NEURO AESTHETIC RESONANCE

CAISEAL BEARDOW

AUTHOR

Caiseal Beardow
c.r.beardow@student.tudelft.nl

MSc Design for Interaction
Faculty of Industrial Design Engineering
Delft University of Technology

SUPERVISORY TEAM

Chair | Dr. J. Derek Lomas
HCI & Design for Wellbeing
Human-Centred Design
Faculty of Industrial Design Engineering

Mentor | Dr. Elif Ozcan Vieira
Sound-driven Design & Research
Human-Centred Design
Faculty of Industrial Design Engineering

Delft, NL
February 2021

TU Delft   Vibe Research Labs.   intheon

“Resonance is in the body and the mind: our bodies to the world as tuning forks. An ecosystem of connected tissue.”

- Lorri Neilsen Glenn

FOREWORD

The following pages document my thesis, *NeuroAesthetic Resonance*, produced to fulfil the graduation requirements of the MSc Design for Interaction programme.

This project has been an intense, continuously challenging and ultimately rewarding experience. The project started with a deceptively simple goal: to try to understand the relationship between our brains and minds in the perception of aesthetics. Having worked with brain data previously in my work with Vibe Research Labs (an in-faculty research collective), I was compelled by its potential to enrich fundamental aesthetic theory. I had also been introduced to the world of brain-computer interfaces and was eager to explore them as an expressive medium. In this project, I saw a rare opportunity to fully immerse myself in a somewhat fringe area of design that satisfied my dual passions for art and science. Despite the many highs and lows of graduating in a global pandemic, I am above all deeply grateful that I was given the space, support and resources to do so. This project would not have been possible without the encouragement of many people who I am fortunate to have in my life.

Firstly, my supervisors, Derek and Elif.
Derek: We've worked together for most of my academic career here in Delft, and this work has shaped my development as a designer. Our collaborations have shown me that there is value in taking the road less travelled and questioning everything — something you have reminded me of throughout this project. Thank you for your generosity, enthusiasm and unwavering belief in the value of this project.
Elif: Although we weren't well acquainted before this project, I am so grateful that we are now! Your knowledge and perspective have been invaluable. Thank you for always valuing my opinions, reminding me of my power as a designer, and encouraging me to embrace myself through my work.

My friends here in Delft: our friendship has been a source of great joy in what has been a difficult year for all of us. Our weekly dinners, movie marathons and Zoom calls have kept me sane and reminded me of the many good things in my life here in the Netherlands that are all too easy to overlook in the midst of a thesis! A special thanks to Freddy, who has accompanied me throughout the graduation journey. Thank you for listening, understanding, and brightening every day in StudioLab.

My family and friends back home in the UK: I can't thank you enough for supporting me through my long and winding journey in higher education, and for cheering me on from afar. Knowing that you will always fight my corner keeps me going, even on my toughest days. My time as a student is finally over — I promise! Looking forward to having tea, bourbons and a pint of Lilley's with you all as soon as I can.

Finally, a big thank you to Tim Mullen and the NeuroPype team at Intheon, whose expertise and feedback have been invaluable in developing the technical outcomes of this project.

GLOSSARY

RESONANCE

A term with diverse scientific and cultural meanings. Originates in physics, where it describes how an oscillatory system increases in amplitude when a resonant frequency is applied to it.

RESONANT FREQUENCY

A frequency that is the same or close to a natural frequency of an oscillatory system. Some systems may have more than one resonant frequency.

EEG

Stands for electroencephalography. EEG is brain wave data, a compound signal that can be processed to extract information about a person's neurological state.

POWER SPECTRAL DENSITY

A unit of measurement for the relative power of a particular frequency within a given spectrum. Often used with EEG data to show changes in amplitude.

PERIODIC STIMULUS

A stimulus that has a specific frequency, such as a flashing light or an auditory sine wave. Commonly used in neuroscience experiments.

NEURAL RESONANCE

An increase in PSD in EEG data at the same frequency as that of a periodic stimulus, and at frequencies relative to it (e.g. double or half).

AESTHETIC RESONANCE

An optimal state in which an aesthetic experience evokes sensory pleasure and personal meaning, and imparts self-transcendental feelings, such as beauty.

CONTENTS

1

PROJECT OVERVIEW

This chapter outlines the project as a whole, including its context, scope and general structure.

1.1 EXECUTIVE SUMMARY

The brain is the foundation of human experience. Our sensory and emotional perceptions of the world around us are all based in neural activity. But does physical brain activity correspond with subjective aesthetic experience? Is it possible to optimise for both?

My project seeks to answer this question by framing brain response and aesthetic experience as forms of resonance. The brain functions through oscillation (commonly known as 'brainwaves') and as such produces measurable resonance phenomena. Aesthetic resonance is a far more metaphorical concept, but has been explored in design literature as a model of enjoyable and meaningful aesthetic experiences, in which a person feels in harmony with the aesthetic properties of their environment. In my work, I explore how design might produce experiences that are optimised for both forms of resonance. In doing so, I aim to contribute knowledge that furthers scientifically informed interaction design and enables the design of effective, enjoyable and personalised brain-computer interfaces (BCIs) and neurotherapeutics. My findings are expressed through an audiovisual installation (Figure 1) that uses a feedback loop between participant and designer to co-compose a data-driven resonant experience. The installation gathers synchronised, labelled EEG and multi-sensory stimulation data (Figure 2), enabling future research in the joint optimisation of neural response and aesthetic experience.

The project draws upon literature on resonance in the domains of neuroscience and aesthetics, exploring the role design could play in bridging these two conceptualisations. Three research questions were used to shape this exploration:

1. Can **neural and aesthetic resonance be evoked simultaneously** by periodic stimuli?
2. Does peak **neural resonance correspond** with peak **aesthetic resonance**?

Figure 1: The final design manifests as an art installation that gathers live EEG data and calculates a measure of neural resonance.

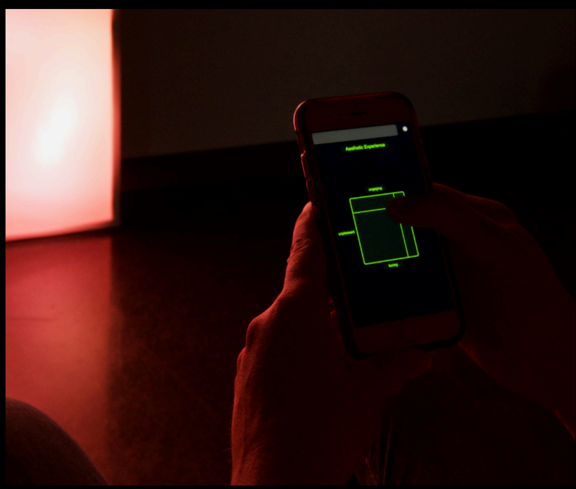


Figure 2: The installation also gathers real-time ratings of aesthetic engagement and pleasure to measure aesthetic resonance.

3. How can both forms of resonance be **embodied in an audiovisual design**?

To address these questions, metrics of neural and aesthetic resonance were developed. The metrics are informed by literature and have been validated through a series of experimental protocols that replicate simple neuroscience experiments. Initial data gathered using the metrics demonstrates that **it is possible to optimise for neural resonance in real-time**, and that this can be done in an **iterative and playful manner**. The metrics were then used in a series of interactive prototypes (Figure 3). Through these prototypes, insights were gathered regarding the embodiment of resonance in (audiovisual) design and the translation of traditional periodic stimuli to a designed experience. The prototypes demonstrate that **more complex, aesthetically resonant stimuli can also evoke neural resonance**.

These insights also informed the final design concept: **a platform for measuring and creating neural and aesthetic resonance through a data-driven, immersive audiovisual experience**. The final design therefore offers three main contributions:

- **resonance metrics;**
- **an audiovisual art installation;**
- **a research platform.**

The **metrics of neural and aesthetic resonance** were developed to be generative for design and supportive of human-centred data science. They are visualised through a real-time data display that allows a designer to optimise an audiovisual design for resonance. The **installation design**, consisting of an algorithmically generated soundscape and a light source (Figure 4), demonstrates how the metrics can inform experience design and facilitates further empirical exploration of resonance in design. Both the resonance

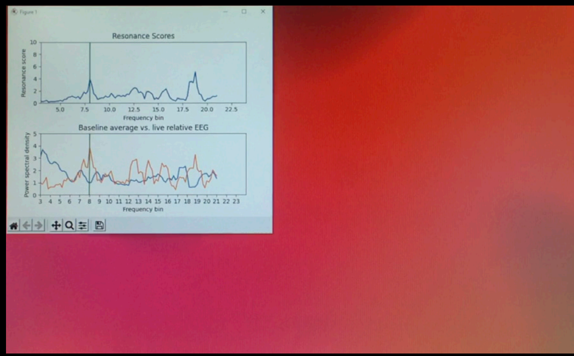


Figure 3: My audiovisual prototypes were able to evoke neural resonance, shown in my real-time data display.

Figure 4: The final design includes an audiovisual art installation that expresses and measures resonance.

metrics and installation are connected by a digital system that collects labelled neural and aesthetic data (Figure 5). The system is envisaged as a **platform for research** into the phenomenon of resonance as a driving factor in experience design.

Although COVID-19 restrictions resulted in a limited sample size for user testing, the data collected during this project suggests that it is indeed **possible to embody neural and aesthetic resonance in design**, and to **optimise such a design for both forms of resonance in an adaptive, iterative manner**. This suggests future potential not only for human-centred BCI design, but the introduction of algorithmic decision-making and machine learning techniques in optimising (bio)data-driven experiences. Additionally, the test provided some evidence that **peak neural resonance may correspond with peak aesthetic resonance** (Figure 6), although further data collection is needed to confirm this.

Questions still remain regarding the precise relationship between neural and aesthetic resonance, but the system developed during this project provides an accessible and generative platform for exploring this relationship in future research.

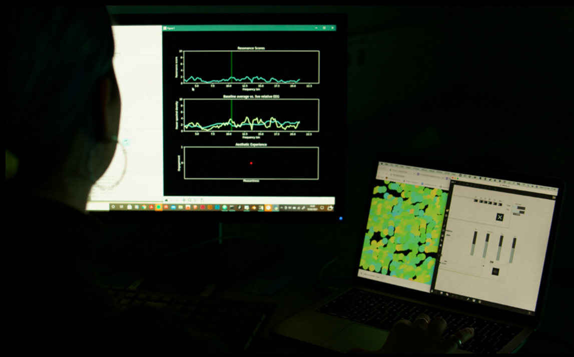


Figure 5: My final design uses real-time neural and aesthetic data to optimise an audiovisual experience for resonance.

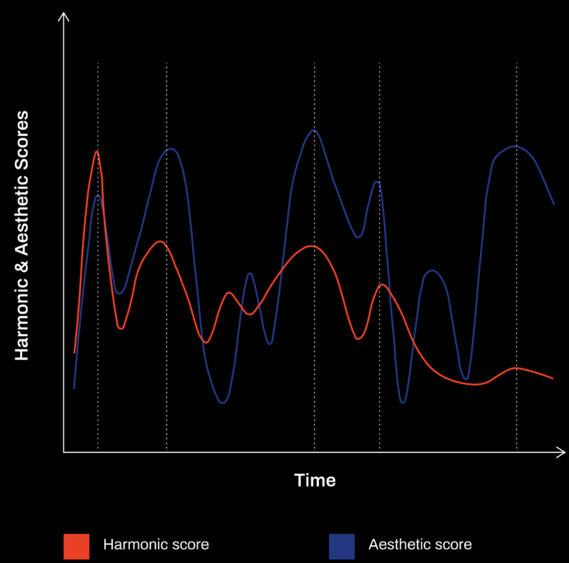


Figure 6: Results from my final user test suggest a potential relationship between neural and aesthetic resonance.

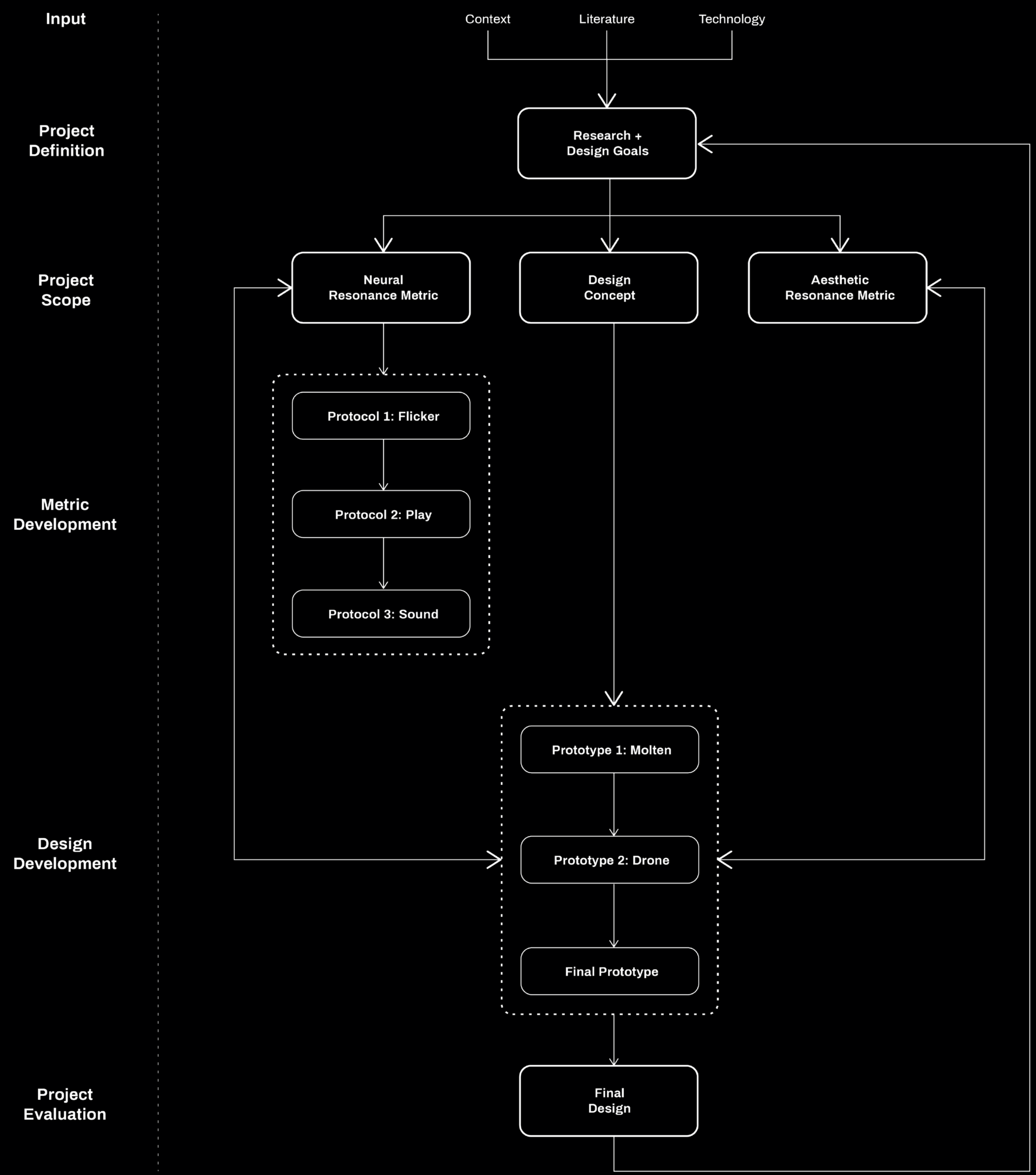


Figure 7: The overall structure of the project, starting with literature review, after which research and design goals were defined. Following this, metrics of neural and aesthetic resonance were developed, including three testing protocols. After the metrics were validated the design concept was developed through a series of prototypes and a final design was produced.

