CHOICE OF SCIENTIFIC METHODOLOGY

A relevant to the previous limitation has also been the dilemma of choosing the appropriate scientific methodology, more specifically in relation to the design of the new passive multi-brain EEG-based BCI system. As demonstrated through the critical review of the use of single- and multi-brain BCIs in mixed-media performances (Chapter 3), one of the differences amongst relevant practices is the use of the commercial 'detection suites' versus the custom-made real-time process and feature extraction of the raw EEG data. The latter, which has also been the choice for the currently discussed study, is based on scientifically established methodologies, developed within the field of modern brain-computer interface design, and combine computational neuroscience, experimental psychology, to great extent biomedical and computer engineering and mathematics. As stated at the beginning of this dissertation, the choice of the research subject has been informed by my previous creative practice, but also my interdisciplinary background in art and sciences. Nevertheless, diving into the waters of biomedical engineering has been a difficult challenge, which however rewarded me with a good understanding of the important principles, the ability to design a system with greater flexibility and also proceed with the analysis of the collected data in relation to the system and its possible future development.

6.2.3 THE SCALE AND MANAGEMENT OF THE LIVE EVENTS

Apart from the creative roles of the director and live visuals and BCI performer that I have acquired as part of the practice-based methodologies implemented in the currently discussed study, my roles also included the overall production of the live events. Having a prior professional experience in managing art events, this initially seemed like a rather straightforward task. Nevertheless, the scale of the performance especially in terms of logistics and finances and in combination with the research itself, soon proved to be a much larger and daunting challenge. It involved identifying funding opportunities and bid writing; leading to budgeting and financial administration; identifying sponsors and supporters; establishing individual agreements with the different collaborators, residents of three different countries; preparing the publicity material; up to the final event and stage management, all of which although were not part of the main study enquiry, their successful implementation was indispensable for the realisation of the research itself. As much as these tasks have been described as a daunting challenge, their completion has been most rewarding. They provided me with a valuable opportunity of learning important aspects of organising a live event in the vibrant and highly international art scene of Glasgow, and the experience of managing a research project with international collaborators.

6.2.4 New challenges arising from the live events

The live public events gave the opportunity to observe in real-life conditions challenges that have not been predicted before (see Chapter 5), but nevertheless present an opportunity for future work. These mainly include in the computational level the inability of a successful connection of the BCI devices to the OpenViBE driver when the assigned COM Ports had values greater than 16 and the noticeable disconnections of the actress' headset. In the experimental level a challenge has been depriving the performer of the consumption of any high caffeine drink twelve hours before each performance and for several consecutive days.

6.2.5 Data collection and analysis

One of the important limitations in *'Enheduanna – A Manifesto of Falling' Live Brain-Computer Cinema Performance*, as in the case of other similar studies (Jola, Pollick and Grosbras 2011, 379; Eaton, Williams and Miranda 2015, 112), has been the data collection in terms of quantity. Due to the demanding logistics of the events (allocation of space, costs etc.), it has not been made possible to repeat the performance several times nor include a large number of audience participants in each event. With six audience participants and one performer participant one can argue that the sample of the data is non-representative. While at the same time, the comparison between participants of different events is difficult, since the duration of live events, no matter how well coordinated they are, can be even slightly different due to possible delays or differences in the transition from scene to scene. However, the results presented in Chapter 5 not only provide strong indications and insight on the perception, cognition and engagement of spectators and performers during a live mixed-media performance, but they can also inform future development and encourage similar studies in real-life settings.

Additionally, the analysis of the collected EEG data also presented challenges not previously predicted (see also Chapter 5). The reasons are two. On the one hand, the recorded datasets were particularly long. On the other hand, the existing software has been designed on the basis of laboratory neuroscientific experiments that usually involve the repetitive recordings of very short periods of brain-activity, such as 3 sec. As a consequence, some of the main encountered issues included: the need of increased computational power, which has been bypassed by down-sampling the datasets; the fact that the available automatic functions for calculating a range of statistics did not seem to reliably work, which was addressed by saving and exporting the values of the plotted data to Microsoft Excel, MATALB and IBM SPSS software and performing manual calculations; and the inability to perform the correlation analysis with the IBM SPSS software. The latter was resolved by using a MATLAB script. Although, the aforementioned challenges were successfully addressed, they nevertheless had an impact in the time-frame for the completion of the data analysis and the Ph.D. research itself.

6.3 New trends

As much as the currently discussed study has the self-fulfilling purpose of making original contributions to knowledge and specify the related limitations, through its lenses it is also possible to identify the new trends in the field and attempt to predict the future. It was previously mentioned that the broader field of BCIs is undergoing a phenomenal research boom, resulting in a continuous development of new methods, hardware, software and applications. In this section, I will briefly discuss the emerging trends that could be directly applicable in the frame of the currently discussed field of enquiry.

6.3.1 HYBRID BCIS

The term hybrid BCI currently refers to: either (a) the combination of more than one – usually two BCIs with different methods of processing and analysing the real-time brain-activity of the user; or (b) the combination of a BCI with another electrophysiological signal i.e. heart rate, galvanic skin response etc. or a signal deriving from another device, such an eye-gaze tracking system (EGTS). EGTS in particular, are hardware and software that can track the movement of the eye's pupil, which then can be used in order to control computer-based applications. Recent developments have also introduced low-cost and open-source systems that are accessible to artists. The combination of the different BCIs or the different inputs in the context of a hybrid BCI can operate simultaneously or sequentially (Pfurtscheller et al. 2010, 1). The advantage of these newer systems compared to previous BCIs is that they offer greater control for the user and flexibility in the design of the applications. An example of a creative application in the first category is *joyBeat*, a brain-controlled drum machine that combines Steady State Visual Evoked Potential (SSVEP), which is a re-active BCI method (see also Chapter 2), and the measurement of the affective states of the user, which is a passive BCI method (Eaton and Miranda 2014). The second category includes wearable applications combining BCIs and EGTS for assisting disabled users, for example by pinpointing and switching on/off electronic devices (Kim and Jo 2015) and controlling wheelchairs (Gneo et al. 2011) or for entertainment purposes, such as controlling a quadcopter (Kim, Kim and Jo 2014) or drone (Kosmyna, Tarpin-Bernard and Rivet 2015). It is yet to see how the combination of BCIs with other systems, like the EGTS, can also be applied in the context of artistic applications like live mixed-media performances.

6.3.2 BCIS, VIRTUAL, MIXED REALITIES AND AGENTS

Amongst the emerging new trends in BCI research and development are also applications that can provide the user with supplemental controls in virtual and mixed realities. These have already been incorporated in the frame of BCI-controlled Virtual Reality (VR) [e] games and applications for entertainment or rehabilitation that in most case use the BCI for navigation or selection of objects (Lotte et al. 2012). In the frame of live performative works there are examples, like the *NeuroDrummer* by Matt Whitman (Mullen et al. 2015), that combine independent visualisations of a performer's brain-activity using a BCI and a projected navigation in a VR environment. A recent development that is expected to push this direction forward is the release by MyndPlay at the end of 2016 of the *MyndBand VR*, the first, to the present knowledge, commercial-grade EEG headset that allows direct integration into VR headsets, like Oculus Rift (MyndPlay 2017b). We are yet to see the first performative works incorporating BCI-controlled VR applications.

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[e] The term Virtual Reality (VR) refers to a '[…] computer-generated simulation of a three-dimensional image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment […]' (Oxford Dictionaries 2017).

At the same time, new theoretical frameworks and positions emerge around the use of autonomous or semi-autonomous agents controlled by BCIs in the context of live performative works. For example, in the Avatar model introduced by Aparicio (2015, 154), the user/s, who are also the actor/s of the performance, control agents that function as their surrogates and can be either virtual avatars, meaning their virtual representations, alter egos and characters, robotic or human. This theoretical model can provide a very interesting future direction for live brain-computer cinema performances.

6.4 FUTURE WORK

The currently discussed study and its results, but also the identified emerging new trends, can further inform plans for future work.

The new passive multi-brain EEG-based BCI system encompass the potential for significant further development based on the following points:

(1) The observed disconnections of the performer's device need to be investigated, in order to identify the underlying cause and possible solution/s. It has already been verified that this was not occurring due to hardware malfunctioning, nor was it an issue related to the Bluetooth transmission and the physical distance to the computer (see also Chapter 5). However, experimenting with different communication protocols could also provide a feasible solution.
(2) Compiling one or more of the system's software components. This will allow for more functions to be automated and the system overall to become more user-friendly for the live visuals and BCI performer.
(3) Increasing the number of the audience participants in each event.
(4) As the results, presented in Chapter 5, showed that there is a significant variability of the Alpha and Lower Gamma Power, associated with the attention and emotional engagement of the audience participants, these two measurements can be incorporated in the architecture of the system, in order to control different components of the mediatised elements of the performance. This will result in enriching the audience's perceived interaction and liveness of the performance and as a consequence of their engagement.
(5) The system's architecture can also be adjusted in order to incorporate the control of virtual objects or agents in a mixed-reality setting according to the Avatar model by Aparicio (2015, 154) and/or the input of other signals deriving from another device, combined as a hybrid BCI.

The results of the EEG data analysis can also lead to further investigations. More specifically, new studies with increased number of audience participants could provide the initial results with statistical significance proving the role of the directing strategy, dramaturgy and narrative structure in increasing the spectators' attention and emotional engagement. The new studies could take place either in the frame of *Enheduanna – A Manifesto of Falling* as originally presented, in the frame of adapted versions that could help reduce the costs and logistics, or in the frame of other live performative works with similar interactive storytelling structure.

Additional studies could look into the effect of real-life conditions like in scene 5, when the performer by directly addressing the audience participants probed the increase of their emotional engagement and emotional facial information processing. The aim could be in particular to investigate the hypothesis of brain-to-brain coupling (see also Chapter 2), between performer and audience participants during live performances.

Moreover, the methodology applied for the real-time processing and feature extraction in the new passive multi-brain EEG-based system can also by combined with an EGTS as a Hybrid BCI. An example of a work-in-progress is the project *'Re-mark' Enabling artists with disabilities to re-engage with their fine art practice using digital technology*, realised in Dundee Contemporary Arts Print Studio, awarded and funded by the Scottish Graduate School for Arts & Humanities (SGSAH) and approved by the Glasgow School of Art Research Ethics Sub-Committee. The project explores how artists with disabilities can access interactive technologies that can limit the need for human intermediaries in their fine art practice. The main aim of the project is to evaluate the use of an open-source EGTS by print artists with Multiple Sclerosis (MS) and following a co-design process to identify and realise points of improvement. Whereas, during the co-design process and the studies conducted also EEG data from the print artists-participants have been collected. The project has already produced a series of important results: (a) a new updated edition of the software previously used that provides the artists with increased control and new functionalities; (b) a new body of creative work that the print artists will further develop in their studio; (c) sufficient data that can lead to future development (Zioga 2016). As part of the future development is also the analysis of the obtained EEG data that can inform the development of a hybrid BCI that can provide in real-time additional control to the EGTS. In the future is also planned the release of an experimental short animation film that will illustrate the process and the combination of the EGTS and EEG data.

6.4 EPILOGUE

To end in the same manner I begun this last chapter, I will use another cliché, common in Ph.D. dissertations. Like many other researchers/voyagers before me, I hope too, that I have been successful in completing and presenting a comprehensive body of practical and written work that is both informative and original but also enjoyable for the reader and spectator.

Over the past three years of conducting the currently discussed research I have had the opportunity of presenting, publishing and even pitching my research and findings, which provided me with most valuable feedback and interaction with diverse international communities of artists, engineers and scientists. A true emancipation process I would say, which together with the conclusions of my research have even more reinforced my belief in interdisciplinarity, despite the still evident – to my surprise – disbelief amongst both engineers/scientists as well as artists. The first might still argue that a project combining creative and scientific methodologies is 'too artistic', whereas the latter might still say that is 'too scientific'. But an interdisciplinary project and research is exactly this, 'too' of every chosen methodology, in order to bridge them and combine them into something new, a new whole greater than the sum of its parts, as Aristotle (350 B.C.E.) would put it. As also mentioned at the beginning of this dissertation, it is of course true that since the 17th century and the Age of Rationalism, art and science have been divided and considered as separate and distinct fields of the human spirit's endeavours (Miller 2011, 2), but nevertheless, with at least the onset of the 20th century, a new horizon of intersections has emerged. Today, 'interdisciplinarity' is a trending term, as interdisciplinary collaborations, projects, practices, research, fields of enquiry and the all-important funding opportunities are announced more and more often – thankfully. But there is still ground to cover. I hope this research, with its defined aims, directions and contributions has added not only a grain of sand in the field of the use of BCIs in live cinema and mixed-media performances, but it has also contributed in the greater discussion of applying creative methodologies in science and scientific methodologies in creative practices.

APPENDIX A. PARTICIPANTS' QUESTIONNAIRES

A.1 AUDIENCE PARTICIPANTS' QUESTIONNAIRES

A.1.1 AUDIENCE PARTICIPANTS' EDINBURGH HANDEDNESS INVENTORY

DIGITAL DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PARTICIPANT EDINBURGH HANDEDNESS INVENTORY[*] (No. 1)

Please indicate with a cross (**+**) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two crosses (**++**).

If you are indifferent, put one check in each column (**+** | **+**).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		+
2. Drawing		+
3. Throwing		+
4. Scissors		++
5. Toothbrush	+	+
6. Knife (without fork)		++
7. Spoon		+
8. Broom (upper hand)	+	+
9. Striking a Match (match)		+
10. Opening a Box (lid)	+	+
Total checks:	LH = 3	RH = 12
Cumulative Total	CT = LH + RH = 15	
Difference	D = RH – LH = 9	
Result	R = (D / CT) × 100 = 60	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)	Right Handed	

[*] Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. In: *Neuropsychololgia*, 9: 97-113.

PARTICIPANT EDINBURGH HANDEDNESS INVENTORY[*] (No. 2)

Please indicate with a cross (**+**) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two crosses (**++**).

If you are indifferent, put one check in each column (**+** | **+**).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		+
2. Drawing		+
3. Throwing		+
4. Scissors		+
5. Toothbrush		+
6. Knife (without fork)		+
7. Spoon		+
8. Broom (upper hand)		+
9. Striking a Match (match)		+
10. Opening a Box (lid)		+
Total checks:	LH = 0	RH = 10
Cumulative Total	CT = LH + RH = 10	
Difference	D = RH – LH = 10	
Result	R = (D / CT) × 100 = 100	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)	Right Handed	

[*] Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. In: *Neuropsychololgia*, 9: 97-113.

DIGITAL DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PARTICIPANT EDINBURGH HANDEDNESS INVENTORY* (No. 3)

Please indicate with a cross (**+**) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two crosses (**++**).

If you are indifferent, put one cross in each column (**+** | **+**).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		++
2. Drawing		++
3. Throwing		++
4. Scissors		++
5. Toothbrush		++
6. Knife (without fork)		++
7. Spoon		++
8. Broom (upper hand)		++
9. Striking a Match (match)		++
10. Opening a Box (lid)		++
Total checks:	LH = 0	RH = 20
Cumulative Total	CT = LH + RH = 20	
Difference	D = RH – LH = 20	
Result	R = (D / CT) × 100 = 100	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)	Right Handed	

* Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. In: *Neuropsychololgia*, 9: 97-113.

PARTICIPANT EDINBURGH HANDEDNESS INVENTORY* (No. 4)

Please indicate with a cross (**+**) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two crosses (**++**).

If you are indifferent, put one cross in each column (**+** | **+**).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		++
2. Drawing		++
3. Throwing		++
4. Scissors		++
5. Toothbrush		++
6. Knife (without fork)		++
7. Spoon		++
8. Broom (upper hand)		++
9. Striking a Match (match)		++
10. Opening a Box (lid)		++
Total checks:	LH = 0	RH = 20
Cumulative Total	CT = LH + RH = 20	
Difference	D = RH – LH = 20	
Result	R = (D / CT) × 100 = 100	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)	Right Handed	

* Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. In: *Neuropsychololgia*, 9: 97-113.

DIGITAL DESIGN STUDIO
THE GLASGOW SCHOOL OF ART

PARTICIPANT EDINBURGH HANDEDNESS INVENTORY* (No. 5)

Please indicate with a cross (**+**) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two crosses (**++**).

If you are indifferent, put one check in each column (**+** | **+**).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		++
2. Drawing		++
3. Throwing		++
4. Scissors		++
5. Toothbrush		+
6. Knife (without fork)		++
7. Spoon		++
8. Broom (upper hand)		++
9. Striking a Match (match)		++
10. Opening a Box (lid)	+	+
Total checks:	LH = 1	RH = 18
Cumulative Total	CT = LH + RH = 19	
Difference	D = RH – LH = 17	
Result	R = (D / CT) × 100 = 90	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)	Right Handed	

* Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. In: *Neuropsychololgia*, 9: 97-113.

PARTICIPANT EDINBURGH HANDEDNESS INVENTORY[*] (No. 6)

Please indicate with a cross (**+**) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two crosses (**++**).

If you are indifferent, put one cross in each column (**+** | **+**).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing		**++**
2. Drawing		**++**
3. Throwing	**+**	
4. Scissors		**+**
5. Toothbrush		**++**
6. Knife (without fork)		**+**
7. Spoon		**++**
8. Broom (upper hand)	**+**	
9. Striking a Match (match)		**+**
10. Opening a Box (lid)		**+**
Total checks:	LH = 2	RH = 12
Cumulative Total	CT = LH + RH = 14	
Difference	D = RH – LH = 10	
Result	R = (D / CT) × 100 = 71	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)	Right Handed	

[*] Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. In: *Neuropsychololgia*, 9: 97-113.

A.1.2 Audience participants' preliminary questionnaire

29 July 2015 – Audience participant 1

DIGITAL DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PARTICIPANT PRELIMINARY QUESTIONNAIRE (No. 1)

Please complete as appropriate.

Age: 28

Gender (Female/Male): Male

Mother tongue: Spanish

When did you last have a coffee or a high caffeine drink?
28.07.2015 by 21:30

When did you last have alcohol?
2807.2015 by 19:00

Do you have a prior knowledge or experience of using a Brain-Computer Interface device? If yes, please give more information i.e. the type/model of device used, the mental tasks performed etc.

NO

29 July 2015 – Audience participant 2

DIGITAL DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PARTICIPANT PRELIMINARY QUESTIONNAIRE (No. 2)

Please complete as appropriate.

Age: 28

Gender (Female/Male): Male

Mother tongue: Spanish

When did you last have a coffee or a high caffeine drink? 8:00 AM today

When did you last have alcohol? half glass 5:30pm

Do you have a prior knowledge or experience of using a Brain-Computer Interface device? If yes, please give more information i.e. the type/model of device used, the mental tasks performed etc. No I don't

30 July 2015 – Audience participant 3

DIGITAL DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PARTICIPANT PRELIMINARY QUESTIONNAIRE (No. 3)

Please complete as appropriate.

Age: 43

Gender (Female/Male): FEMALE

Mother tongue: ENGLISH

When did you last have a coffee or a high caffeine drink?
BLACK TEA, 8AM TODAY

When did you last have alcohol?
~~To~~ TWO DAYS AGO, 2PM

Do you have a prior knowledge or experience of using a Brain-Computer Interface device? If yes, please give more information i.e. the type/model of device used, the mental tasks performed etc.

NO PRIOR KNOWLEDGE OR EXPERIENCE.

30 July 2015 – Audience participant 4

DIGITAL DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PARTICIPANT PRELIMINARY QUESTIONNAIRE (No. 4)

Please complete as appropriate.

Age: 33

Gender (Female/Male): MALE

Mother tongue: ENGLISH

When did you last have a coffee or a high caffeine drink?
ABOUT 9PM LAST NIGHT (A TEA)

When did you last have alcohol?
ABOUT 8PM LAST NIGHT (A STOUT)

Do you have a prior knowledge or experience of using a Brain-Computer Interface device? If yes, please give more information i.e. the type/model of device used, the mental tasks performed etc.
I RECENTLY TRIED SOMETHING SIMILAR OUT AT A DEMO AT ACM CREATIVITY & COGNITION 2015 - I DON'T KNOW ANYTHING ABOUT THE DEVICE, IT WAS JUST FOR A FEW MINUTES.