1.2.1 DESIGNING WITH THE BRAIN

The human brain is, to most of us, a black box: complex, opaque and unknowable (Figure 8). The field of neuroscience seeks to elucidate its contents. As the brain is connected to all manner of bodily processes, so too is neuroscience to other scientific domains. From computational modelling to psychology, neuroscience incorporates a wide spectrum of approaches to and perspectives on human experience. A number of specialisations within the field have emerged as a result of this diversity.

Cognitive neuroscience, for example, investigates the neurological basis of cognition and emotion. In doing so, it links measurable neural phenomena to aspects of human experience that might otherwise seem enigmatic. As a discipline, cognitive neuroscience seeks to demonstrate how our experience of the world around us is inherently shaped by our biological capacities for perceiving it[1]. It also posits that perceptual and physical responses to our environment correspond to responses in the brain: “a representation of information in patterns of neural activity”[1].

Understanding the science of cognition not only has implications for scientists and clinicians, but for other disciplines concerned with human perception — including those with traditionally qualitative approaches to the subject, such as design. In the past few decades, there has been increasing interest within the design community regarding the application of neuroscience principles in designing interactive products, environments and experiences[2]. The opportunities in neuroscience-informed design are twofold: an enriched understanding of how designed artefacts are perceived on an anatomical basis, and suggestions as to how this relationship between psychology and physiology might be leveraged to design for intended effects. Despite this, there remains a

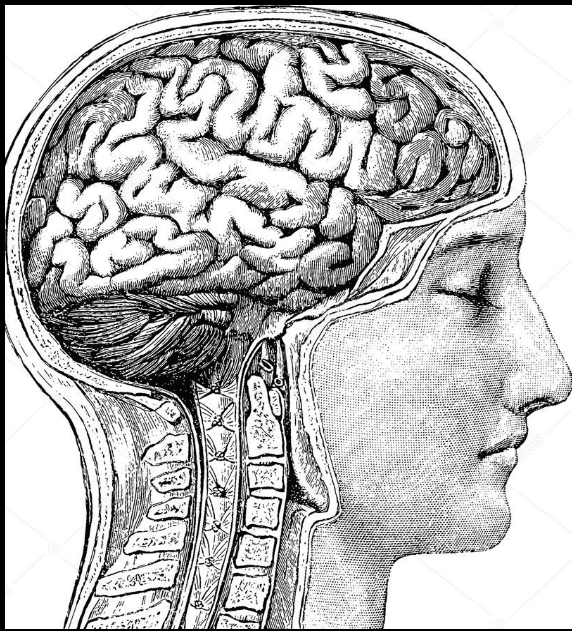


Figure 8: Modern neuroscience has revolutionised the way we understand the brain, from a black box to a network of interconnected systems[39].

tension between scientific rigour and designerly intuition: conditions for scientific validity are not always conducive to a holistic design process, particularly when working with a subject as intricate as the brain. A combination of experimental and user-centred approaches is needed to begin to reconcile the two.

1.2.2 BRAIN-COMPUTER INTERFACES

Brain-computer interfaces (BCIs) demonstrate how principles of neuroscience and design might be applied simultaneously to facilitate meaningful interactions (Figure 9). A BCI is defined as an interface that "measures central nervous system (CNS) activity and converts it into artificial output", which ultimately "changes the ongoing interaction between the CNS and its external or internal environment"[3]. Measurement is usually in the form of electroencephalography (EEG), which measures the brain's electrical activity in spectral (wave) form. As consumer-grade EEG devices have become increasingly accessible and accurate, some BCIs have also evolved from controlled laboratory experiments to vehicles for artistic expression. According to practitioner Nina Sobell, BCIs are driven by the "transmutation of neural signals into realms of sounds and images that render the internal workings of the mind perceptible"[4]. As such, BCIs are not only a means for scientifically-informed research, but a platform for design and exploration of the boundaries of interaction (Figure 10).

All BCIs — whether scientifically or artistically motivated, or both — require stimuli that can reliably evoke a recognisable brain response. Such stimuli are usually periodic in nature; in other words, they have a specific frequency. Common examples include flickering LEDs and auditory sine waves. When an individual is shown such a stimulus at a given frequency, it is possible to identify the strength of neural response to the stimulus by looking at brain activity in the region of its frequency. For

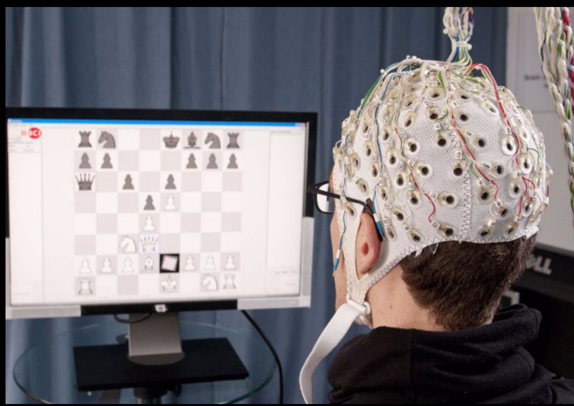


Figure 9: BCIs allow users to directly or indirectly influence their environment through their neural activity, using EEG data.

Figure 10: An example of an art installation facilitated by a BCI (eeg_deer by Dmitry Morozov, 2014). There is increasing interest in the subjective experience of BCIs — and how to design this.

example, if a BCI system uses 40Hz flickering LEDs, an increase in brain activity at around 40Hz indicates a response. This mechanism is used by BCIs to detect attention (such as looking at a flashing letter on a screen, as in Figure 11), to infer intention, and to translate this to interface actions (such as constructing a word). Although this approach enables relatively consistent interactions between the user and BCI, these interactions are limited in terms of experiential value. This is primarily due to the repetitive and intense nature of periodic stimuli, which can cause both physical and mental fatigue[5]. The one-dimensional nature of these stimuli means that they do not usually enhance the user experience of BCIs, but are rather a necessary discomfort for such systems to function. As BCIs continue to be developed for clinical, therapeutic and artistic applications, the matter of experience design becomes increasingly important — and yet remains relatively unexplored in literature.

The system developed during this project uses live brain data to augment the aesthetic properties of the user's environment, according to principles from both neuroscience and aesthetics literature. In doing so, it aims to explore the potential relationship between neural response and aesthetic experience, and the extent to which they may be optimised simultaneously. The results of this exploration serve as input for future BCI design: by designing an audiovisual experience that produces measurable neural responses alongside positive aesthetic outcomes, this project suggests that the user experience of BCIs can be improved whilst maintaining their efficacy.

1.2.3 NEUROTHERAPEUTICS

The use of periodic stimuli to augment brain activity has also been investigated as a therapeutic medium. In recent decades, a number of studies have investigated how

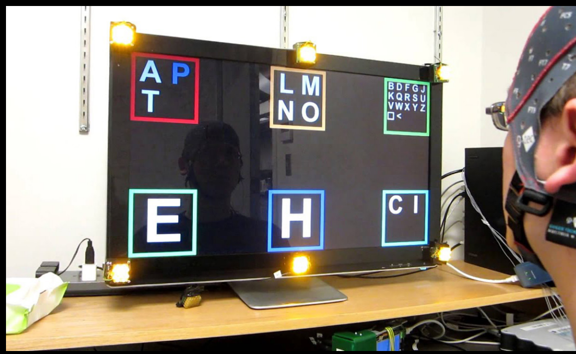


Figure 11: A BCI 'speller' that uses EEG response to visual flicker to detect which letter a person is looking at[36].

entraining brain activity to the frequencies of oscillating light and sounds can improve outcome measures for a variety of physical and psychological conditions, including anxiety, fibromyalgia and Alzheimer’s[6]. Although clinical trials have often been limited in scope, the results are promising: audiovisual entrainment appears to be a fruitful alternative to existing treatment modalities that merits further investigation.

However, as in the case of BCIs, the stimuli used in neurotherapy trials are often monotonous in nature, with reliability of brain response prioritised over patient experience. This is understandable, as the focus in such cases is establishing scientific evidence (or at least strong potential) for measurable health benefits of neurotherapy. Despite this, it is important to consider the subjective experience of neurotherapy stimuli: an unpleasant clinical experience could deter patients from adhering to or seeking treatment, and in the case of entrainment-based therapies, could perhaps be detrimental to positive health outcomes.

As previously discussed, the core inquiry of this project concerns the relationship between neural response and subjective aesthetic experience. The system created during this project seeks to optimise for both outcomes, and in doing so suggests that the experience of neurotherapy can be as enriching as it is effective.

1.3 GOALS

1.3.1 RESEARCH QUESTIONS

As previously discussed, this project aims to explore the relationship between neural activity and aesthetic experience, framing both using the concept of resonance. The project hypothesises that it is possible to simultaneously evoke neural and aesthetic resonance through a designed experience — and seeks to explore whether there is a relationship between the two forms of resonance.

To investigate this hypothesis, the following three research questions were defined:

1. Can **neural and aesthetic resonance be evoked simultaneously** by periodic stimuli?
2. Does peak **neural resonance correspond** with peak **aesthetic resonance**?
3. How can both forms of resonance be **embodied in an audiovisual design**?

1.3.2 DESIGN GOALS

This project seeks to create aesthetically resonant experiences that are also able to evoke neural resonance, with a focus on measurable outcomes and exploration of the design space. Consequently, the following three design goals were defined for the project:

1. Create a **personalised and engaging multi-sensory experience** that is driven by resonance;
2. Design **audiovisual stimuli** that are both **neurally and aesthetically resonant**;
3. Create an accessible system for **measuring and producing resonance** that is **generative for designers**.

1.4 APPROACH

1.4.1 RESEARCH THROUGH DESIGN

At the core of this project is an approach known as Research through Design (RtD) (Figure 12). Originating from theory developed by Frayling[7], RtD is an established methodology in various design disciplines, particularly in human-computer interaction (HCI). According to HCI practitioners and researchers Zimmerman, Forlizzi and Evenson, research through design is about "making the right thing" — using the design cycle of ideation, iteration and evaluation to articulate what should be addressed in a current state, and what the resulting preferred state might look like[8]. RtD is especially useful in situations where there is a gap between theoretical knowledge and real-world contexts. As previously discussed, although the body of research on (neural) resonance and entrainment is strong, the relationship between this research and tangible applications is less so. With this in mind, RtD seems a natural choice for this project.

The RtD in HCI model, as proposed by Zimmerman et al.[8], can be approximately split into three groups. Each of these groups concerns different members of the HCI community and corresponding deliverables.

The first group consists of researchers and knowledge in fields related to, but separate from, interaction design. Their knowledge — in the form of technology, data, models and theory — informs the work of interaction designers. In this project, I will draw upon the knowledge of neuroscientists, engineers and design theorists.

The second group consists of interaction designers, who produce artefacts that allow them to explore their area of research. This is the group that I will occupy during this project, as I produce and iterate upon prototypes in response to research questions.

The third group consists of HCI practitioners,

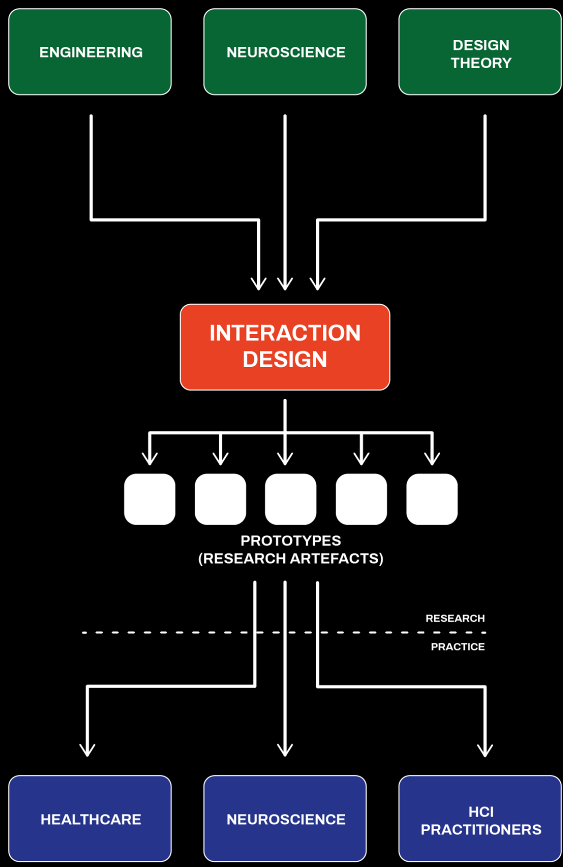


Figure 12: An adapted version of the RtD in HCI model by Zimmerman et al.[8] for this project and context.

who are separated in the model by a research/practice barrier. The artefacts produced by interaction designers overcome this barrier by linking the knowledge of the first group to real-world contexts. In this project, my prototypes will seek to communicate both background theory and my own findings to practitioners of HCI, design and (neuro)science, and hopefully to the general public as well.