31 July 2015 – Audience participant 5

DIGITAL: DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PARTICIPANT PRELIMINARY QUESTIONNAIRE (No. 5)

Please complete as appropriate.

Age:
25

Gender (Female/Male):
Female

Mother tongue:
Danish

When did you last have a coffee or a high caffeine drink?
06:30, 31/7-2015

When did you last have alcohol?
29/7-2015

Do you have a prior knowledge or experience of using a Brain-Computer Interface device? If yes, please give more information i.e. the type/model of device used, the mental tasks performed etc.
No

31 July 2015 – Audience participant 6

DIGITAL DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PARTICIPANT PRELIMINARY QUESTIONNAIRE (No. 6)

Please complete as appropriate.

Age: 30

Gender (Female/Male): Female (circled)

Mother tongue: ROMANIAN

When did you last have a coffee or a high caffeine drink? 07:30 AM

When did you last have alcohol? 29/07/2015

Do you have a prior knowledge or experience of using a Brain-Computer Interface device? If yes, please give more information i.e. the type/model of device used, the mental tasks performed etc.

NO.

A.1.3 AUDIENCE PARTICIPANTS' EXPERIENCE QUESTIONNAIRE

29 July 2015 – Audience participant 1

DIGITAL DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PARTICIPANT EXPRERIENCE QUESTIONNAIRE (No. 1)

Please complete as appropriate.

What did you do during the study?

I just saw the performance and try to imagine what was about without reading the subtitles (It got tired at some point to read them).

Did you use any specific strategy related to mental tasks?

I don't think any specific strategy. I just left myself to take part of them. Sometimes I got confused about what to choose. Tho, I just make a selection of 2.

Was there anything special in the performance for you?

I felt somehow conected with the performance, throgout the colors and sounds.

Did you think/understand that your brain-activity was interacting with the audio and videos during the performance?

I couldn't say understand exactly, but somehow I got a feeling about something going conected ~~between~~ between

If yes, when?

I do function a lot throw colors and concepts. Sounds cause me some feelings. Tho, I got confused of what I actually I was feeling compted with the projections and sounds arround the 2nd and 3rd part.

And how?

I feld like colors expressed my feelings throgout the ~~[illegible]~~ performance. But sounds influence my self more than feeling being part of them.

29 July 2015 – Audience participant 2

DIGITAL DESIGN STUDIO
THE GLASGOW SCHOOL OF ART

PARTICIPANT EXPRERIENCE QUESTIONNAIRE (No. 2)

Please complete as appropriate.

What did you do during the study?

Besides watching the play, I was thinking stuff related and not related with the play

Did you use any specific strategy related to mental tasks?

Not particulary, I tried to think something specific but didn't notice any difference

Was there anything special in the performance for you?

If by special means meaningful, the last part were it talks about humanity was very touching

Did you think/understand that your brain-activity was interacting with the audio and videos during the performance?

Kind off but didn't notice any changes wile I was trying to think something difference

If yes, when?

I'm guessing the background noise image or ~~the~~ loud noises but not sure

And how?

Because it was something that looked different and diffose from the rest of the movie

30 July 2015 – Audience participant 3

DIGITAL: DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PARTICIPANT EXPRERIENCE QUESTIONNAIRE (No. 3)

Please complete as appropriate.

What did you do during the study?

Watched & listened to all element of the performance. Thought about some of the textual references. Also thought of non-related things such as I was slightly hungry. I experimented with imagining I was a/with a man I like &/riding my bike fast downhill &/doing yoga.

Did you use any specific strategy related to mental tasks?

Perhaps my answer to the previous question is this? I was aware that I wanted to stay engaged. I wondered if I "squeezed" hard enough I could make the screen go green.

Was there anything special in the performance for you?

Very impressed by the physical control demonstrated by the actress. I enjoyed the Part 2 psychometric-type questions. Some of the texts I found moving.

Did you think/understand that your brain-activity was interacting with the audio and videos during the performance?

I believed that it must have been.

If yes, when?

When I was thinking about the content. When I was hearing "stressful" sounds e.g. the actress shouting. When I was trying to work out what were the images. I did not see any particular evidence however.

And how?

I picked up from being told so that the colour saturation was being affected however what I saw did not appear to correllate with my thoughts. Although, there was an intense pink patch when I was deliberately imagining the man I like.

30 July 2015 – Audience participant 4

DIGITAL: DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PARTICIPANT EXPRERIENCE QUESTIONNAIRE (No. 4)

Please complete as appropriate.

What did you do during the study?

I TRIED TO TAKE IT ALL IN, NOT TRYING TO AFFECT THINGS. I PROBABLY FIDGETED AROUND QUITE A BIT. I WAS TRYING HARD TO CONCENTRATE ON READING THE TEXTS

Did you use any specific strategy related to mental tasks?

WHEN THE QUESTIONS WERE ON SCREEN I TRIED FOCUSSING ON THE ANSWERS I WANTED TO CHOOSE! SIMILARLY AT THE START I TRIED 'WILLING' CERTAIN COLOURS TO BE.

Was there anything special in the performance for you?

I THINK THE WHOLE THING IS PRETTY SPECIAL.

Did you think/understand that your brain-activity was interacting with the audio and videos during the performance?

I DIDN'T THINK IT WAS REALLY

If yes, when?

AT THE BEGINNING I WONDERED IF MY BRAIN-ACTIVITY WAS INFLUENCING ANYTHING BUT DECIDED NOT. LATER I ~~(?)~~ THOUGHT MAYBE MY BRAIN WAS INFLUENCING THE SOUNDS!

And how?

31 July 2015 – Audience participant 5

DIGITAL DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PARTICIPANT EXPRERIENCE QUESTIONNAIRE (No. 05)

Please complete as appropriate.

What did you do during the study?

watch the performance

Did you use any specific strategy related to mental tasks?

No. Just trying to follow the performance

Was there anything special in the performance for you?

I was very attracted to the visuals and changes of color – also listening to the texts in the different languages

Did you think/understand that your brain-activity was interacting with the audio and videos during the performance?

yes

If yes, when?

the shift to 'you' where the light was directed on us, the participants, otherwise I was unsure when.

And how?

The shapes forming on the screen, the organic formations as well as the color-schemes..

31 July 2015 – Audience participant 6

DIGITAL DESIGN STUDIO
THE GLASGOW SCHOOL OF ART

PARTICIPANT EXPRERIENCE QUESTIONNAIRE (No. 6)

Please complete as appropriate.

What did you do during the study?

watched the performance

Did you use any specific strategy related to mental tasks?

Not exactly, I just paid attention to the screen & sounds & the actress.

Was there anything special in the performance for you?

I enjoyed the fragments in French. Also I didn't expect a performance in Greek, so that was a nice surprise

Did you think/understand that your brain-activity was interacting with the audio and videos during the performance?

yes

If yes, when?

I read that this was going to take place at the beginning of the performance, on the screen. There were prompts during the performance for ex "we" mentioned on the screen - so I guess at this point data from our brains were used.

And how?

The colours were supposed to get brighter & warmer, which did happen.

A.2 PERFORMER PARTICIPANT'S QUESTIONNAIRES

A.2.1 PERFORMER PARTICIPANT'S EDINBURGH HANDEDNESS INVENTORY

DIGITAL DESIGN STUDIO
THE GLASGOW SCHOOL OF ART

PERFORMER EDINBURGH HANDEDNESS INVENTORY* (No. 1)

Please indicate with a cross (**+**) your preference in using your left or right hand in the following tasks.

Where the preference is so strong you would never use the other hand, unless absolutely forced to, put two crosses (**++**).

If you are indifferent, put one cross in each column (**+** | **+**).

Some of the activities require both hands. In these cases, the part of the task or object for which hand preference is wanted is indicated in parentheses.

Task / Object	Left Hand	Right Hand
1. Writing	+	+
2. Drawing	+	+
3. Throwing	+	+
4. Scissors		+
5. Toothbrush	+	+
6. Knife (without fork)		+
7. Spoon		+
8. Broom (upper hand)	+	+
9. Striking a Match (match)	+	+
10. Opening a Box (lid)	+	+
Total checks:	LH = 7	RH = 10
Cumulative Total	CT = LH + RH = 17	
Difference	D = RH – LH = 3	
Result	R = (D / CT) × 100 = 17	
Interpretation: (Left Handed: R < -40) (Ambidextrous: -40 ≤ R ≤ +40) (Right Handed: R > +40)	Ambidextrous	

* Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. In: *Neuropsychololgia*, 9: 97-113.

A.2.2 Performer participant's preliminary questionnaire

29 July 2015 – Performer participant

DIGITAL DESIGN STUDIO
THE GLASGOW SCHOOL OF ART

PERFORMER PRELIMINARY QUESTIONNAIRE (No. 1)

Please complete as appropriate.

Age:
36

Gender (Female/Male):
Femal

Mother tongue:
Greek

When did you last have a coffee or a high caffeine drink?
Yesterday morning

When did you last have alcohol?
Before 2 weeks

Do you have a prior knowledge or experience of using a Brain-Computer Interface device? If yes, please give more information i.e. the type/model of device used, the mental tasks performed etc.
Only in some rehearsals of this project. Never before

30 July 2015 – Performer participant

DIGITAL DESIGN STUDIO
THE GLASGOW SCHOOL OF ART

PERFORMER PRELIMINARY QUESTIONNAIRE (No. 2)

Please complete as appropriate.

Age:

35

Gender (Female/Male):

Female

Mother tongue:

Greek

When did you last have a coffee or a high caffeine drink?

Yes a coffee with half dose of caffeine coffee and half dose of decaf coffee

When did you last have alcohol?

Last night

Do you have a prior knowledge or experience of using a Brain-Computer Interface device? If yes, please give more information i.e. the type/model of device used, the mental tasks performed etc.

No apart of our rehearsals now.
Today I didn't notice anything new. I was more focused and technical and I felt less pain. That I think was also obvious to the cursors on the screen

31 July 2015 – Performer participant

DIGITAL DESIGN STUDIO
THE GLASGOW SCHOOL OF ART

PERFORMER PRELIMINARY QUESTIONNAIRE (No. 3)

Please complete as appropriate.

Age:

36

Gender (Female/Male):

Female

Mother tongue:

Greek

When did you last have a coffee or a high caffeine drink?

Yesterday afternoon

When did you last have alcohol?

Two days ago

Do you have a prior knowledge or experience of using a Brain-Computer Interface device? If yes, please give more information i.e. the type/model of device used, the mental tasks performed etc.

I have not any prior knowledge or experience of using Brain-Computer Interface device. My first time was during the rehearsals of this project

A.2.3 PERFORMER PARTICIPANT'S EXPERIENCE QUESTIONNAIRE

29 July 2015 – Performer participant

DIGITAL: DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PERFORMER EXPRERIENCE QUESTIONNAIRE (No. 1)

Please complete as appropriate.

What did you do during the study?

I performed

Did you use any specific strategy related to mental tasks?

No

Was there anything special in the performance for you?

My experience = the experiencing the acting part and relating it to the colours I had for an acting environment

Did you think/understand that your brain-activity was interacting with the audio and videos during the performance?

Yes

If yes, when?

The times that I wasn't focused on my acting and payed attention to the environment

And how?

By the colours - I also observed at the times that I could face the screen and was calm that my pain signals (I have a leg injury) were obvious on the screen and were also specificly coloured

30 July 2015 – Performer participant

DIGITAL: DESIGN STUDIO THE GLASGOW SCHOOL OF ART

PERFORMER EXPRERIENCE QUESTIONNAIRE (No. 2)

Please complete as appropriate.

What did you do during the study?

I rehearsed, performed and did the tests of the performance

Did you use any specific strategy related to mental tasks?

No

Was there anything special in the performance for you?

My whole experience as a performer

Did you think/understand that your brain-activity was interacting with the audio and videos during the performance?

Yes

If yes, when?

All the time

And how?

The colours were changing according to my concentration and emotional involvement

31 July 2015 – Performer participant

DIGITAL DESIGN STUDIO
THE GLASGOW SCHOOL OF ART

PERFORMER EXPRERIENCE QUESTIONNAIRE (No. 3)

Please complete as appropriate.

What did you do during the study?

I was the performer

Did you use any specific strategy related to mental tasks?

No

Was there anything special in the performance for you?

The whole experience was special for me

Did you think/understand that your brain-activity was interacting with the audio and videos during the performance?

Yes

If yes, when?

all the time

And how?

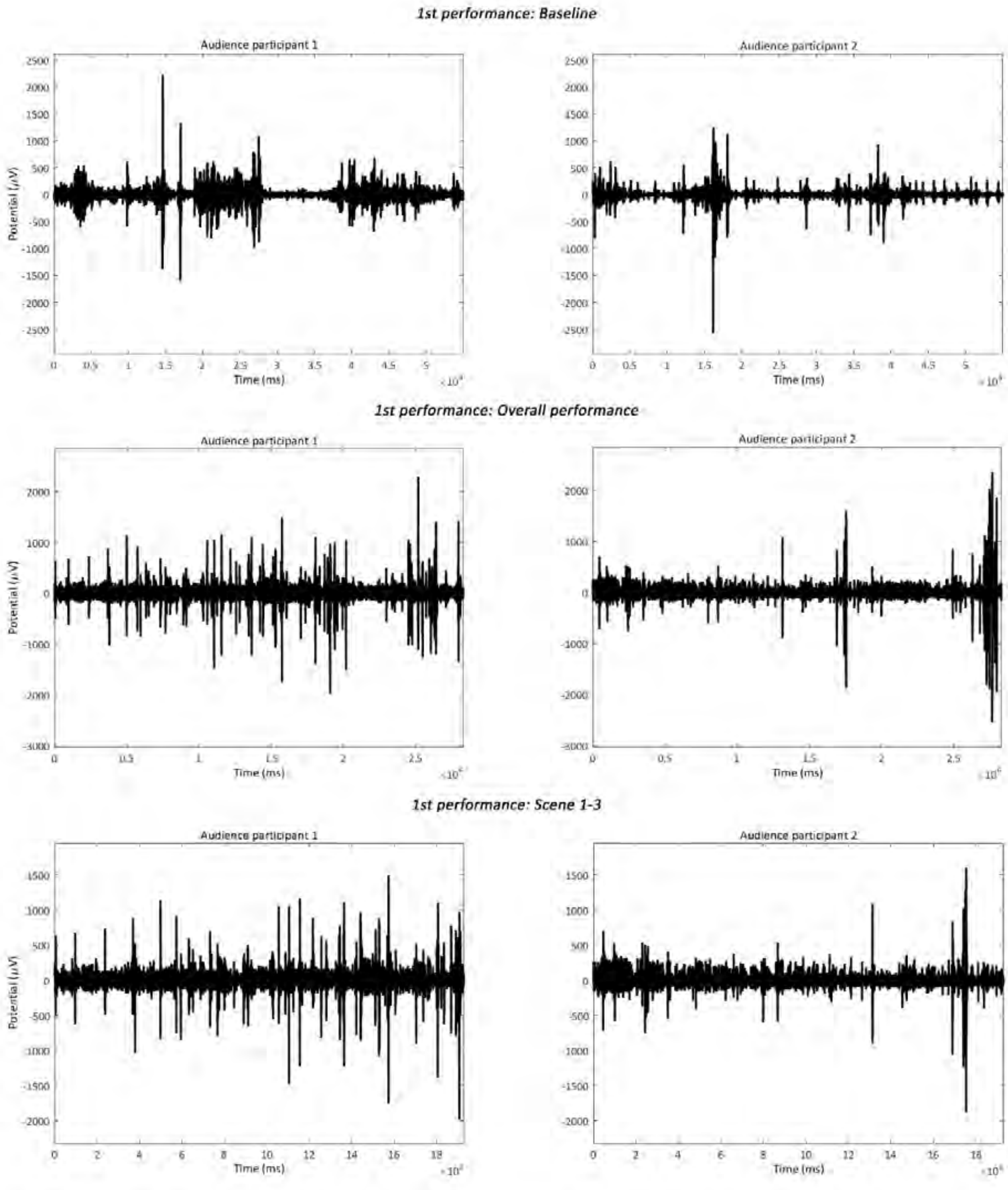
I was performing so I was supposed to interact with the ~~audio~~ colours in the screen
~~Also I was wearing a device so the audien~~
I was wearing a device so the audience could see the screen changing colours due to my brain activity

Appendix B. Participants' Analysis

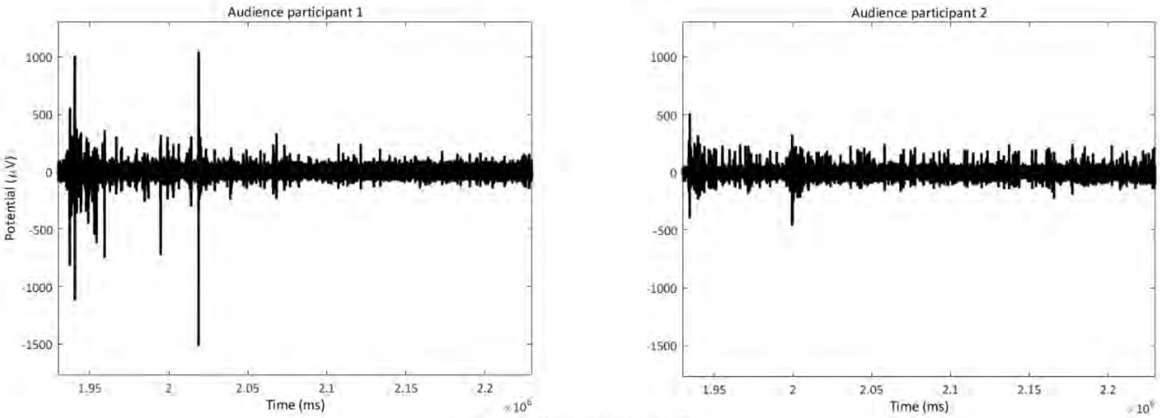
B.1 Audience participants' analysis

B.1.1 Audience participants' 4-40Hz Signal Potential (mV) in the Time domain (ms) analysis

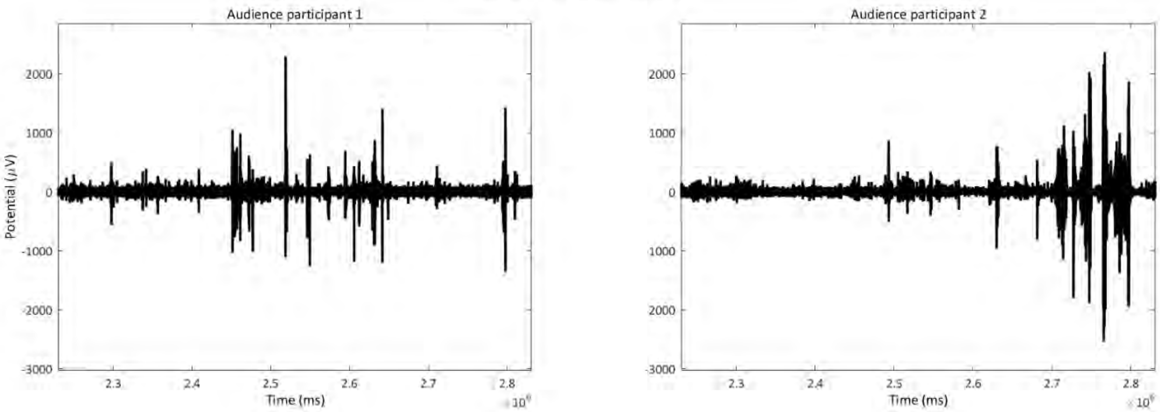
29 July 2015 – Audience participants 1 and 2