1.4.2 DATA-DRIVEN DESIGN

This project is based on the knowledge of disciplines whose investigations largely involve the collection and analysis of data. This data can be a mixture of quantitative (as in EEG) and qualitative (as in aesthetics). Both forms of data will be collected and analysed throughout the course of this project. Data will also be a key driver for the prototypes I develop, as the main goal of these prototypes is to create a closed-loop system between a participant, their data, and their environment (audiovisual stimuli).

EEG data is central to the project as it will form the basis of the metric I will develop for neural resonance. Additionally, it will serve as both an input variable for the prototypes I develop and an indication of their effects on participants. This data will be gathered using best practices gathered from literature, including a screening process to filter out at-risk groups (migraine sufferers, for example) and a data management protocol for anonymising and storing recordings.

In addition to neural resonance, I will also explore how aesthetic resonance can be measured. This will involve both qualitative and quantitative data, such as semantic analysis and Likert scales. Further to this, I will assess my prototypes against key criteria developed in response to the research and design goals outlined in the previous section. I will refer to relevant literature and draw upon best practices according to the goal in question.

1.5 DESIGN OUTCOMES

1.5.1 RESONANCE METRICS

As discussed in the previous section, the final design uses EEG data and aesthetic ratings (collected using a custom app, shown in Figure 15) to calculate measures of neural and aesthetic resonance. The metrics developed for both forms of literature draw upon relevant literature and were tested through a series of validation protocols.

Throughout the course of the project, focus was placed on making the metrics accessible and generative for design. This was done by creating a real-time data display (Figure 13), which allows a designer to track the effects of their design decisions on the degree of resonance experienced by the participant. This in turn enables the designer and participant to explore the design space together and jointly optimise for the participant's neural and aesthetic resonance (Figure 17). Although the metrics of resonance are simplified by necessity, both the validation protocols and prototype tests carried out during this project show them to be sufficiently robust to be generative for design and to enable meaningful scientific findings.

1.5.2 INSTALLATION DESIGN

A physical installation, consisting of an algorithmically generated soundscape and a light source (Figure 14), was designed and built to demonstrate how the above described resonance metrics could inform experience design. The installation is both an expression of resonance in design and a vehicle for exploring this concept empirically.

An art installation was chosen as the most suitable context for collecting resonance data, as the abstract and ephemeral nature of the design fits well with the expectations visitors may have in a gallery setting. By framing the installation as art, visitors are expected to be

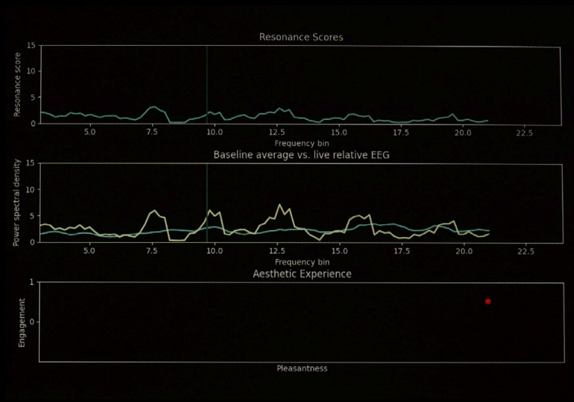


Figure 13: Live data display showing participant's neural and aesthetic resonance data, which is used to optimise the experience design.

Figure 14: A participant sits in front of the light installation, which changes according to their EEG data and aesthetic rating.

more open to exploring the design space, and more readily able to report on their experience (as required for my aesthetic resonance metric).

1.5.3 RESEARCH PLATFORM

The resonance metrics and physical installation are connected by a digital system (Figure 16) that collects data, interprets it and translates it to audiovisual designs. This system was created as an intentionally open-source platform that uses standardised communication methods, such as OSC and Lab Streaming Layer. This means that, in future, any number of audio and visual sources can be connected to the system, using a variety of programs. These sources can then be assessed using the resonance metrics and real-time data display.

The system is thus envisaged as a research platform for exploring the phenomenon of resonance, enabling designers to collect both neural and aesthetic data in a consistent way. As more data is collected using diverse audiovisual sources, generalisable findings can be produced regarding the relationship between neural and aesthetic resonance in the context of design. The platform can consequently support designers' understanding of resonance as an experiential factor and an optimisation question for interaction design. As the data is chronologically synchronised and labelled, it also invites the application of machine learning techniques to further explore optimisation possibilities.

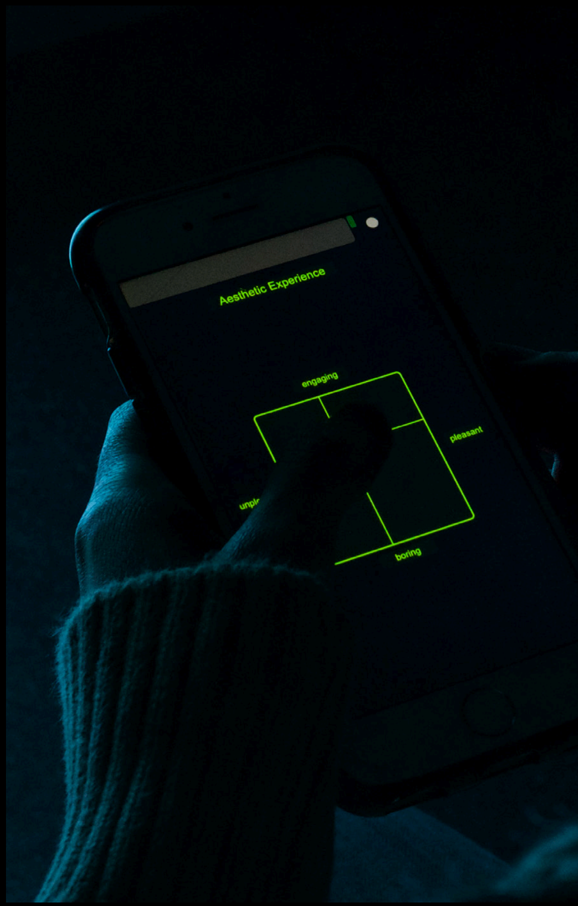


Figure 15: A custom app allows the participant to give real-time aesthetic feedback, which is shown in the data display.

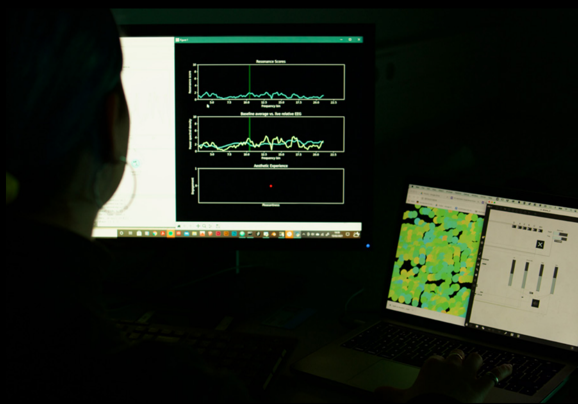


Figure 16: The designer uses controls in MAX/MSP to adjust algorithmically generated ambient music, which in turn influences the light installation.

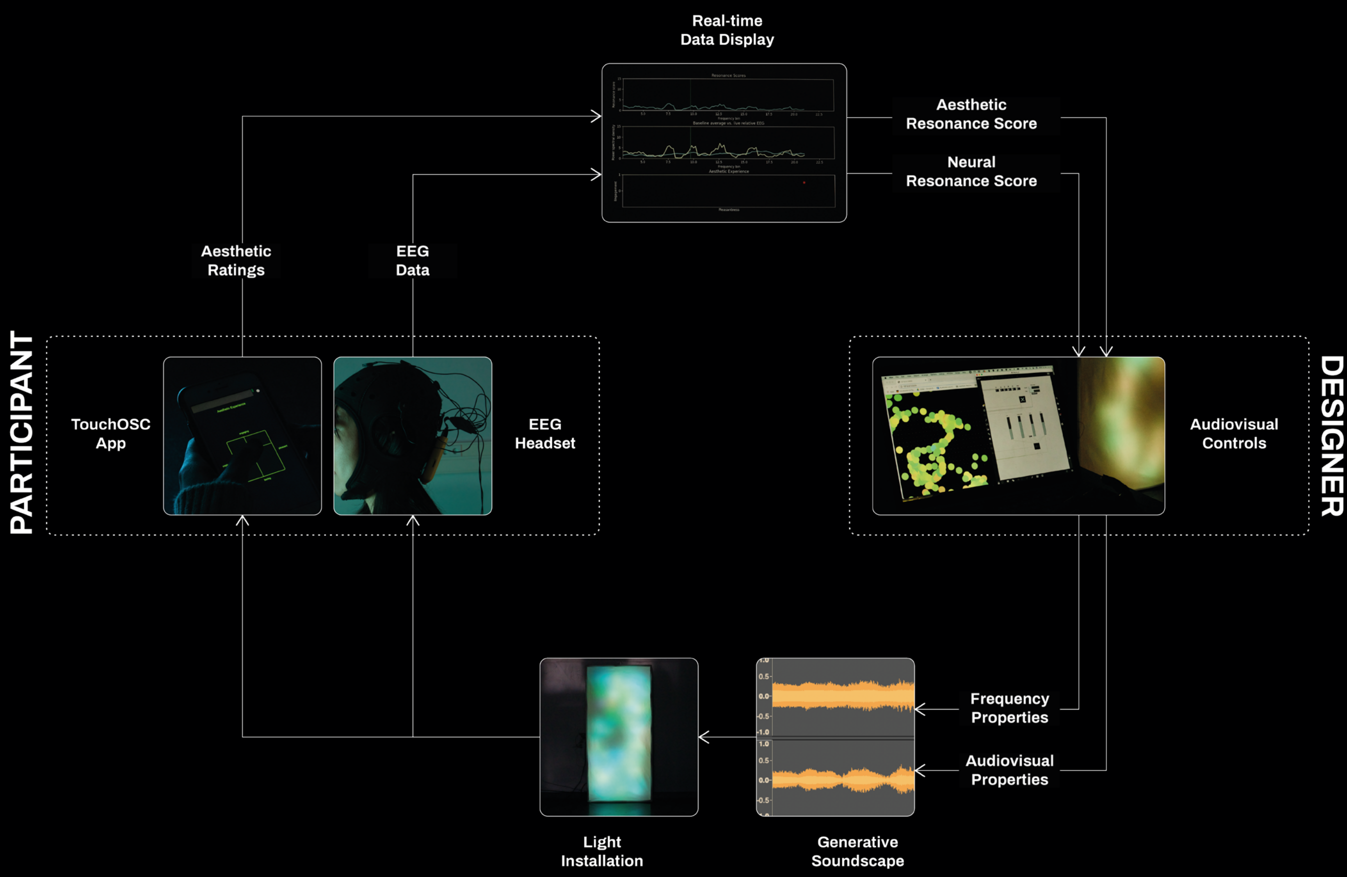


Figure 17: The participant and designer optimise for resonance through a data-driven feedback loop, facilitated by the designed system.

2

UNDERSTANDING RESONANCE

This chapter explores the context of neural activity and aesthetic experience, using resonance as a conceptual frame to compare the two. It concludes with a hypothesis, based on this context, that shapes the prototypes and experiments in subsequent chapters.

2.1 WHAT IS RESONANCE?

2.1.1 THE CONCEPT OF RESONANCE

Resonance is a term with diverse meanings. Originating in physics, it is often used to describe decidedly more emotive phenomena.

Generally, we use “resonance” to describe the relationship between ourselves and the experiencing of an “other” — a person, object or environment — that is characterised by emotional depth, meaning, and pleasure. When asked for an opinion of your favourite song, for example, you might say: “It really resonates with me.” This song stirs your emotions, imparts a sense of (personal) significance, and is particularly enjoyable to listen to. Similarly, you might resonate with a friend who understands your feelings and worldview implicitly, and who puts you at ease in their company.

In our environment, our relationships and the artefacts we create: where there is expression and emotion, there may also be resonance. The cultural nature of this conceptualisation of resonance differs, however, to the original context of the term.

2.1.2 ORIGINS OF RESONANCE

Traditionally, the term “resonance” is used in physics to describe an increase in amplitude that occurs when an external frequency is equal (or very close) to a natural frequency of the physical system to which it is applied (Figure 18). This external frequency is known as a resonant frequency, of which some systems may have multiple. As resonance is inherently oscillatory, all types of waves can produce it — acoustic, magnetic and nuclear, to name a few.

As a result, the scientific concept of resonance is not exclusive to physics, and can be found in fields such as chemistry, medicine and music. This version of resonance seems somewhat at odds with how we use the concept in conversation. After all, a physics experiment is hardly comparable in emotional terms to

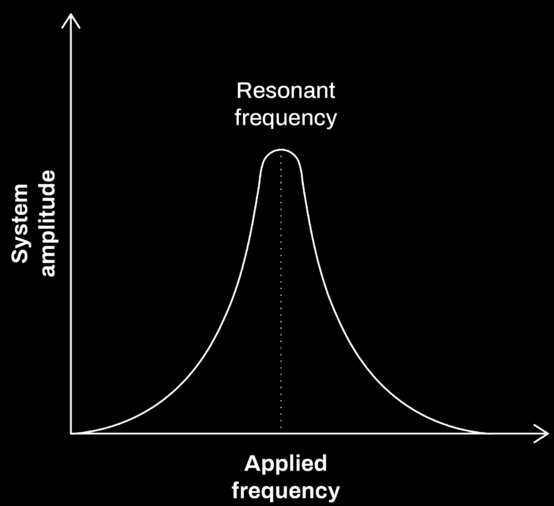


Figure 18: A typical resonance curve. When the system’s resonant frequency is applied, the amplitude of the system is maximised in response.

a striking work of art. However, empirical resonance is far more human than we might think. As previously mentioned, resonance occurs in oscillatory systems, which produce waves. The human brain is one such system. Our brains constantly produce electrical activity that is oscillatory in nature, and as such can demonstrate measurable resonance.

Key takeaways:

- **Culturally, resonance has connotations of unity and connection.**
- **The term was originally used in a scientific context to describe how oscillatory systems react to specific frequencies applied to them.**
- **Resonance can occur in any system where waves exist, including the human brain.**

2.2 THE RESONANT BRAIN

2.2.1 NEURAL OSCILLATIONS

The concept of resonance, in both a physical and psychological sense, is well-established in neuroscience literature. This is unsurprising, as brain activity produces oscillations — more commonly known as 'brain waves' — that are subject to resonance phenomena, as all waves are. Neural oscillations occur when groups of neurons act synchronously.