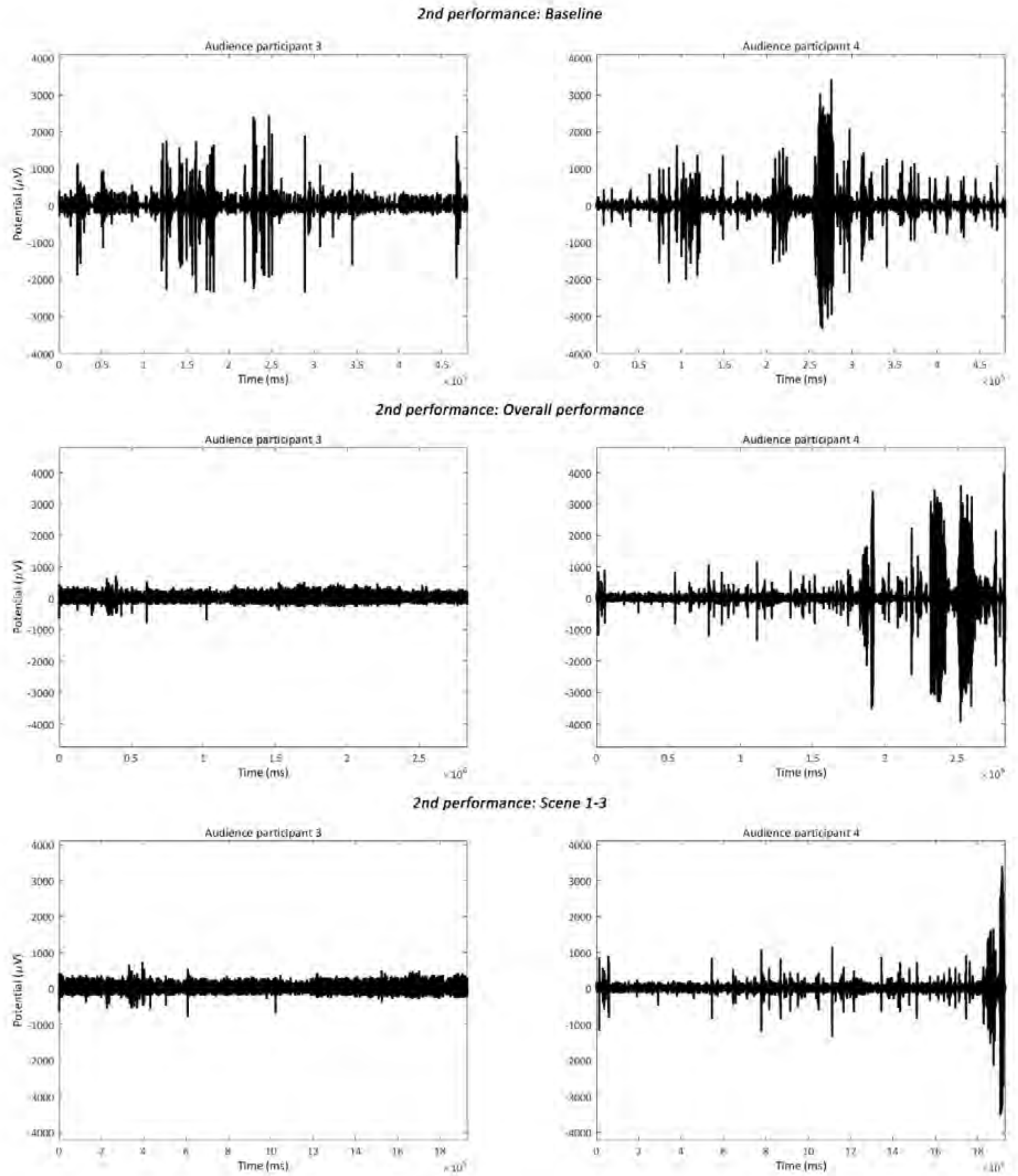
1st performance: Scene 4



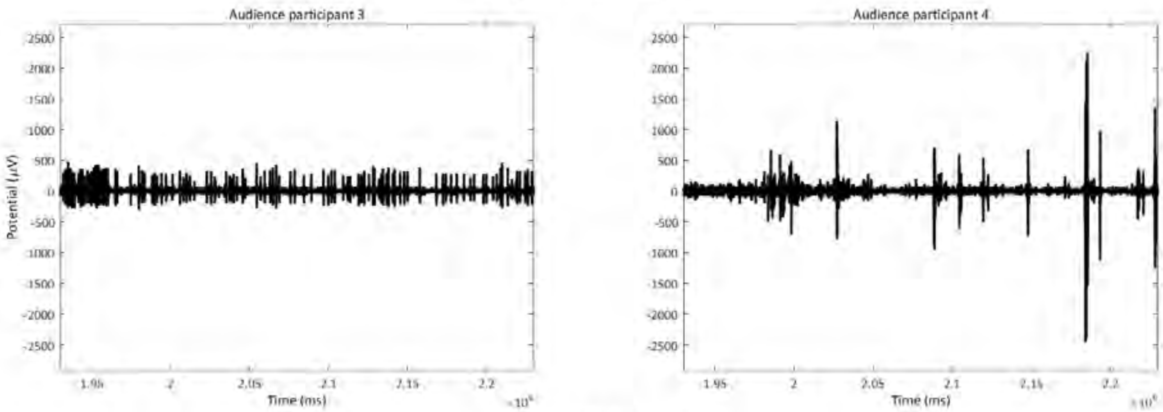
1st performance: Scene 5



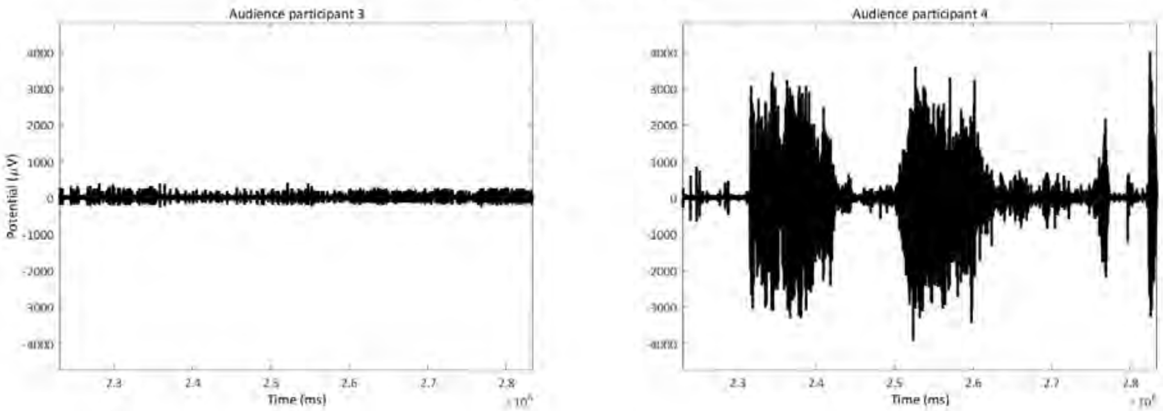
30 July 2015 – Audience participants 3 and 4



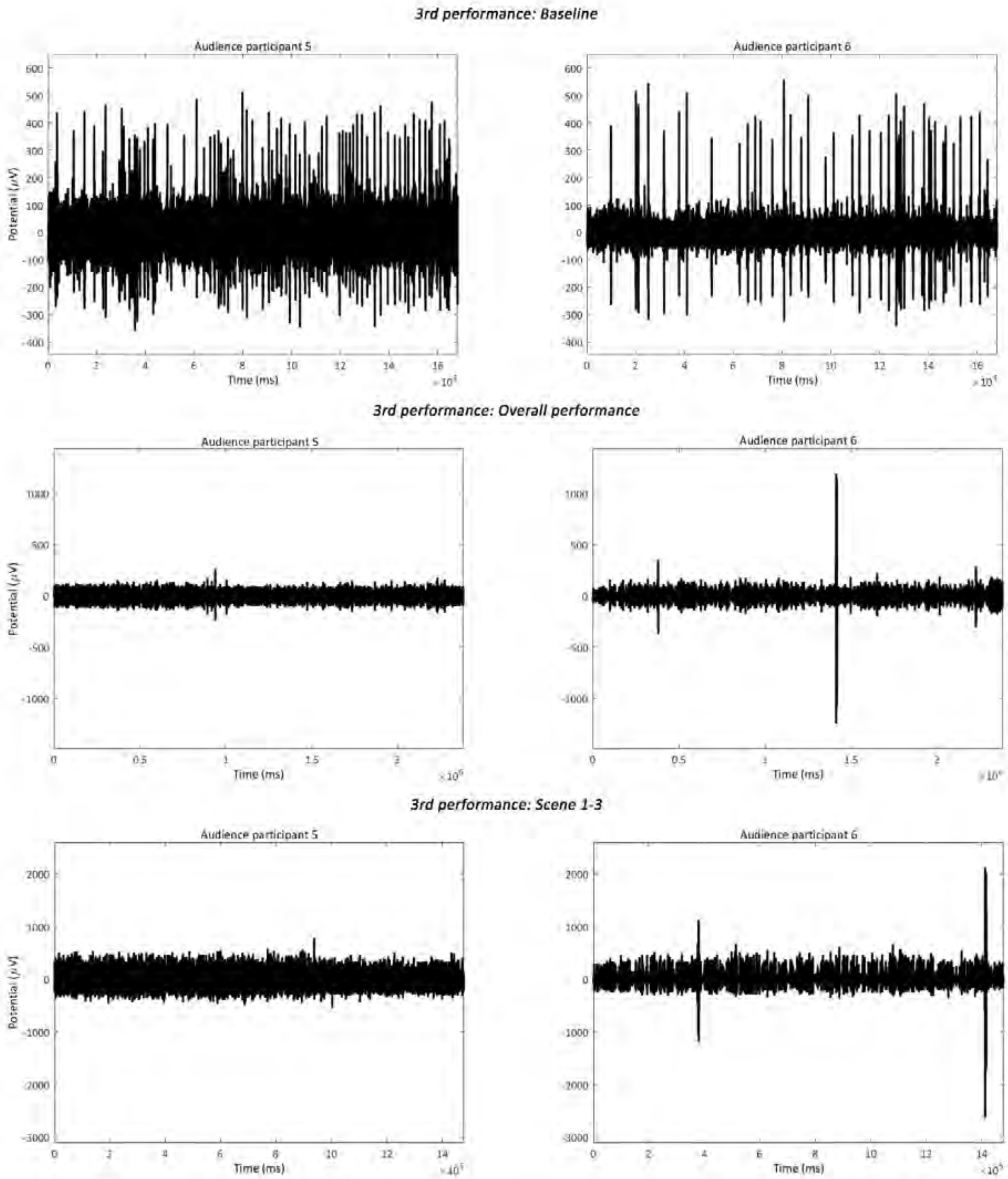
2nd performance: Scene 4



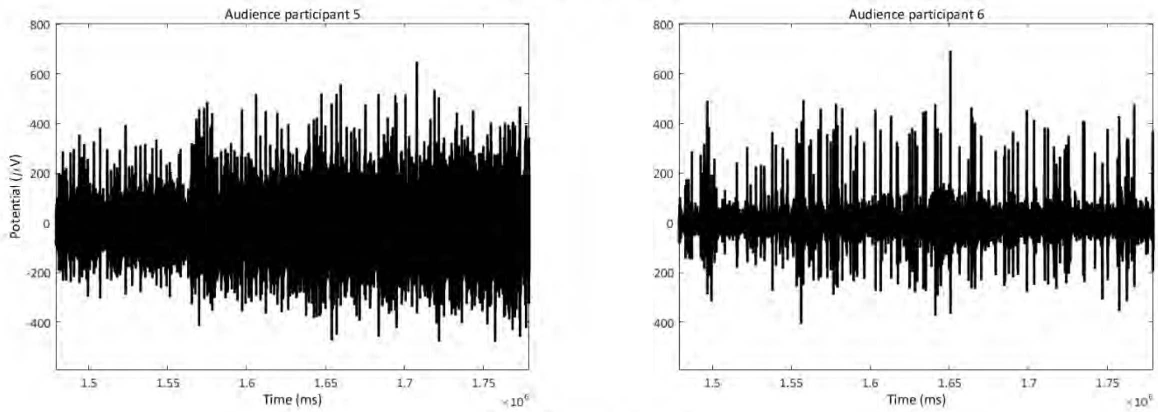
2nd performance: Scene 5



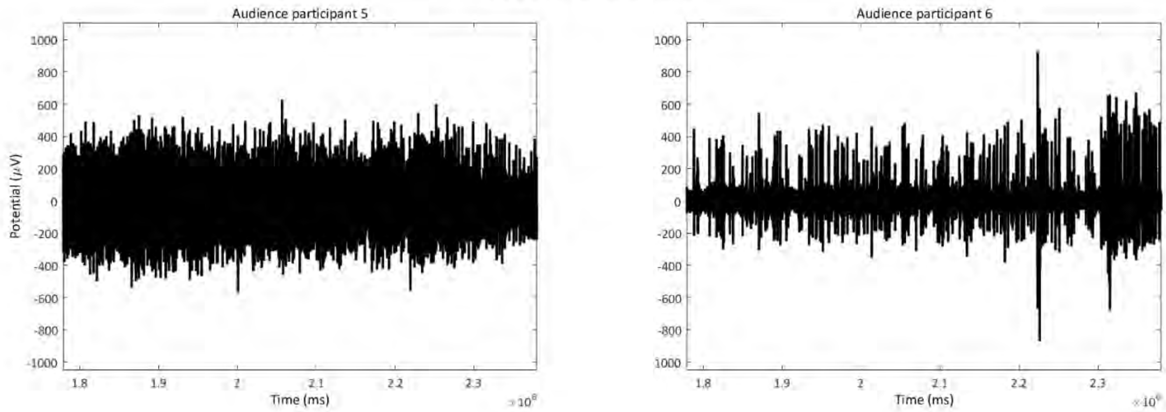
31 July 2015 – Audience participants 5 and 6



3rd performance: Scene 4



3rd performance: Scene 5



B.1.2 AUDIENCE PARTICIPANTS' INTRA-SUBJECT VARIABILITY OF THE 4-40HZ LOG POWER SPECTRAL DENSITY 10*LOG10(MV²/HZ)

29 July 2015 – Audience participant 1

Frequency		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Theta	4.03	75.72	66.37	66.47	66.26	66.09
	5.04	78.30	69.04	69.26	68.53	68.53
	6.05	77.48	68.12	68.43	67.19	67.46
	7.06	75.70	66.49	66.65	66.61	65.91
Mean		76.80	67.50	67.70	67.15	67.00
(scene-p)/p %				0.29%	-0.53%	-0.75%
(scene-b)/b %			-13.77%	-13.44%	-14.38%	-14.63%
Alpha	8.06	74.00	65.03	65.08	65.28	64.74
	9.07	73.31	63.20	63.40	63.30	62.46
	10.08	72.96	62.25	62.55	61.49	61.53
	11.09	71.52	61.02	61.21	60.56	60.62
	12.09	69.82	59.73	59.85	59.66	59.39
Mean		72.32	62.25	62.42	62.06	61.75
(scene-p)/p %				0.27%	-0.30%	-0.81%
(scene-b)/b %			-16.19%	-15.87%	-16.54%	-17.13%
Beta	13.10	68.03	59.26	59.27	58.79	59.45
	14.11	67.09	59.16	58.91	58.59	60.10
	15.12	65.76	58.84	58.45	57.80	60.25
	16.13	65.37	58.73	58.28	57.37	60.35
	17.13	64.72	58.92	58.48	57.42	60.54
	18.14	64.34	58.81	58.37	57.12	60.49
	19.15	63.31	59.11	58.82	57.38	60.51
	20.16	64.09	59.39	59.04	57.65	60.91
	21.17	64.11	58.80	58.29	57.87	60.40
	22.17	64.21	58.91	58.41	57.82	60.55
	23.18	64.18	58.82	58.42	57.53	60.32
	24.19	63.73	58.81	58.56	56.95	60.12
Mean		64.91	58.96	58.61	57.69	60.33
(scene-p)/p %				-0.60%	-2.21%	2.27%
(scene-b)/b %			-10.09%	-10.75%	-12.52%	-7.59%

Frequency		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Lower Gamma	25.20	62.35	58.82	58.57	56.58	60.24
	26.20	64.47	59.02	58.73	56.31	60.60
	27.21	66.00	58.56	58.25	56.27	60.11
	28.22	66.14	58.82	58.48	56.18	60.51
	29.23	65.27	58.79	58.70	55.84	60.00
	30.24	64.78	58.22	57.78	55.70	60.07
	31.24	65.27	58.05	57.45	55.50	60.19
	32.25	65.33	57.77	57.13	55.20	59.99
	33.26	65.60	57.92	56.93	54.73	60.74
	34.27	64.56	57.76	56.84	54.54	60.51
	35.28	64.16	57.64	57.03	54.26	59.93
	36.28	64.94	57.71	57.47	54.01	59.37
	37.29	65.23	57.46	56.91	54.00	59.66
	38.30	65.14	57.50	56.46	53.19	60.52
	39.31	63.97	56.44	55.49	52.82	59.27
Mean		64.88	58.03	57.48	55.01	60.11
(scene-p)/p %				-0.96%	-5.50%	3.46%
(scene-b)/b %			-11.80%	-12.88%	-17.95%	-7.93%

29 July 2015 – Audience participant 2

Frequency		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Theta	4.03	76.40	66.35	65.18	64.67	69.18
	5.04	77.09	69.40	67.88	66.98	72.75
	6.05	75.66	68.17	66.45	65.40	71.76
	7.06	75.68	66.83	64.96	63.57	70.61
Mean		76.21	67.69	66.12	65.16	71.08
(scene-p)/p %				-2.37%	-3.89%	4.77%
(scene-b)/b %			-12.59%	-15.26%	-16.96%	-7.22%
Alpha	8.06	73.58	65.71	63.62	61.61	69.75
	9.07	71.24	64.60	61.78	59.84	69.18
	10.08	69.59	63.88	60.36	58.64	68.84
	11.09	68.51	62.14	58.68	57.21	67.06
	12.09	66.77	62.12	57.89	57.02	67.36
Mean		69.94	63.69	60.47	58.86	68.44
(scene-p)/p %				-5.33%	-8.20%	6.94%
(scene-b)/b %			-9.81%	-15.67%	-18.81%	-2.19%
Beta	13.10	64.93	61.90	57.30	56.62	67.28
	14.11	63.58	62.77	56.03	55.50	68.73
	15.12	63.00	63.35	55.50	54.59	69.50
	16.13	63.25	61.13	54.82	53.46	67.01
	17.13	60.97	59.63	54.05	52.92	65.34
	18.14	60.58	58.57	53.41	52.66	64.15
	19.15	59.77	59.64	52.86	52.45	65.60
	20.16	59.28	58.44	52.47	52.19	64.22
	21.17	58.42	57.51	52.18	52.14	63.11
	22.17	56.12	56.52	51.55	51.79	62.00
	23.18	55.84	56.51	51.08	51.16	62.14
	24.19	56.18	56.80	50.55	50.95	62.63
Mean		60.16	59.40	53.48	53.04	65.14
(scene-p)/p %				-11.06%	-12.00%	8.82%
(scene-b)/b %			-1.28%	-12.49%	-13.43%	7.65%

Frequency		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Lower Gamma	25.20	55.28	56.47	49.87	50.44	62.37
	26.20	53.41	55.48	49.37	49.71	61.27
	27.21	54.63	55.11	48.97	49.35	60.91
	28.22	54.43	55.96	48.63	49.57	61.99
	29.23	53.99	55.59	48.45	49.57	61.57
	30.24	53.30	54.20	48.46	49.31	59.87
	31.24	52.86	54.06	48.18	48.64	59.79
	32.25	53.46	54.04	47.96	48.57	59.82
	33.26	53.09	54.11	47.84	49.00	59.92
	34.27	53.06	53.05	47.67	48.49	58.63
	35.28	52.05	52.83	47.41	48.24	58.41
	36.28	52.11	52.67	47.37	48.22	58.22
	37.29	52.35	53.22	47.22	48.50	58.94
	38.30	52.84	53.23	46.96	48.16	59.03
	39.31	52.01	52.01	46.69	47.90	57.55
Mean		53.26	54.14	48.07	48.91	59.89
(scene-p)/p %				-12.62%	-10.68%	9.60%
(scene-b)/b %			1.62%	-10.79%	-8.88%	11.07%