Brain activity (i.e. neural oscillations) can be measured using electroencephalography, known as EEG. EEG uses electrodes on the scalp to pick up electrical signals produced by the brain. These signals are then analysed to determine the strength of different frequencies within them across a given spectrum (usually between 1 and 70Hz).

The spectrum of frequencies observed in EEG is typically divided into several bands: delta (0.1-4Hz), theta (4-8Hz), alpha (8-12Hz), beta (13-30Hz) and gamma (>30Hz), as shown in Figure 19. Different frequency bands will exhibit differing levels of strength (i.e. amplitude), depending on the individual and the current state of their brain[9]. The alpha band is, historically, the most widely-studied in EEG research, in part due to its prevalence during states of relaxed wakefulness and calm[9]. This also means that the alpha band is of interest in wellbeing applications of EEG data[10].

The spectral content of EEG signals can be used to infer current neural activity, often in relation to a stimulus. Neural oscillations have been linked to processes such as perception, motor control and information transfer[11].

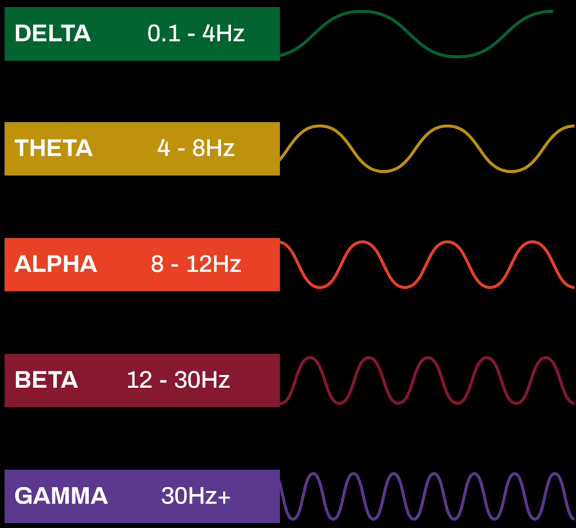


Figure 19: Brainwaves, or neural oscillations, can be split into five categories depending on their frequency.

2.2.2 NEURAL RESONANCE

Neural oscillations are also nonlinear. Nonlinear oscillations have several universal properties, one of which being 'higher-order resonance'. Higher-order resonance refers to the effects of a stimulus on the amplitude of an oscillation.

More specifically, it describes a phenomenon in which, depending on the frequency of a stimuli, an increase in amplitude is observed at both the stimulus frequency and at (sub-)harmonic frequencies of that stimulus. For example, if a 2Hz stimulus is applied, the greatest increase in amplitude is observed at 2Hz but smaller responses can also be seen at 1, 4 and 8Hz. Response size also increases with stimulus intensity. We can see from these numbers that there is a proportional relationship between them, and can therefore make predictions for the responses we would expect for stimuli of various frequencies.

This is equally true for neural oscillations — the same kind of proportional amplitude responses can be observed in EEG data. One of the most commonly-cited studies in this area is that of Christoph Herrmannn, who investigated EEG responses to LEDs blinking on and off at a specific frequency — known as “flicker” — between 1 and 100 Hz. His findings show that neural resonance phenomena occur when 10, 20, 40 and 80 Hz flicker is applied, at both fundamental (equal to stimulus) frequencies and harmonics [11] (Figure 20). In a similar way, oscillating audio signals have been found to produce frequency-related responses in EEG[12], with detectable resonance phenomena[13]. Although relatively little is known about the specifics of this frequency-following relationship compared to that of flicker, there appears to be potential for various types of tonal audio to produce entrainment effects [14].

Additionally, Herrmannn discusses how neural resonance within the frequency range known as alpha — approximately 8-12Hz — has been observed and is associated with a “variety of perceptual and cognitive functions”, from sensory coding to memory. Herrmannn’s study demonstrates that neural resonance is a measurable phenomenon with an established role in perception.

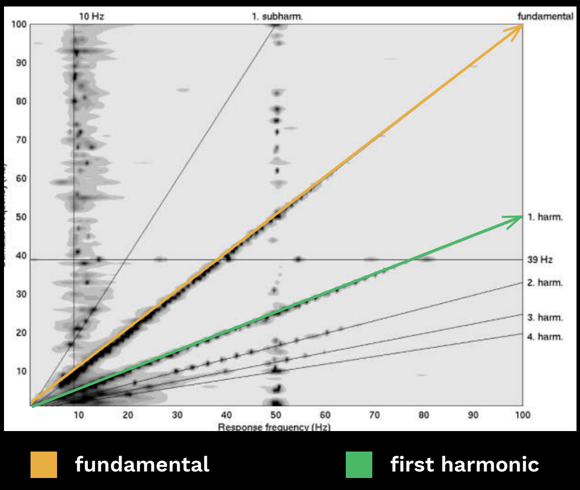


Figure 20: Resonance phenomena observed by Herrmannn[11] at 10, 20, 40 and 80Hz. The fundamental and first harmonic responses are highlighted.

This relationship between neural oscillations and audiovisual perception can be leveraged with the intention of modulating brain activity. Such modulation is known as brain entrainment.

2.2.3 BRAIN ENTRAINMENT

In neuroscience, resonance is often discussed in proximity to entrainment. Entrainment is “the process through which two physical or biological systems become synchronised by virtue of interacting with each other”[15]. Where two systems exhibit rhythmic (oscillatory) behaviour, entrainment may occur. The distinguishing factor of entrainment from other rhythmic processes is its element of autonomy[16]. This means that the two systems in question should be able to oscillate outside of their interaction with each other. In human physiology, many bodily processes can be framed as such systems — including brain activity, as previously discussed, but others such as respiration and cardiac activity as well. Consequently, it is possible to entrain these systems to an external source of oscillation.

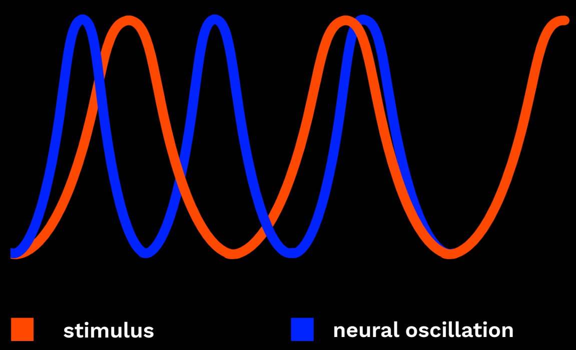


Figure 21: Neural oscillations can be entrained to those of external stimuli, such as flickering lights or binaural beats.

Entrainment to an external stimulus is a well-established topic in neuroscience research, typically achieved through periodic stimuli such as flickering lights and drone sounds (Figure 21). Entrainment is also significant in the cognition of music. Trost and colleagues propose that entrainment is a mechanism for the induction of emotional affect when listening to music, and that by extension entrainment is experienced as a pleasant and desirable state[15].

2.2.4 ENTRAINMENT FOR WELLBEING

Beyond music, neural entrainment — also known as brainwave entrainment (BWE) — has been explored more generally as a means for influencing brain activity, particularly in a wellbeing context. This exploration originates (in contemporary science) in Pierre Janet's experiments with hysteria patients in late-19th century France. Janet reported increased relaxation and alleviation of hysteria (an antiquated term for psychological stress) in patients when exposed to flickering light[17]. A number of studies have since investigated the positive physiological and psychological effects of entrainment, with findings ranging from possible treatment for migraines to reduction in anxiety[17]. Such studies almost unanimously employ audiovisual stimuli (i.e. light and sound) as an entrainment mechanism. These stimuli are designed to elicit the greatest and most reliable neural response possible, with a definite 'substance over style' ethos — starkly flickering LEDs and monotonous sine waves are common examples. Although their effects on the brain are well-established, there is comparatively little discussion in literature of how they are experienced subjectively.

This is significant in a wellbeing context, as an individual's wellbeing is influenced by both qualitative and quantitative factors[18]. If the resonant properties of the brain are to be leveraged for wellbeing outcomes, it would follow that subjective experience of neural resonance is equally as important as quantitative measures and merits investigation. For an entrainment experience to contribute maximally to wellbeing, it should be optimised both for neural and personal resonance: in other words, effectiveness and enjoyment.

Again, we can observe a gap between empirical and subjective conceptualisations of resonance. The relationship — if any — between what is neurally resonant and perceived as resonant remains unclear, but may hold much significance for the development of entrainment-based therapies, and for brain-computer interfaces generally.

Key takeaways:

- **The brain can be conceptualised as a nonlinear oscillator that exhibits resonance.**
- **Resonance is observed most strongly at fundamental (identical to stimulus) and harmonic frequencies. Neural resonance in the alpha range (8-12Hz) is associated with perceptual functions.**
- **Neural entrainment describes the synchronisation of brainwaves to the frequency of an external stimulus. It has been used to alleviate various physical and psychological symptoms.**

2.3 NEUROAESTHETICS

2.3.1 FROM PROCESS TO EXPERIENCE

The field of neuroaesthetics addresses this gap between neural phenomena and subjective experiences, specifically in relation to the experience of aesthetics.

Neuroaesthetics is an emergent discipline within cognitive neuroscience that involves the study of the biological mechanisms underpinning aesthetic experiences. As a result, it brings together knowledge and theory from (empirical) aesthetics and neuroscience to seek connections between qualitative experiences and quantitative neural phenomena.

The discipline can take two forms: descriptive or experimental[19]. In descriptive neuroaesthetics, qualitative observations of aesthetic experiences are related to relevant neural phenomena. In experimental neuroaesthetics, typical components of an empirical study are used: hypotheses, quantitative data, and statistical analysis. Data is collected according to the neural phenomena that relate to the perceptual systems involved in a particular aesthetic experience — for example, steady-state visual evoked potentials (SSVEP) can be used to measure visual response to an artwork.

2.3.2 THE AESTHETIC TRIAD

In both forms, neuroaesthetics defines aesthetic experience in relation to specific neural processes. These processes are defined by neuroaesthetics researchers Chatterjee and Vartanian as “the aesthetic triad”[19] (Figure 22). The triad consists of three systemic pairs: emotion-valuation, knowledge-meaning and sensory-motor[19].

Aesthetic experiences are the result of interactions between the three systems in the triad. It is important to note that the three systems do not always carry equal weight, and there can be significant individual variability —

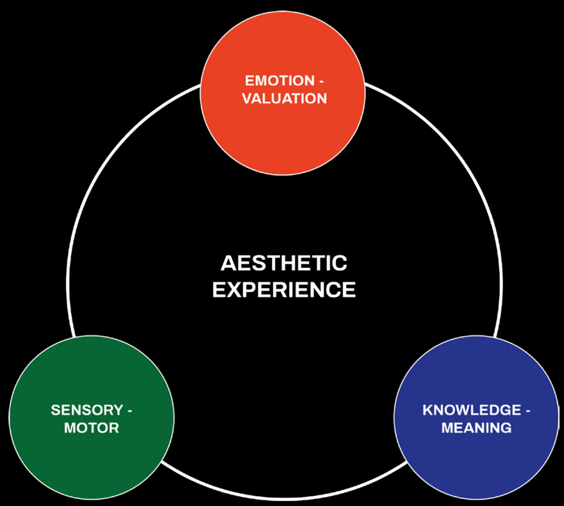


Figure 22: The aesthetic triad, adapted from the model presented by Chatterjee and Vartanian[19].

especially in the knowledge-meaning system, where cultural and historic influences play a major role[19]. Despite this, there are sufficient consistencies (across both individuals and studies) such that researchers have been able to relate specific aspects of aesthetic experiences to particular neural regions and properties.

Aesthetic experiences as defined by the triad are much closer to the conceptualisation of resonant experiences: one that elicits emotions, evokes meaning and produces sensory pleasure. Although not all resonant experiences concern aesthetics, many of them do — viewing a painting, for example, is an aesthetic experience, the specific properties of which may give rise to resonance.

In this way, neuroaesthetics not only gives insight into the relationship between neural activity and subjective experience, but the aesthetic properties of such experiences that can contribute to perceived resonance.

Key takeaways:

- **In neuroaesthetics, aesthetic experiences are defined as the result of three neural systemic pairs: sensory-motor, emotion-valuation and knowledge-meaning.**
- **The three system pairs interact with each other to differing extents during an aesthetic experience.**
- **This definition of aesthetic experience is similar to how we describe a resonant experience - emotionally impactful, personally meaningful and pleasurable.**

2.4 AESTHETIC RESONANCE

2.4.1 RESONANT INTERACTIONS

Design literature gives further insight into the connection between aesthetics and resonance, going so far as to combine the two in the form of "aesthetic resonance": an interaction between an individual and the aesthetic properties of their environment that results in perceived resonance.

Aesthetic resonance describes an emotional response to our environment that "feels like unity" and can be described as "an instance of perfect harmony"[20]. It has also been used to describe a form of environmental feedback loop, in which our behaviour and our environment's response to it feel aesthetically synchronised, and we feel in harmony with this environment as a result[21].

Crucially, the effects of one's behaviour on an entity and its response must be clear in order for that entity to elicit aesthetic resonance. In other words, the feedback loop between an individual and a designed entity must be made apparent through interacting with the entity itself[22] (Figure 23).

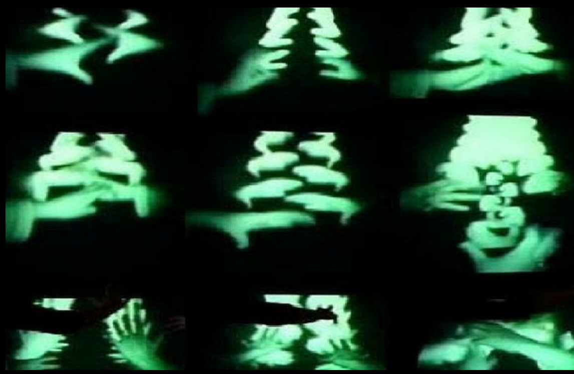


Figure 23: Examples of aesthetically resonant interpersonal environments[22].

2.4.2 RESONANCE IN DESIGN

Resonance is an increasingly established concept in design literature, with particular relevance to the fields of human-computer interaction (HCI), value-driven design, and interaction design in general[5]. Designers use the term to describe the experience of interacting both naturally and meaningfully with an artefact, system or environment, in such a way that the said entity feels — on both physical and emotional levels — as if made specifically for oneself (Figure 24).