30 July 2015 – Audience participant 3

Frequency		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Theta	4.03	74.15	66.71	66.89	67.54	65.51
	5.04	76.76	69.24	69.41	70.08	68.03
	6.05	75.53	67.79	67.95	68.78	66.56
	7.06	74.33	65.77	65.93	66.87	64.44
Mean		75.20	67.38	67.55	68.32	66.13
(scene-p)/p %				0.25%	1.37%	-1.88%
(scene-b)/b %			-11.60%	-11.32%	-10.07%	-13.70%
Alpha	8.06	73.92	63.65	63.82	64.77	62.23
	9.07	73.17	61.46	61.67	62.44	60.03
	10.08	72.37	59.54	59.78	60.27	58.18
	11.09	71.43	57.89	58.19	58.32	56.47
	12.09	70.78	56.61	57.01	56.20	55.25
Mean		72.33	59.83	60.09	60.40	58.43
(scene-p)/p %				0.44%	0.94%	-2.39%
(scene-b)/b %			-20.90%	-20.37%	-19.76%	-23.79%
Beta	13.10	69.39	55.38	55.76	54.71	54.29
	14.11	69.24	54.48	54.86	53.50	53.55
	15.12	67.48	53.95	54.31	52.89	53.19
	16.13	66.84	53.38	53.75	52.26	52.58
	17.13	66.89	52.92	53.26	51.83	52.19
	18.14	66.13	52.43	52.73	51.59	51.76
	19.15	66.04	52.03	52.28	51.26	51.54
	20.16	65.62	51.76	51.96	50.92	51.48
	21.17	64.84	51.61	51.75	50.85	51.52
	22.17	63.90	51.62	51.86	50.58	51.29
	23.18	62.40	51.66	51.88	50.75	51.31
	24.19	61.87	51.59	51.75	50.86	51.42
Mean		65.89	52.73	53.01	51.83	52.18
(scene-p)/p %				0.53%	-1.74%	-1.07%
(scene-b)/b %			-24.94%	-24.28%	-27.11%	-26.27%

Frequency		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Lower Gamma	25.20	61.31	51.46	51.64	50.47	51.32
	26.20	60.96	51.45	51.64	50.24	51.37
	27.21	60.28	51.52	51.78	50.24	51.22
	28.22	59.91	51.45	51.68	50.48	51.12
	29.23	60.05	51.46	51.65	50.74	51.16
	30.24	59.91	51.46	51.67	50.73	51.12
	31.24	59.71	51.47	51.65	50.61	51.25
	32.25	59.45	51.31	51.46	50.42	51.22
	33.26	59.19	51.05	51.20	50.31	50.88
	34.27	59.32	51.07	51.22	50.14	50.96
	35.28	59.95	51.07	51.25	50.01	50.94
	36.28	59.78	50.95	51.18	50.15	50.54
	37.29	59.81	50.89	51.11	50.09	50.54
	38.30	59.28	50.69	50.84	50.14	50.44
	39.31	58.95	50.18	50.33	49.60	49.95
Mean		59.86	51.16	51.35	50.29	50.93
(scene-p)/p %				0.37%	-1.74%	-0.45%
(scene-b)/b %			-16.99%	-16.56%	-19.02%	-17.52%

30 July 2015 – Audience participant 4

Frequency		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Theta	4.03	77.04	75.66	69.60	69.77	81.42
	5.04	79.54	78.90	72.98	72.48	84.66
	6.05	78.84	78.34	71.84	71.59	84.23
	7.06	78.21	77.38	70.61	68.62	83.36
Mean		78.41	77.57	71.26	70.61	83.42
(scene-p)/p %				-8.86%	-9.85%	7.01%
(scene-b)/b %			-1.08%	-10.04%	-11.04%	6.01%
Alpha	8.06	77.68	77.22	70.07	67.21	83.27
	9.07	76.29	76.53	71.33	65.83	82.21
	10.08	74.53	75.63	70.25	66.77	81.32
	11.09	74.80	75.16	68.64	65.18	81.12
	12.09	73.27	74.61	68.36	64.98	80.51
Mean		75.31	75.83	69.73	65.99	81.69
(scene-p)/p %				-8.75%	-14.91%	7.16%
(scene-b)/b %			0.68%	-8.01%	-14.12%	7.80%
Beta	13.10	73.25	74.34	67.89	63.38	80.28
	14.11	72.44	73.82	67.84	62.50	79.68
	15.12	71.76	73.09	66.39	61.07	79.09
	16.13	71.64	72.61	65.19	60.64	78.73
	17.13	71.99	72.18	66.24	60.89	78.03
	18.14	70.74	71.72	66.57	60.97	77.38
	19.15	69.75	71.37	65.39	61.02	77.21
	20.16	69.87	71.06	64.56	60.48	77.02
	21.17	69.05	71.02	64.28	60.55	77.01
	22.17	68.79	70.77	63.47	59.87	76.86
	23.18	68.14	70.59	64.37	59.67	76.49
	24.19	68.15	70.11	64.44	58.12	75.91
Mean		70.46	71.89	65.55	60.76	77.81
(scene-p)/p %				-9.67%	-18.31%	7.61%
(scene-b)/b %			1.98%	-7.49%	-15.97%	9.44%

Frequency		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Lower Gamma	25.20	68.27	69.89	62.99	57.12	75.93
	26.20	67.79	69.45	62.09	57.18	75.56
	27.21	66.96	69.24	62.84	57.11	75.18
	28.22	66.79	69.20	64.02	57.12	74.88
	29.23	66.59	68.92	63.60	56.67	74.63
	30.24	65.95	68.27	62.93	57.27	73.98
	31.24	65.82	68.26	62.76	56.98	74.02
	32.25	65.87	68.49	61.50	56.89	74.54
	33.26	65.46	68.12	61.14	55.94	74.17
	34.27	64.87	67.55	60.98	55.46	73.53
	35.28	65.12	67.37	60.85	55.33	73.34
	36.28	66.69	67.39	61.46	55.62	73.24
	37.29	66.37	67.21	61.41	55.70	73.03
	38.30	65.44	67.07	60.53	56.82	73.03
	39.31	65.02	66.84	60.57	56.40	72.75
Mean		66.20	68.22	61.98	56.51	74.12
(scene-p)/p %				-10.07%	-20.73%	7.96%
(scene-b)/b %			2.96%	-6.81%	-17.15%	10.69%

31 July 2015 – Audience participant 5

Frequency		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Theta	4.03	67.66	66.31	66.30	66.53	66.25
	5.04	70.65	68.91	68.91	69.08	68.85
	6.05	69.45	67.72	67.81	67.72	67.51
	7.06	67.57	66.14	66.30	65.95	65.83
Mean		68.83	67.27	67.33	67.32	67.11
(scene-p)/p %				0.09%	0.07%	-0.25%
(scene-b)/b %			-2.32%	-2.23%	-2.25%	-2.57%
Alpha	8.06	65.64	64.41	64.63	64.01	64.06
	9.07	63.86	62.80	62.87	62.40	62.81
	10.08	61.94	61.50	61.39	61.20	61.91
	11.09	60.14	60.82	60.42	60.86	61.67
	12.09	59.33	60.44	59.89	60.27	61.62
Mean		62.18	61.99	61.84	61.75	62.41
(scene-p)/p %				-0.25%	-0.40%	0.67%
(scene-b)/b %			-0.30%	-0.56%	-0.70%	0.37%
Beta	13.10	58.71	60.48	59.71	60.41	61.98
	14.11	58.59	60.75	59.97	60.49	62.31
	15.12	58.00	61.19	60.20	61.09	62.98
	16.13	58.09	61.84	60.71	61.83	63.78
	17.13	58.43	62.35	61.27	62.33	64.24
	18.14	58.90	62.92	61.75	62.62	65.01
	19.15	59.17	63.54	62.32	63.41	65.62
	20.16	59.67	64.15	62.92	63.80	66.31
	21.17	60.18	64.76	63.60	64.51	66.81
	22.17	61.24	65.32	64.24	65.05	67.29
	23.18	61.77	65.84	64.73	65.57	67.84
	24.19	61.93	66.28	65.13	66.36	68.23
Mean		59.56	63.28	62.21	63.12	65.20
(scene-p)/p %				-1.72%	-0.26%	2.94%
(scene-b)/b %			5.89%	4.27%	5.65%	8.65%

Frequency		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Lower Gamma	25.20	62.49	66.66	65.40	67.00	68.64
	26.20	62.99	67.02	65.62	67.53	69.10
	27.21	63.34	67.13	65.74	67.80	69.13
	28.22	63.52	67.20	65.87	67.85	69.16
	29.23	64.04	67.04	65.72	67.85	68.92
	30.24	63.61	66.88	65.50	67.58	68.86
	31.24	62.55	66.54	65.29	67.47	68.28
	32.25	61.97	66.16	64.76	67.12	68.07
	33.26	61.24	65.57	64.19	66.62	67.40
	34.27	60.43	64.92	63.48	65.78	66.92
	35.28	59.91	64.41	62.94	64.85	66.59
	36.28	59.77	63.79	62.41	64.00	65.96
	37.29	59.63	63.08	61.66	63.78	65.12
	38.30	58.82	62.46	61.15	62.93	64.47
	39.31	57.53	61.80	60.54	62.30	63.73
Mean		61.46	65.38	64.02	66.03	67.36
(scene-p)/p %				-2.12%	0.99%	2.94%
(scene-b)/b %			6.00%	4.00%	6.93%	8.76%

31 July 2015 – Audience participant 6

Frequency		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Theta	4.03	67.00	68.34	68.46	67.53	68.38
	5.04	69.77	70.73	70.81	70.07	70.85
	6.05	68.59	69.41	69.51	68.85	69.42
	7.06	66.75	68.00	68.27	66.98	67.74
Mean		68.03	69.12	69.26	68.36	69.10
(scene-p)/p %				0.21%	-1.11%	-0.03%
(scene-b)/b %			1.58%	1.78%	0.49%	1.55%
Alpha	8.06	65.11	66.10	66.36	64.89	65.96
	9.07	63.60	64.53	64.84	63.55	64.17
	10.08	61.79	62.97	63.41	61.84	62.25
	11.09	60.11	61.47	62.01	60.09	60.55
	12.09	58.25	59.96	60.48	58.76	59.01
Mean		61.77	63.01	63.42	61.83	62.39
(scene-p)/p %				0.65%	-1.91%	-0.99%
(scene-b)/b %			1.96%	2.59%	0.09%	0.99%
Beta	13.10	57.15	59.32	60.06	57.05	58.06
	14.11	55.65	57.62	57.98	56.05	57.36
	15.12	54.48	55.96	56.09	55.25	55.95
	16.13	53.63	54.76	54.67	54.46	55.10
	17.13	53.68	54.38	54.31	54.21	54.64
	18.14	54.05	53.90	53.84	53.58	54.19
	19.15	53.11	53.63	53.71	53.22	53.63
	20.16	52.87	54.26	54.74	53.54	53.25
	21.17	53.16	54.06	54.55	53.27	53.05
	22.17	52.80	53.96	54.52	52.79	52.91
	23.18	52.84	53.84	54.32	53.14	52.83
	24.19	53.06	53.34	53.67	52.99	52.57
Mean		53.87	54.92	55.20	54.13	54.46
(scene-p)/p %				0.52%	-1.46%	-0.84%
(scene-b)/b %			1.91%	2.41%	0.47%	1.08%

Frequency		Baseline	Overall perf.	Scene 1-3	Scene 4	Scene 5
Lower Gamma	25.20	52.93	53.10	53.40	52.75	52.42
	26.20	52.63	52.46	52.46	52.64	52.39
	27.21	52.45	52.46	52.50	52.29	52.43
	28.22	52.71	52.21	52.29	52.23	52.01
	29.23	53.21	51.88	51.87	52.25	51.73
	30.24	52.57	52.52	52.84	52.21	51.78
	31.24	52.16	51.94	52.05	52.12	51.52
	32.25	51.83	51.23	51.27	51.54	50.95
	33.26	51.70	51.29	51.37	51.35	51.08
	34.27	51.74	51.92	52.37	51.21	51.02
	35.28	51.35	51.42	51.67	51.06	50.94
	36.28	51.14	50.93	51.11	50.76	50.57
	37.29	51.13	50.82	51.04	50.58	50.36
	38.30	50.83	50.71	50.95	50.58	50.13
	39.31	50.88	50.16	50.36	50.10	49.65
Mean		51.95	51.67	51.84	51.58	51.27
(scene-p)/p %				0.32%	-0.18%	-0.79%
(scene-b)/b %			-0.54%	-0.22%	-0.72%	-1.33%

B.1.3 AUDIENCE PARTICIPANTS' POWER SPECTRAL DENSITY ONE-WAY ANOVA ANALYSIS

Alpha power test of within-subjects effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Parts	Sphericity Assumed	185.171	4	46.293	3.422	**.028**	.406
	Greenhouse-Geisser	185.171	1.884	98.282	3.422	.078	.406
	Huynh-Feldt	185.171	2.986	62.011	3.422	.045	.406
	Lower-bound	185.171	1.000	185.171	3.422	.124	.406
Error(Parts)	Sphericity Assumed	270.595	20	13.530			
	Greenhouse-Geisser	270.595	9.420	28.725			
	Huynh-Feldt	270.595	14.930	18.124			
	Lower-bound	270.595	5.000	54.119			

Alpha power pairwise comparisons

(I) Parts		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval od Difference	
					Lower Bound	Upper Bound
Baseline	Overall perf.	4.544	2.414	1.000	-6.980	16.069
	Scene 1-3	5.984	2.287	.473	-4.931	16.898
	Scene 4	7.162	2.234	**.238**	-3.501	17.826
	Scene 5	3.126	3.108	1.000	-11.708	17.961
Overall perf.	Baseline	-4.544	2.414	1.000	-16.069	6.980
	Scene 1-3	1.439	1.088	1.000	-3.754	6.632
	Scene 4	2.618	1.641	1.000	-5.215	10.451
	Scene 5	-1.418	1.258	1.000	-7.425	4.589
Scene 1-3	Baseline	-5.984	2.287	.473	-16.898	4.931
	Overall perf.	-1.439	1.088	1.000	-6.632	3.754
	Scene 4	1.179	.604	1.000	-1.705	4.063
	Scene 5	-2.857	2.325	1.000	-13.954	8.240
Scene 4	Baseline	-7.162	2.234	**.238**	-17.826	3.501
	Overall perf.	-2.618	1.641	1.000	-10.451	5.215
	Scene 1-3	-1.179	.604	1.000	-4.063	1.705
	Scene 5	-4.036	2.857	1.000	-17.675	9.602
Scene 5	Baseline	-3.126	3.108	1.000	-17.961	11.708
	Overall perf.	1.418	1.258	1.000	-4.589	7.425
	Scene 1-3	2.857	2.325	1.000	-8.240	13.954
	Scene 4	4.036	2.857	1.000	-9.602	17.675

Lower Gamma power test of within-subjects effects

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Parts	Sphericity Assumed	148.560	4	37.140	2.899	**.048**	.367
	Greenhouse-Geisser	148.560	2.006	74.040	2.899	.101	.367
	Huynh-Feldt	148.560	3.354	44.299	2.899	.061	.367
	Lower-bound	148.560	1.000	148.560	2.899	.149	.367
Error(Parts)	Sphericity Assumed	256.254	20	12.813			
	Greenhouse-Geisser	256.254	10.032	25.543			
	Huynh-Feldt	256.254	16.768	15.283			
	Lower-bound	256.254	5.000	51.251			

Lower Gamma power pairwise comparisons

(I) Parts		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval od Difference	
					Lower Bound	Upper Bound
Baseline	Overall perf.	1.501	2.075	1.000	-8.406	11.407
	Scene 1-3	3.811	1.744	.806	-4.515	12.136
	Scene 4	4.879	2.450	1.000	-6.814	16.573
	Scene 5	-1.013	2.818	1.000	-14.462	12.436
Overall perf.	Baseline	-1.501	2.075	1.000	-11.407	8.406
	Scene 1-3	2.310	1.237	1.000	-3.595	8.215
	Scene 4	3.379	1.882	1.000	-5.606	12.364
	Scene 5	-2.513	1.133	**.772**	-7.920	2.893
Scene 1-3	Baseline	-3.811	1.744	.806	-12.136	4.515
	Overall perf.	-2.310	1.237	1.000	-8.215	3.595
	Scene 4	1.069	1.082	1.000	-4.098	6.235
	Scene 5	-4.823	2.353	.956	-16.053	6.406
Scene 4	Baseline	-4.879	2.450	1.000	-16.573	6.814
	Overall perf.	-3.379	1.882	1.000	-12.364	5.606
	Scene 1-3	-1.069	1.082	1.000	-6.235	4.098
	Scene 5	-5.892	2.891	.971	-19.691	7.907
Scene 5	Baseline	1.013	2.818	1.000	-12.436	14.462
	Overall perf.	2.513	1.133	**.772**	-2.893	7.920
	Scene 1-3	4.823	2.353	.956	-6.406	16.053
	Scene 4	5.892	2.891	.971	-7.907	19.691

B.2 Performer participant's analysis

B.2.1 Performer participant's intra-subject variability of the 4-40Hz Log Power Spectral Density 10*log10(mV²/Hz)

Rehearsal

Frequency		Baseline	Overall perf.
Theta	4.03	75.25	82.91
	5.04	76.76	85.26
	6.05	75.42	83.97
	7.06	73.38	82.60
Mean		75.20	83.68
(scene-b)/b %		11.28%	
Alpha	8.06	72.68	81.39
	9.07	69.85	80.34
	10.08	67.63	79.49
	11.09	65.38	78.62
	12.09	63.18	77.62
Mean		67.74	79.49
(scene-b)/b %		17.34%	
Beta	13.10	61.70	76.72
	14.11	61.02	76.26
	15.12	60.74	75.96
	16.13	59.00	75.27
	17.13	57.78	74.72
	18.14	59.14	74.12
	19.15	59.23	73.66
	20.16	58.96	73.42
	21.17	57.02	73.00
	22.17	56.30	72.43
	23.18	56.07	71.87
	24.19	57.09	71.25
Mean		58.67	74.06
(scene-b)/b %		26.23%	

Frequency		Baseline	Overall perf.
Lower Gamma	25.20	56.33	71.13
	26.20	55.05	70.85
	27.21	55.95	70.78
	28.22	56.69	70.76
	29.23	55.01	70.47
	30.24	55.08	55.08
	31.24	54.34	70.01
	32.25	54.32	69.80
	33.26	54.79	69.82
	34.27	54.41	69.84
	35.28	55.35	69.70
	36.28	54.92	69.64
	37.29	55.31	55.31
	38.30	53.49	69.54
	39.31	52.91	69.27
Mean		54.93	70.09
(scene-b)/b %		27.60%	

30 July 2015 – 2nd performance

Frequency		Baseline	Overall perf.
Theta	4.03	74.23	81.70
	5.04	77.01	84.34
	6.05	75.58	83.35
	7.06	73.52	82.18
Mean		75.08	82.89
(scene-b)/b %		10.40%	
Alpha	8.06	71.77	80.79
	9.07	71.15	79.88
	10.08	69.91	79.05
	11.09	68.61	78.09
	12.09	66.77	77.33
Mean		69.64	79.03
(scene-b)/b %		13.48%	
Beta	13.10	66.07	76.89
	14.11	65.51	76.04
	15.12	65.99	75.22
	16.13	65.24	74.71
	17.13	62.78	74.30
	18.14	62.92	73.71
	19.15	63.51	73.38
	20.16	63.19	73.05
	21.17	62.08	72.63
	22.17	60.47	72.32
	23.18	60.58	72.00
	24.19	**59.78**	**71.49**
Mean		**63.18**	**73.81**
(scene-b)/b %		16.83%	

Frequency		Baseline	Overall perf.
Lower Gamma	25.20	59.11	71.05
	26.20	59.89	70.89
	27.21	59.53	70.63
	28.22	58.60	70.46
	29.23	58.74	70.22
	30.24	58.66	58.66
	31.24	57.67	69.48
	32.25	57.72	69.65
	33.26	57.89	69.62
	34.27	57.47	69.34
	35.28	56.75	68.85
	36.28	56.23	68.49
	37.29	56.05	56.05
	38.30	55.65	68.04
	39.31	54.61	67.59
Mean		57.64	69.48
(scene-b)/b %		20.55%	

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