In design terms, resonance can be said to originate from the theory of direct perception — also a commonly-cited source of the term "affordance"[22]. It would then follow that resonance in design has close ties with our perceptual experience, and with the cognitive processes that result in this experience. Consequently, drawing upon the knowledge and approaches of neuroaesthetics can enrich designers' understanding of resonance, aesthetically resonant experiences, and how to design (for) them.

According to design literature, aesthetically resonant experiences can be framed as a feedback loop between a person and an artefact or environment, enabled by its aesthetic properties. In this we can see an aspirational state for interaction design: seamless, intelligible and effortless interaction between user and interface. It is therefore significant for interaction design in particular to better understand how aesthetically resonant experiences come to be, and how to facilitate them through design.

Figure 24: Design explorations of resonant interactions by Hummels, Ross and Overbeeke[37].

Key takeaways:

- **Aesthetic resonance involves a feedback loop between a person and a designed entity, where the effects of their behaviour are communicated and responded to by this entity.**
- **How to elicit aesthetic resonance is a key question for design, as it is closely related to perception and cognition of designed artefacts.**

2.5 DESIGNING RESONANCE

2.5.1 PROJECT HYPOTHESIS

Having explored the cultural and scientific context of resonance, it is clear that resonance can be used as a conceptual frame with which to investigate the relationship between neural activity and aesthetic experience. Resonance occurs in both the brain and psyche as a result of the self interacting or bearing witness to an external entity. Whether this entity can simultaneously evoke neural and aesthetic (psychological) resonance remains unclear, but is a pertinent question for designers.

Considering its context, the overarching hypothesis for this project is defined as follows:

It is possible to design an experience that simultaneously elicits neural and aesthetic resonance.

A causal relationship between neural and aesthetic resonance cannot be assumed in this hypothesis. However, this project aims to investigate the possibility of a correlational relationship between the two, and to contribute knowledge that furthers understanding of this relationship.

2.5.2 GENERAL RESEARCH QUESTIONS

To address my project hypothesis, I defined several overarching research questions that address the design-centred, technical and scientific aspects of this project (as discussed in the first chapter):

1. Can **neural and aesthetic resonance be evoked simultaneously** by periodic stimuli?
2. Does peak **neural resonance correspond** with peak **aesthetic resonance**?
3. How can both forms of resonance be **embodied in an audiovisual design**?

Throughout the project, my various prototypes and evaluations would be constructed with their own specific research questions, but designed to contribute to the three overarching questions shown here.

As with any hypothesis, being able to consistently and accurately measure both variables (neural resonance and aesthetic resonance) is essential. The first step towards addressing this project's hypothesis was therefore to **design a measurement system for neural resonance** and to determine its **validity**.

3

MEASURING RESONANCE

This chapter details the development of a system to measure neural resonance that forms the basis of subsequent prototypes. It begins with an explanation of the system metrics and how they were decided upon, followed by a system overview and detailed explanations of data flows.

3.1 METRICS

3.1.1 KEY VARIABLES

The first step to understanding the relationship between neural and aesthetic resonance was to determine how I could measure neural resonance, simply and reliably, in real-time.

Neural resonance, as previously discussed, is a well-established principle in neuroscience literature that has been linked to a variety of perceptual processes. As a result, there are also established methods and protocols for measuring it. Christoph Herrmannn's work exploring human EEG responses to 1-100Hz flicker[11] is often cited in this regard. In his work, he shows how neural resonance can be shown graphically by **plotting stimulus frequency against response frequency** (that is, response power at each frequency bin in a person's EEG) (Figure 25). From this, we can see two key forms of data to track when measuring neural resonance: **stimulus frequency** (or frequencies) and **EEG response**, sorted into frequency bins.

Herrmannn also discusses the significance of individual variability in detecting neural resonance. As previously detailed, each person exhibits peaks in their EEG spectrum — frequencies at which there is naturally greater oscillatory activity. This variability has particular significance in the alpha (8-12Hz) range, where oscillations are though to play a major role in perception and sensory coding[11]. It is therefore suggested that stimuli and experiences designed to amplify or influence neural activity should take individual peaks into account[23] to maximise their intended effects. From this, we can extract another key variable: **individual peak alpha**. This value should be calculated from a person's EEG during a baseline state (eyes closed, no stimuli) for maximum accuracy.

Further to this, the presence of peaks (and troughs) in individual EEG has implications for how stimulus responses are measured. If a person has a peak alpha frequency of 9Hz, for

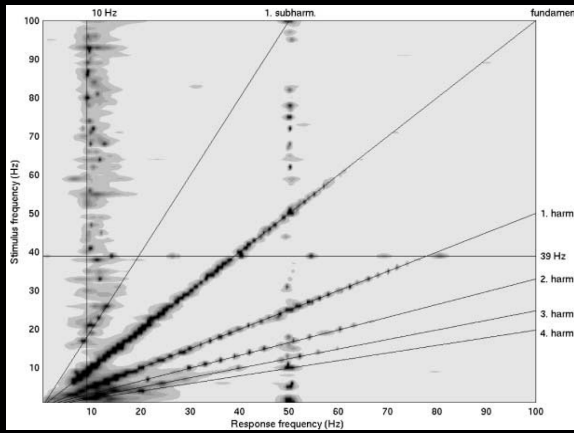


Figure 25: Neural resonance phenomena as observed by Herrmannn[11], showing response frequency (X axis) plotted against stimulus frequency (Y axis).

example, we would expect to see more activity around this frequency in general. Activity of the same magnitude at 9Hz and, say, 10Hz would therefore not represent the same degree of resonance, as the baseline activity at 9Hz for that person is greater regardless. Consequently, EEG response data should be compared to baseline EEG activity for each participant, and expressed as a proportional increase — i.e. how much greater activity is at each frequency compared to normal (Figure 26).

This aligns with the approach taken by Herrmannn[11] and others, in which an initial baseline recording (eyes closed, no stimuli) is used to track relative changes in activity throughout a subsequent experiment. Two further variables become apparent from this: **individual baseline activity**, and **proportional response** — both of which can be extracted from a person's live EEG data.

In summary, there are four key data types to track when measuring neural resonance:

1. **stimulus frequency;**
2. **individual baseline EEG;**
3. **individual peak alpha;**
4. **proportional response to stimuli.**

2.2.1 SYSTEM REQUIREMENTS

Although neural resonance (and the measurement thereof) is firmly within the scientific domain, this project is not so. At the heart of the project is the Research through Design Method (RtD). This method, as previously discussed, draws upon relevant techniques and theory from other domains to enrich the interaction design process and, ultimately, translate this theory to design practice. Because of this, typical methods for measuring neural resonance must be adapted to the fundamental requirements of the project, as a (intended) work of experiential design.

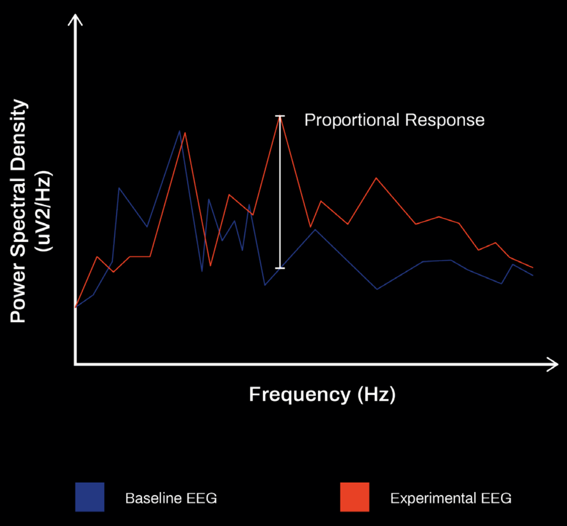


Figure 26: By comparing current EEG response to a baseline recording, a proportional response can be calculated.

EEG Collection

In laboratory settings, EEG is typically collected using a wet electrode device. Such devices generally consist of a fabric cap and (wired) metal electrodes, each of which filled with saline gel. The cap must be fitted snugly to the scalp with a generous amount of gel to maximise signal quality. Raw EEG is broadcast from the device to a computer, usually with device-specific software. This software is often integrated with a suite known as Lab Streaming Layer (LSL), a server and recording app developed for time-synchronised collection of biosignal data. The raw data is then processed and manipulated as required for the experiment in question, depending on what information or phenomenon is being monitored.

The primary goal of this project is to produce a personalised and potentially therapeutic multi-sensory experience, driven by neural resonance. With this in mind, the hardware required to facilitate EEG collection should either be incorporated fully into the narrative of the experience, or made as unobtrusive as possible. In either case, the aim is to make the **physical requirements** for measuring neural resonance **well-incorporated into the designed experience**. However, there are trade-offs between ease of use and accuracy when it comes to EEG hardware. A wet electrode device will often give a higher-quality signal with greater granularity of data, but is obviously less convenient and rather more daunting to participants than some commercially available alternatives. These alternatives also have their own drawbacks: data is often down-sampled or averaged before broadcasting and electrode placement is usually fixed. Electrode placement is a particularly significant issue — especially with perceptual phenomena, getting signals from the right *parts* of the scalp (and therefore brain) is essential for meaningful data.

Considering these parameters, I decided to use

Figure 27: The Enobio 8-channel cap, a typical lab-grade wet electrode EEG device. This particular model was used during this project for all EEG recordings.

a **laboratory-grade wet electrode cap** (Figure 27) during the development of my resonance metric, to ensure that data was as accurate and detailed as possible. Once my metric had been developed and validated, it would be possible in future to test it with more lightweight hardware.

Signal Processing

EEG data is, by nature, complex and often contains artefacts (disturbances or noise caused by unrelated events, such as jaw movement) (Figure 28). This means that raw data must undergo pre-processing to prepare it for analysis and make sure that it is representative of the neural phenomena being monitored. This often involves filtering out unnecessary data (e.g. very high- or low-frequency EEG responses), re-sampling the filtered data, and averaging over the various channels (electrodes) used on the EEG device. All of these steps should be completed before the data is used to calculate any key variables.

Pre-processing is not time-intensive, in that it can be performed on live data in a matter of milliseconds. However, it is usually necessary to collect a ‘chunk’ of data — often between 30 and 45 seconds — to calibrate the process. With this calibration data, pre-processing algorithms can characterise artefacts and other types of signal noise, so that they can be detected and removed from live data. The neural resonance measurement system should therefore include a **calibration period** during which baseline (no stimuli) data can be collected and pre-processed, ensuring the robustness of subsequent live data.

Accessibility

As the developed neural resonance metric is intended to drive an experiential design, it is essential that the measurement system can **interface with other programs and hardware**. This includes stimuli control (LEDs and audio

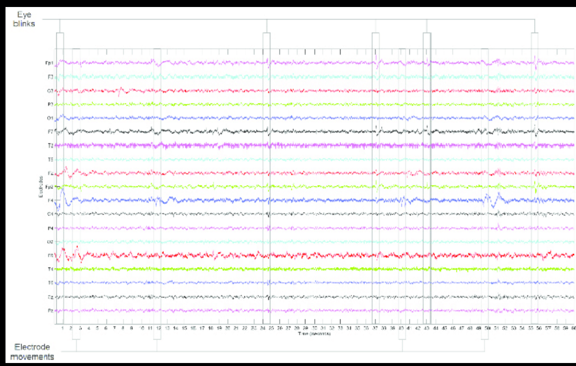


Figure 28: A one-minute sample of raw EEG data, in this case recorded using 20 channels (electrodes), by Albert et al[38].

generators, for example) and other outputs, such as data storage and visualisation. Although the native software for EEG devices is generally standalone, broadcasting data to LSL opens up opportunities for connections with compatible interfaces. In terms of experience flow, **centralising data collection and processing** as much as possible is preferable: keeping "messy" aspects of the measurement pipeline together ensures that the number and complexity of variables being sent to other programs is kept to a minimum. This reduces data backlog and improves the continuity of the resulting experience. The measurement system should also **label and store data** appropriately for further interpretation, as a resource both for this project and for stakeholders.

EEG data is also very difficult to interpret without some kind of visual representation. It is therefore important to include a **real-time visualisation** of key variables, not only to monitor the effects of stimuli, but to inform future design decisions. This visualisation allows the direct comparison of quantitative data and qualitative, subjective experience during user tests, which is needed to understand the relationship between neural and aesthetic resonance, and to iterate upon the designed experience as a result. Plotting key variables can also serve as an informal test of the metric's validity and reliability: the distribution and shape of live data can be compared with those established in literature for the neural phenomenon in question, whilst plots can be compared between participants to observe the degree of variability.

In summary, the core design requirements for my neural resonance measurement system are as follows:

- **A laboratory-grade EEG device with variable electrode placement;**
- **A robust pre-processing protocol with calibration data;**

- **Centralised data handling with good inter-program connectivity;**
- **Real-time visualisation of key variables.**

3.2.1 BASIC SYSTEM

Drawing upon the key variables and design requirements outlined in the previous section, I designed a basic system (Figure 30) for measuring neural resonance. The system is represented as a simple flow diagram, with software, hardware and human system actors on the same (informational) hierarchical level. Data flow is represented by arrows, with general steps for data handling (and the results thereof) shown as colour-coded states.

At the core of the system is, naturally, **EEG data**. As previously mentioned, an 8-channel wet electrode system was chosen for the development of my neural resonance metric, to improve the accuracy of collected data and to allow for measurements from specific regions of the brain (Figure 29). A response to photic (light) stimuli, for example, is often measured in the occipital region of the brain[24], whereas for audio responses, focusing on the parietal region is generally preferred[25].

EEG data is handled in various ways throughout the system, centred around **NeuroPype,** a neural signal processing software (produced by Intheon). This results in key variables (discussed in the previous section) and a number of visual outputs. Together, these system products give a real-time indication of the degree of neural resonance a participant is currently experiencing within a chosen range of frequencies. As previously discussed, I have chosen to focus on the alpha (8-12Hz) range due to its role in perceptual processes and established resonance phenomena. The system is therefore tailored to alpha frequencies (and their harmonics), but can be manually adjusted to encompass any desired range. All data is logged via a **control script** in CSV format for further analysis.

Stimuli will vary depending on the experimental protocol and goals, but generally can be split into visual and audio categories. Information

Figure 29: Regions of the scalp used in EEG measurement. Each region corresponds to a different area of the brain, which interact differently depending on the specific neural process.

about these stimuli (frequency, for example) is also logged by the control script to enable correlational analysis of stimulus and neural response.

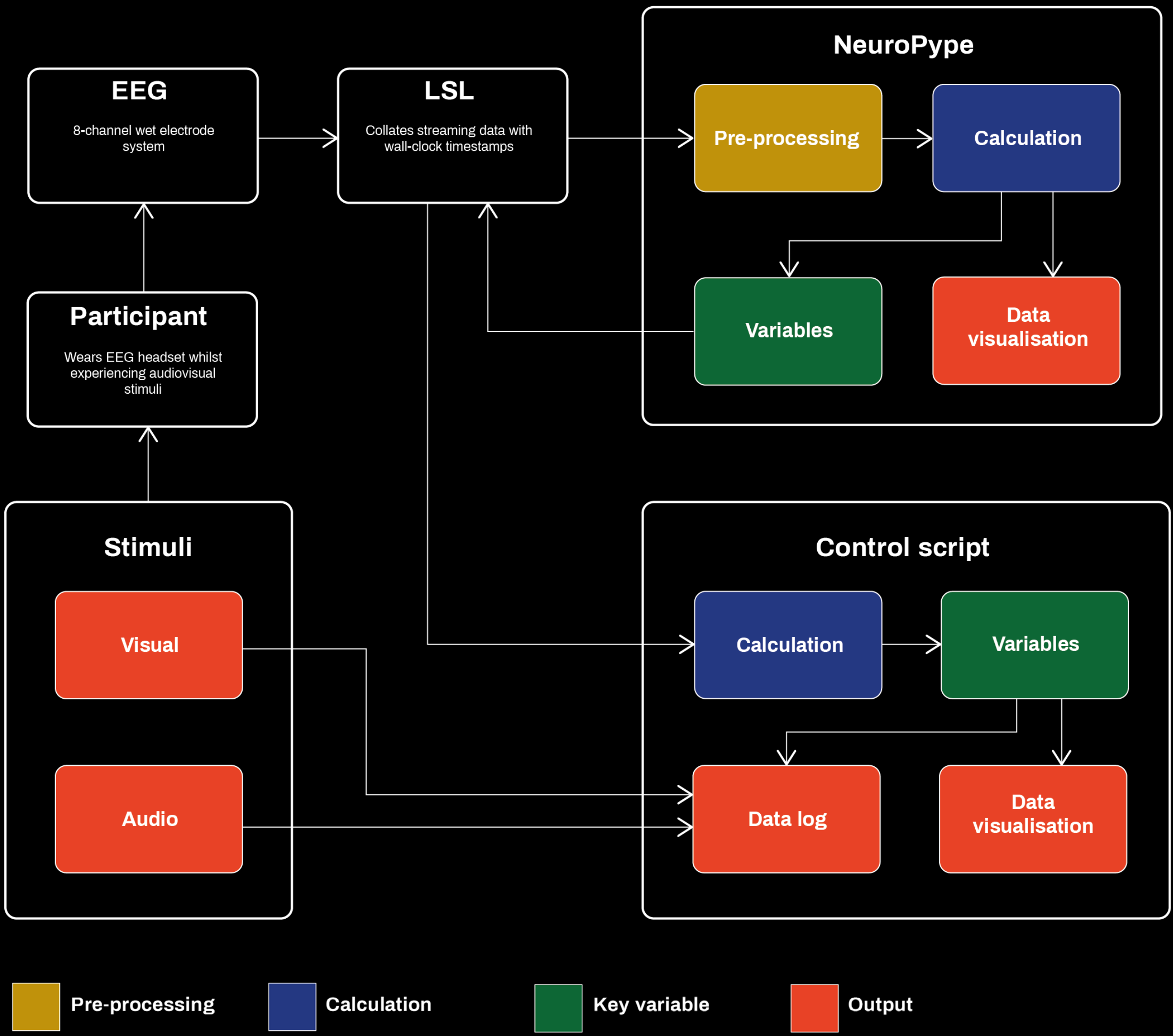


Figure 30: Basic system diagram for developing and testing my neural resonance metric. The system is comprised of a participant and their EEG data, Lab Streaming Layer (LSL), NeuroPype (signal processing software), a control script, and audiovisual stimuli.

3.2.2 NEUROPYPE

NeuroPype is a Python-based software suite for processing biosignals, with a focus on EEG. It consists of a server, a data pipeline designer, and various tools for interfacing with hardware. A pipeline is made by connecting a series of nodes — self-contained processes with data inputs and outputs — to pre-process data, make calculations, and output the results of these calculations in various formats.

Pre-processing

Figure 31 shows the beginning of the general pipeline I designed to calculate key variables for my neural resonance metric (Figure 31). Streaming data is received via **LSL**, originating either directly from the EEG device in real-time, or from a previous recording (EDF file). The data is passed through a **filter** that removes very low and very high frequencies (often associated with artefacts or noise). Depending on the experimental protocol, a **range of electrodes** (channels) can be selected if needed. Data is then **averaged across selected electrodes** to produce a mean value. Next, a **moving window** is applied to the data, which continuously outputs the last n seconds of data (in this case, 5). This means that subsequently calculated variables will also be continuously updated, but will take recent 'events' in the data into account, giving a better impression of how the EEG signal changes over time.

Spectral Analysis

The EEG data is then passed to a **Multitaper Power Spectrum** node, which uses the Multitaper method to calculate the spectral density of the raw EEG signal (Figure 32). This means that, for each frequency in a given range at given intervals (in this case, 0.2Hz), the 'power' of this frequency in the raw signal is estimated. Each interval is referred to as a '**frequency bin**'. Estimating the spectral density of the signal in this way gives key information regarding how the brain is responding in real-

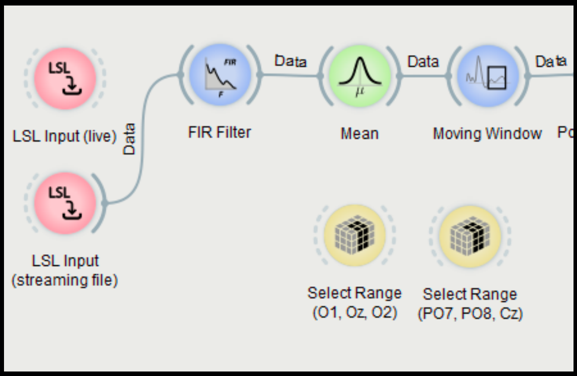


Figure 31: LSL input and simple pre-processing in the data pipeline. Here, two examples of electrode selection are shown - the first for visual response. and the second for auditory response.

time to stimuli.

After the spectral density of the raw data has been calculated, the power spectrum undergoes **frequency normalisation** (a corrective process for natural data sources, i.e. humans). The pipeline then branches into three paths. In the first, the power spectrum is constrained to a suitable range (0-24Hz, to cover the alpha range and its harmonics) before being plotted in real-time. This gives a simple visualisation of the live EEG data and serves as a reference point for later calculations.

In the second, the power spectrum is constrained to 3-24Hz, omitting low-frequency data that is not needed for further calculations. The constrained data is sent back out to LSL as an array, with one value per frequency bin (106 in total). The peak frequency in the first harmonic range (16-24Hz) is also calculated and sent to LSL.

In the third, the power spectrum is constrained to the alpha range (8-12Hz), and the peak frequency within this range is calculated, i.e. live peak alpha. This is sent to LSL and plotted as a bar chart for ease of reference.

This means that, in summary, the pipeline outputs three streams to LSL (Figure 33), containing three forms of data:

1. **live peak alpha;**
2. **live peak first harmonic;**
3. **spectral density of live data (per frequency bin).**

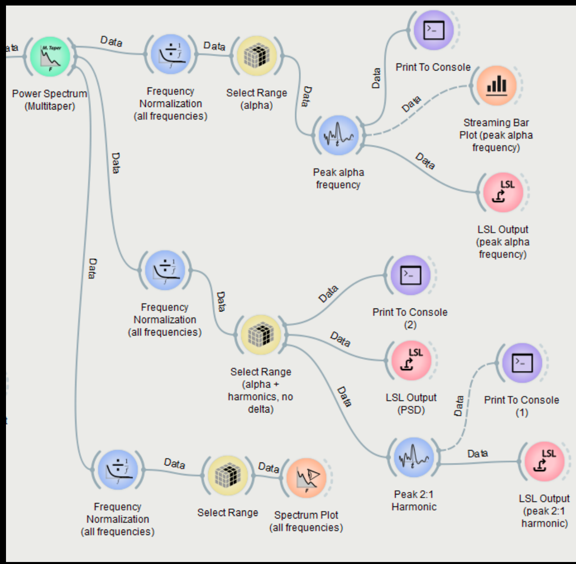


Figure 32: Multitaper power spectrum and three calculation pathways to produce three forms of data.

```
INFO: type:  control
data:  array([[[3.13493372e-07]]
 [[2.41443688e-07]];
 [[3.63066161e-07]];
 [[2.991...0418382e-06]];
 [[5.11766660e-06]];
 [[3.99276333e-06]];
 [[3.73992301e-06]]])
shape: (106, 1, 1)
INFO: type:  control
data:  array([[[23.6]]])
shape: (1, 1, 1)
INFO: type:  control
data:  array([[[10.8]]])
shape: (1, 1, 1)
```

Figure 33: Example LSL output from the NeuroPype pipeline. Highlighted in order: live spectral density, peak first harmonic and peak alpha frequency.

3.2.3 CONTROL SCRIPT

EEG is inherently temporal data, meaning it is important to synchronise this data with other information in the system, such as stimulus frequency. To collect all data types in a time-synchronised and efficient manner, a control script was developed. Writing a custom script for data handling also opens up opportunities for transforming and inspecting data, and iterating quickly upon these transformations, depending on the specific research and design goals being used. The script was written in Python, chosen for its interoperability with many programs (including NeuroPype), LSL compatibility, and efficiency in handling numerical data.

Data Handling

The script begins by connecting to the three **LSL streams** produced by NeuroPype, containing live spectral density data, live peak alpha and live peak first harmonic. After this, a connection is established to the current source of **stimulus data** (serial messages, for example). The script then continuously checks for new data from all sources, appending each new data point to a series of arrays, organised by data type (Figure 34). Current values for all data types are stored separately as variables and updated with each new received data point. This means that the current neural response can be efficiently tracked and visualised, whilst historic responses are stored for further analysis.

Calculating Resonance

Making a distinction between historic and current data becomes especially important when calculating neural resonance. As discussed in the previous section, to accurately represent a resonance response, the current spectral density of a person's EEG should be compared to a **baseline recording** to find the percentage increase at frequencies of interest (namely, the current stimulus frequency and

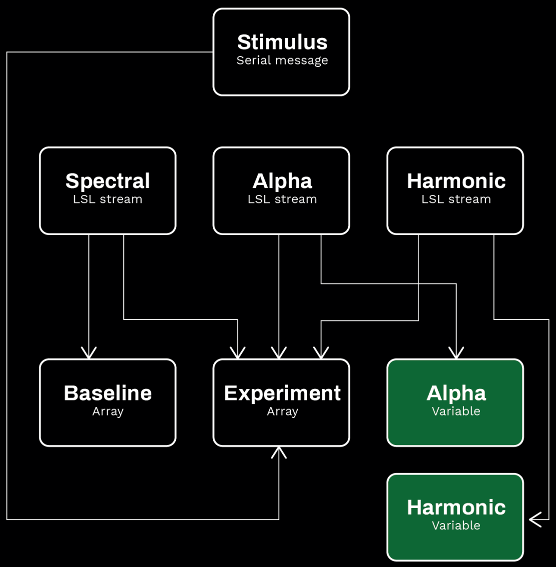


Figure 34: Data input flow for the control script. Three LSL streams are stored in various ways. During the baseline period, spectral data is stored in a separate array for later comparison to experimental data.

its harmonics). This means that each recording session should begin with a short period of EEG collection under typical baseline conditions (eyes closed, no stimuli). When the script is initiated, it stores all incoming spectral data until a signal (a serial message, for example) is received to indicate that the baseline period has concluded. Upon receiving this signal, the spectral data collected during the baseline period is averaged per frequency bin to produce a simple model of an individual's baseline neural activity. All EEG data received after this is then **compared to the baseline model** (Figure 35). By expressing the current spectral power at each frequency bin as a percentage of the corresponding baseline value, an initial **metric of neural resonance** is produced.

Visualisation

Of course, it is difficult to conceptualise this kind of data without some visual equivalent. To improve the interpretability of the live data, two **graphs** are plotted and updated in real-time (Figure 36). The first graph shows the **calculated resonance** at each frequency bin, whereas the second shows the **live spectral data** overlaid on the **baseline model**. Both graphs also have a vertical line that indicates the current **stimulus frequency** on the x-axis. Together, these graphs allow whoever is using the system to visually track neural resonance in relation to stimuli.

Finally, upon terminating the script, all collected data is formatted and stored in CSV files for further analysis — one for the baseline data, one for the experimental data, and one for the resonance values calculated from them. Together, these files enable more detailed analysis of a person's response to the stimuli in question, as well as comparisons between individuals to look for more general conclusions about the experimental design.

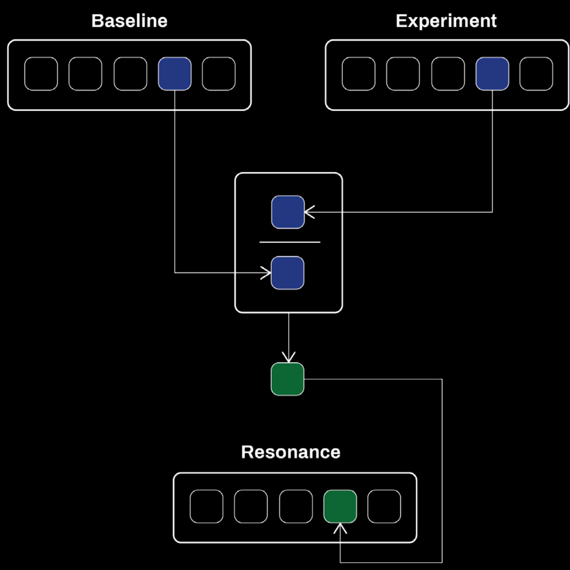


Figure 35: For each frequency bin, the corresponding entry in the baseline and live experiment data are compared. This value is the resonance score for that frequency. Each score is then stored in another array.

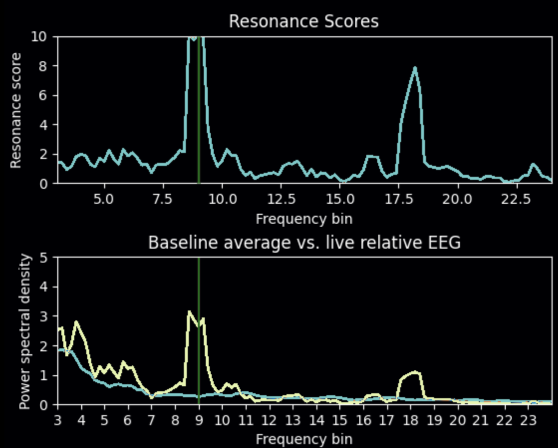


Figure 36: Live plots showing current resonance scores, the baseline model, live spectral data and the current stimulus frequency.

4

SYSTEM VALIDATION

This chapter sets out the general aims for validating my neural resonance measurement system. It then details a series of three experimental protocols, each designed to test different aspects of the system and address associated research questions. The chapter concludes with general insights and implications for the aesthetic development of future prototypes.

4.1 ASSESSMENT

4.1.1 RESEARCH QUESTIONS

Once the basic system was complete, I used it to test a series of protocols, each focusing on different research questions. My overall goal was to validate the accuracy and reliability of my system and to observe the degree of resonance detection achieved with different conditions. To this end, for each protocol I assessed my results with the following three questions:

1. **Do the stimuli produce a noticeable resonance response?**
2. **Is there a relationship between stimulus frequency and the properties of this response?**
3. **How does this response relate to a person's EEG data as a whole?**

The first protocol, *Flicker*, uses flickering LEDs to detect visually evoked resonance responses. The second, *Play*, explores a more free-form method of producing neural resonance. The third, *Waves*, combines sound and light to investigate the effect of layering on my resonance metric.

4.2 PROTOCOL 1: FLICKER

4.2.1 EXPERIMENTAL SETUP

My first protocol draws upon the methods used in simple neuroscience experiments. In this protocol, I used flickering LEDs, known as ‘flicker’, as my stimulus. Flicker is a well-established method for evoking visual responses known as steady-state visually evoked potentials (SSVEPs). An SSVEP is the brain’s response to changing characteristics of a visual stimulus — in this case, LEDs flashing on and off.

Goals

My goals for this test were as follows:

- **Test basic system for real-time responsiveness and accuracy.**
- **Identify resonance responses numerically and graphically.**

Stimuli

For this protocol, LEDs were used as the single (visual) stimulus. 22 addressable LEDs, mounted on a conductive strip, were fitted inside an empty VR headset Figure 38). The LEDs were set to 0% saturation and 100% brightness throughout (i.e. bright, neutral white light).

The LED strip was then connected to an Arduino Uno microcontroller, which was programmed with a simple script to control the frequency at which the LEDs flickered (Figure 37). The script used a state machine structure to perform what is known as a ‘frequency sweep’: a timed routine in which the LEDs flickered at a specific frequency for a fixed period, followed by a short pause without flicker, and then followed by the next flicker period at a different frequency. Continuing with the focus on alpha range frequencies, the LEDs were set to flicker at frequencies from 8-12Hz in 1Hz intervals, resulting in 5 total flicker periods. The current flicker frequency was

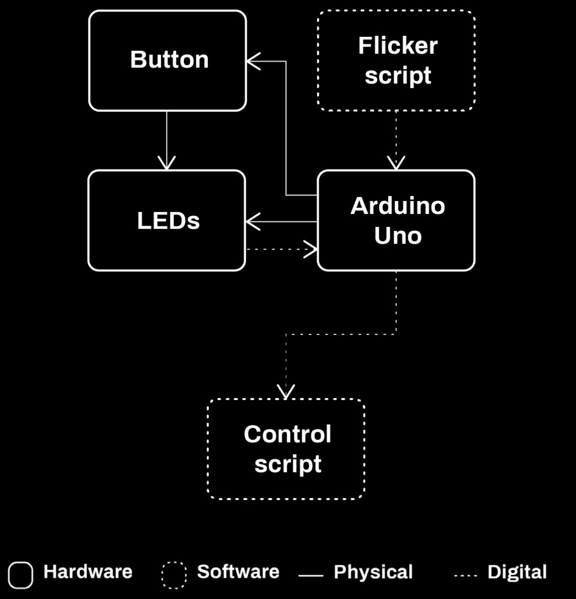


Figure 37: Information flow between the hardware and software used to control the stimulus (LEDs).

logged throughout in the main control script via serial messages. Finally, a physical button was connected to the Arduino as a power switch, to toggle the LEDs (and serial messages) on or off.

Method

1. Participants (n=2, both male) were recruited by convenience sampling. Both participants had been screened for pre-existing health conditions that could introduce risk in relation to flashing lights (e.g. photosensitive epilepsy or migraines), or that could affect their neurological activity.
2. Each recording session began by briefly explaining the purpose and structure of the protocol to the participant, including a typical verbal consent agreement. The participant was then fitted with an Enobio 8-channel wet electrode EEG device. Electrodes were focused around the occipital and parietal regions, placed on channels PO7, O1, Oz, O2, PO8, PO3, PO4 and Pz.
3. Once the EEG device had been connected to LSL, NeuroPype and the control script were initiated. For the first 30 seconds of recording the participant sat undisturbed with their eyes closed whilst their baseline EEG data was collected (Figure 39). After 30 seconds, the LED headset was switched on automatically, with a serial message sent simultaneously to the control script to trigger the production of the participant's average baseline model and the collection of experimental data.
4. The LEDs flickered at a given frequency (8-12Hz, in 1Hz intervals, ascending) for 30 seconds, followed by 5 seconds with the LEDs switched off. The post-baseline routine was therefore approximately 3 minutes long. This approach is adapted from Herrmannn[11]. The current flicker frequency was continuously logged by the control script via serial messages.
5. During the post-baseline routine, resonance

Figure 38: Stimulus hardware setup used in the Flicker protocol.

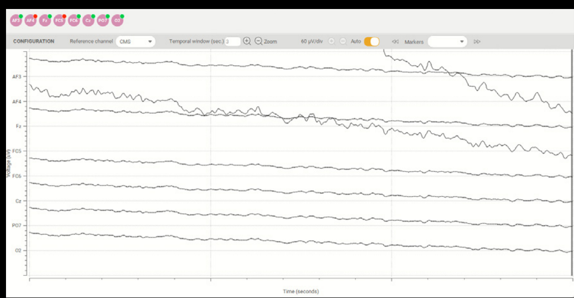


Figure 39: Example raw EEG data collected in NIC2, the EEG device's native software.

scores were continuously calculated and plotted, along with the participant's baseline model and live spectral data.

4.2.2 RESULTS & ANALYSIS

At the end of each recording session, the CSV files produced by the control script were imported into JMP, a statistical analysis software. Figure 40 shows a summary graph of the baseline EEG collected from the first participant. Looking at the shape of the data, we see a pronounced peak in the alpha range at approximately 9.6Hz (Figure 40). This value can be considered as the participant's peak alpha frequency (or at least for the duration of the trials following the baseline measurement).

An ordinal logistic fit model was produced using the first participant's experimental data, to assess the predictability of stimulus frequency based on their EEG — in other words, the strength of the relationship between the two variables. The confusion matrix of this model (Figure 41) indicates a high level of predictability, as demonstrated by the confusion matrix, which shows a good accuracy rate (i.e. few false predictions). This indicates that the EEG data collected is indeed reflective of the stimuli presented, and that changes in this data relating to the stimuli are reasonably consistent.

Figure 42 shows a graph of the first participant's experimental data. In the graph, we see clear resonance phenomena during the 9Hz and 10Hz stimuli periods. Resonance phenomena are characterised by a peak at the fundamental (same as stimulus) frequency and an additional peak at the first harmonic (double the stimulus) frequency. This would suggest that the participant experiences greatest neural resonance at stimulus frequencies between 9 and 10Hz, which also appears to correspond with their baseline peak alpha (9.6Hz).

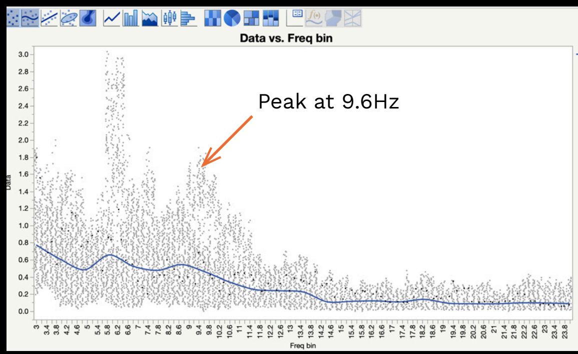


Figure 40: Graph of the first participant's baseline EEG data, showing a peak alpha of approximately 9.6Hz.

Confusion Matrix

Training

Actual Stimulus Hz	Predicted Count 8	9	10	11	12
8	564	18	0	0	0
9	11	559	21	0	0
10	0	21	574	26	0
11	0	0	31	585	11
12	0	0	0	9	628

Figure 41: Confusion matrix of the fit model produced from the first participant's experimental data.

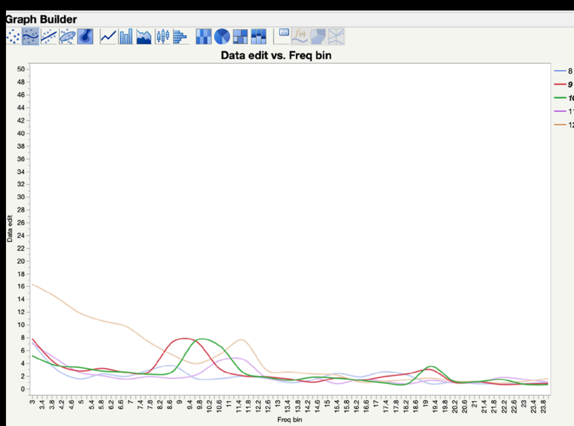


Figure 42: Graph of the first participant's experimental EEG data, showing resonance during 9Hz and 10Hz stimulus periods.

The second participant's baseline data showed a clear peak at approximately 8Hz, in addition to significant activity between 8 and 9.6Hz. From this, the second participant's baseline peak alpha can be estimated as in the region of 8-8.4Hz. This participant's responses differed somewhat in terms of distribution compared to the first participant's. However, resonance responses were also visible, particularly during the 8Hz and 9Hz stimulus periods. In both cases there were pronounced peaks at the fundamental frequency, with smaller peaks at the harmonic frequency (around 16Hz and 18Hz respectively). Again, there appears to be a relationship between the participant's baseline peak alpha and the stimulus frequency(ies) at which they experience most neural resonance.

4.2.3 CONCLUSIONS

In response to my three general assessment goals:

- **The stimulus successfully produced noticeable resonance responses** at certain frequencies. This was characterised numerically by greater resonance scores at the fundamental (stimulus) frequency and first harmonic, and was also visually apparent in graphs of the experimental data.
- There appeared to be a **relationship between the participant's baseline peak alpha** and the range of frequencies that evoked the **greatest resonance response**. This should be investigated further, however, before drawing concrete conclusions.
- All presented stimuli produced some form of response at the stimulus frequency, but the presence of **harmonic peaks** differentiated more and less resonant frequencies.

In relation to my protocol-specific goals:

- The ordinal fit model and its confusion matrix, as detailed above, show that the basic system was able to collect data with **sufficient accuracy** such that it was representative of the expected neural phenomena. This means that the basic system can be **used in similar protocols** with a good degree of confidence.

- **Resonance responses were clearly visible** in the experimental data of both participants. This means that the **stimulus was delivered correctly**, i.e. frequencies were translated accurately and were perceptible.

4.3 PROTOCOL 2: PLAY

4.3.1 EXPERIMENTAL SETUP

My second protocol builds upon the conclusions of the first, moving from a predefined frequency sweep to a more free-form approach. Now that I had confirmed the accuracy of the basic system and gained a better understanding of how neural resonance was represented in it, I wanted to consider the participant's experience of the session. A traditional frequency sweep is advantageous scientifically in that it is clearly defined and thus makes it easier to establish a relationship between stimuli and data. However, its rigidity and repetitiveness are not conducive to an aesthetically meaningful or enjoyable experience. To begin to address this, my second protocol focused on finding an individual's neural resonance peaks with a trial and error approach informed by their baseline data — essentially a human-controlled hill-climbing algorithm, in which a person's baseline peak alpha was used as the starting point. This starting point was chosen to further investigate the potential relationship between peak alpha and resonance seen in the previous protocol.

Goals

My goals for this test were as follows:

- **Investigate the potential relationship between baseline peak alpha and resonant alpha frequencies;**
- **Determine the efficacy of a more playful, free-form approach to resonance peak-finding.**

Stimuli

This protocol used the same stimulus set-up as before, with 22 addressable LEDs mounted in a VR headset, connected to an Arduino Uno. However, the script used to control the LEDs differed in that, instead of a finite state machine, the current value of a physical slider was mapped to the current LED flicker frequency (Figure 43). This approach meant that

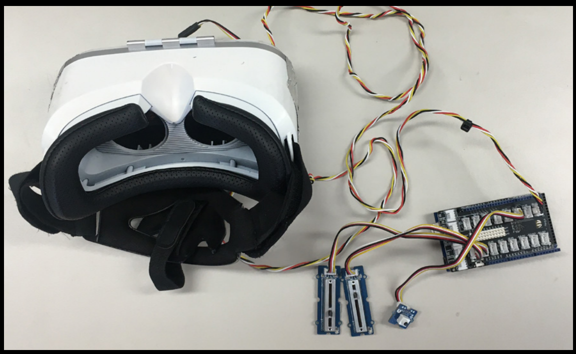


Figure 43: The LED headset and EEG device were used as before, with the addition of sliders to control the frequency and brightness of the LEDs.

the frequency could be set at smaller intervals — 8-12Hz, as before, but with steps of 0.1Hz. This also allowed me to target a participant's peak alpha more specifically with the stimulus. A button was used to control LED power as before, with all LEDs again set to white (Figure 44).

<u>**Method**</u>

1. The test was carried out with the first participant from the previous protocol. This was done to allow comparison between their data from both protocols, which would help to assess the effects of the Play approach.
2. The recording session began by briefly explaining the purpose and structure of the protocol to the participant, including a typical verbal consent agreement. The participant was then fitted with an Enobio 8-channel wet electrode EEG device. Electrodes were focused around the occipital and parietal regions, with the same channels used as before.
3. For the first 30 seconds of recording the participant sat undisturbed with their eyes closed whilst their baseline EEG data was collected. After 30 seconds, the LED headset was switched on automatically, with a serial message sent simultaneously to the control script to trigger the production of the participant's average baseline model and the collection of experimental data.
4. The LEDs were manually set with the slider to flicker first at the participant's baseline peak alpha (9.6Hz). Using my live data and resonance score graphs, I watched for a resonance response at this frequency to establish the effect of the LEDs.
5. I then looked for local peaks in the alpha range on my live graphs. I followed these peaks to explore if, and for how long, a resonance response could be evoked at these peaks. This was repeated until a stable resonance response was found in the alpha

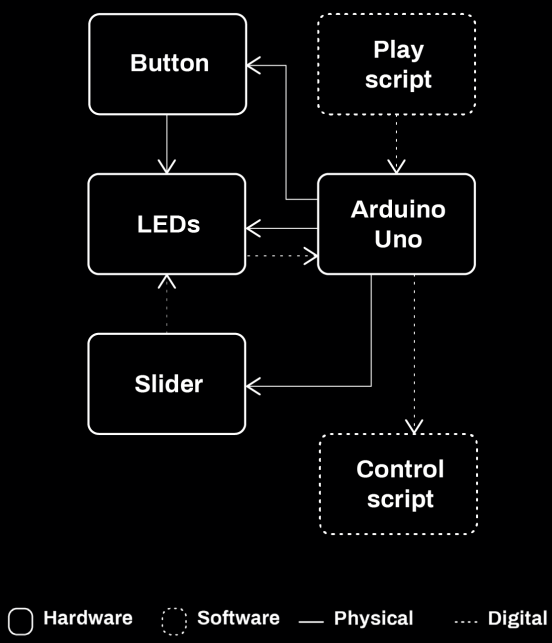


Figure 44: Information flow between the hardware and software used to control the stimulus (LEDs).

range, including a peak at the first harmonic.

4.3.2 RESULTS & ANALYSIS

Figure 45 shows live graphs from the beginning of the experimental period, where the stimulus frequency was set to 9.6Hz to match the participant's baseline peak alpha. After a short period of time (about 15 seconds), a clear resonance response was visible in the graphs. Crucially, the increase in EEG activity at the fundamental (stimulus) frequency is accompanied by an increase at the first harmonic. As shown in the previous protocol, this differentiates a resonance response from entrainment, where usually there is only a discernible peak at the fundamental frequency.

As the stimulus frequency was changed in a more responsive manner, the number of datapoints per stimulus frequency was not consistent, nor were all frequencies selected. This meant that the data analysis techniques from the previous protocol would not be as conclusive. However, looking at the live graphs (Figure 45) in conjunction with the raw data gave clear indications of resonance in real-time.

Figure 46 shows the spectrogram in NIC2 (the native software for the Enobio EEG device), captured whilst the resonance response at 9.6Hz shown in Figure 45 was occurring. We can clearly see areas of strong response at around 9.6Hz and 19Hz respectively. However, it is important to note that the response is not bound strictly to these singular frequencies, but rather there is a small range of response centred around them. We see this in Figure Y with red and orange regions at 9.6Hz, but blue in a range of 8-10Hz.

If there is a local range of frequencies at which resonance is detected, centred around the stimulus frequency, then the question arises as to whether the inverse is true — i.e. if there is a similar local range of frequencies that can produce resonance, centred around a

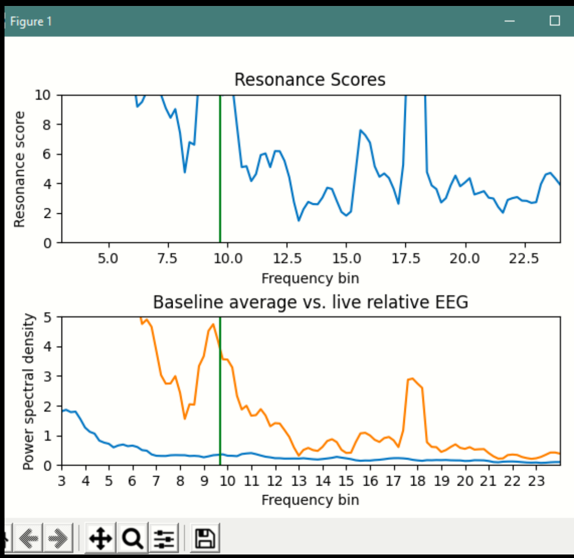


Figure 45: Live graphs showing a resonance response to the initial stimulus frequency of 9.6Hz, set to match the participant's baseline peak alpha.

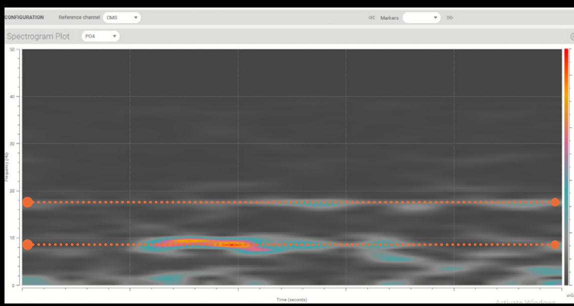


Figure 46: Live spectrogram confirming the resonance response at 9.6Hz. In this we can see how the response is not strictly bound to the stimulus frequency, but rather a small range around it.

particular frequency. To explore this, I set the stimulus frequency to various points within the range of 8-10Hz. I found that it was possible to elicit a resonance response at several of them, particularly at 9Hz (Figure 47). This would suggest that if a stimulus frequency is close enough to an individual's peak resonant frequency (in this case, hypothesised as their baseline peak alpha), then it has a good chance of producing neural resonance.

4.3.3 CONCLUSIONS

Referring to my three general assessment goals:

- The stimulus again produced **noticeable resonance responses** at a number of frequencies.
- Setting the stimulus frequency to match the participant's **baseline peak alpha** produced a sizeable resonance response.
- Although traditional numerical analysis was not conclusive, there was clear evidence of resonance in the **live EEG data**.

In response to my protocol-specific goals:

- There appears to be a l**ocal range around the baseline peak alpha** at which resonance responses can be achieved and maintained.
- The **playful approach** to stimulus control was able to produce resonance at a number of frequencies, suggesting possibilities for a **more complex and engaging** resonance experience.

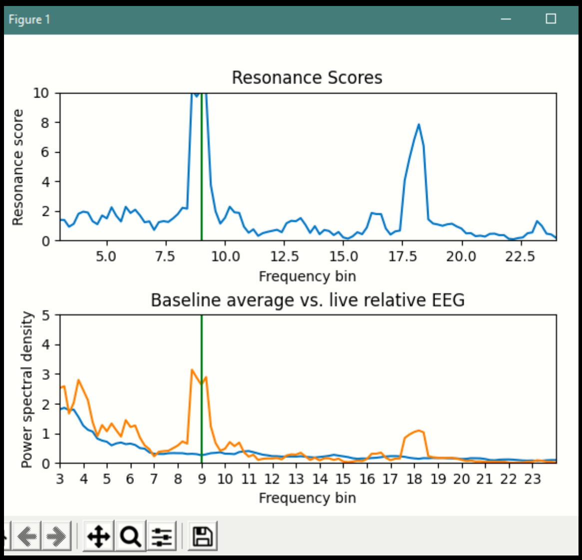


Figure 47: Live graphs showing a resonance response to 9Hz flicker. Clear peaks are visible at the fundamental and harmonic frequencies (9Hz and 18Hz respectively).

4.4 PROTOCOL 3: SOUND

4.4.1 EXPERIMENTAL SETUP

My third protocol introduced a different stimulus: audio. Having investigated various ways of delivering light flicker, I wanted to consider other aspects of an audiovisual experience and confirm their suitability for evoking neural resonance. As I was introducing a new factor into the experiment, I decided to return to the more regimented frequency sweep performed in the first protocol, to maximise interpretability of the experimental data. This protocol used an amplitude-modulated carrier tone as an audio input; more specifically, a 400Hz tone modulated between 8 and 12Hz in 1Hz intervals. This essentially created a translation of the first protocol into the audio space.

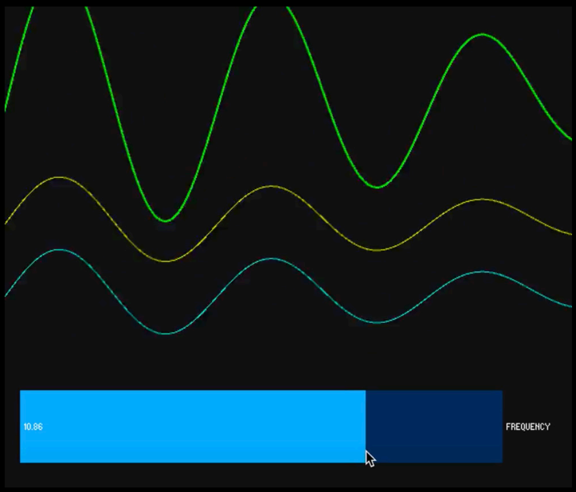


Figure 48: The audio stimulus is controlled using an interactive sketch made in Processing. The blue slider sets the modulation frequency of the carrier wave.

Goals

My specific goals for this protocol were as follows:

- **Evoke resonance response(s) to an auditory, oscillatory stimulus;**
- **Compare neural responses between the auditory stimulus and flicker, as in the first protocol.**

Stimuli

A sine carrier wave of 400Hz was generated using Processing (a Java-based creative coding environment) (Figure 48). The amplitude of this sine wave was modulated at frequencies between 8 and 12Hz in 1Hz steps, giving 5 distinct sounds in total. Amplitude modulation involves ‘fitting’ a carrier wave to the amplitude of the modulating wave, meaning that the carrier wave sounds like it is oscillating at the modulation frequency. 400Hz is a mid- pitch frequency, roughly comparable to the middle G key on a piano.

A state machine structure was again used to control the timing of each stimulus period

(Figure 49). The audio was presented in stereo. Earphones were used (as opposed to over-ear headphones) so that the EEG device and electrodes would not be disturbed.

Method

1. The test was carried out with the first participant from the previous protocol. This was done to allow comparison between their data from both protocols, which would help to assess the effects of the Sound approach.
2. The recording session began by briefly explaining the purpose and structure of the protocol to the participant, including a typical verbal consent agreement. The participant was then fitted with an Enobio 8-channel wet electrode EEG device. Electrodes were spread across the scalp, with electrodes in parietal, crown and frontal regions (channels PO7, PO8, Cz, FC5, FC6, Fz, AF3 and AF4).
3. For the first 30 seconds of recording the participant sat undisturbed with their eyes closed whilst their baseline EEG data was collected. After 30 seconds, the audio was initiated, with a serial message sent simultaneously to the control script to trigger the production of the participant's average baseline model and the collection of experimental data.
4. As in the first protocol, each audio frequency was presented for 30 seconds, followed by a 5-second pause. The current modulation frequency was continuously recorded and logged with experimental EEG data.
5. During the post-baseline routine, resonance scores were continuously calculated and plotted, along with the participant's baseline model and live spectral data.

4.4.2 RESULTS & ANALYSIS

The participant's baseline data (Figure 50) is consistent with previous protocols. Most of their alpha-range activity is in the range of 9-10Hz,

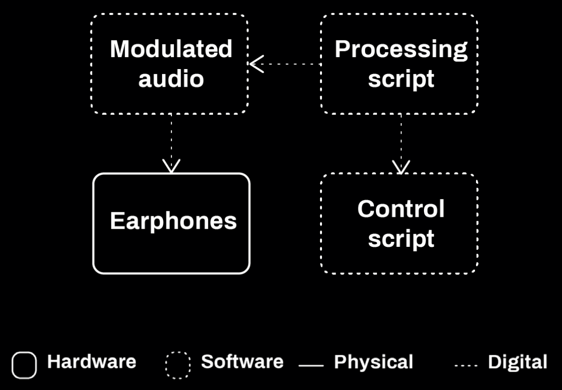


Figure 49: Information flow between the hardware and software used to control the stimulus (audio).

with an approximate peak around 9.6Hz (Figure 50). Based on the findings of my previous two protocols, this means we would expect to see the greatest neural response (and, hopefully, resonance phenomena) to 9Hz and 10Hz stimuli.

The results of the protocol are less clear-cut in terms of stimulus response compared to previous protocols. Figure 51 shows neural response, organised by frequency bin as before, plotted against stimulus frequency. There is a relatively high level of low-frequency neural activity across all stimuli, which is quite typical. This can result from a number of factors — signal noise or movement, for example. Although stimulus responses are less pronounced than in previous protocols, we are still able to see some hierarchy in terms of which stimulus frequencies elicited the strongest responses, and whether these responses bore relation to the stimulus frequency.

Looking at the experimental data in more detail, it appears that the strongest responses generally were a result of 10Hz and 12Hz stimulation (Figure 52). 10Hz in particular shows the most coherent response, with a small but pronounced peak around the stimulus frequency, although first harmonic (20Hz) activity is not apparent. 12Hz also shows a similar peak around the stimulus frequency, accompanied by smaller peaks at the first harmonic (24Hz) and, interestingly, halfway between the two (18Hz). The significance of this is unclear, but could merit further investigation.

Based on the findings of previous protocols, we would indeed expect to see greater response around the frequency of a person's baseline peak alpha. In this case the baseline peak was 9.6Hz, so the resonance response at 10Hz is in line with this expectation. However, the responses at 10Hz and 12Hz both demonstrate heightened activity around the baseline peak (9.6Hz), which then raises the question as to whether this was the result of the stimuli or

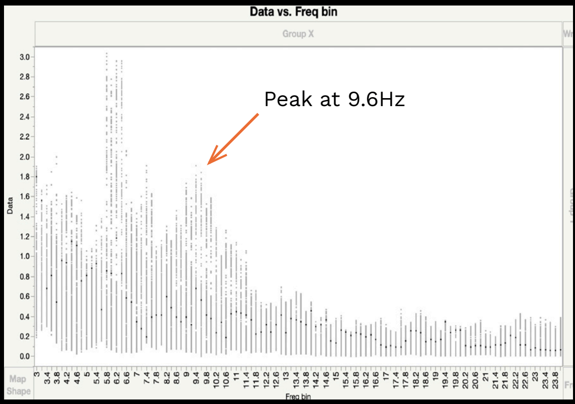


Figure 50: The participant's baseline EEG data, showing a peak alpha of around 9.6Hz, as in previous protocols.

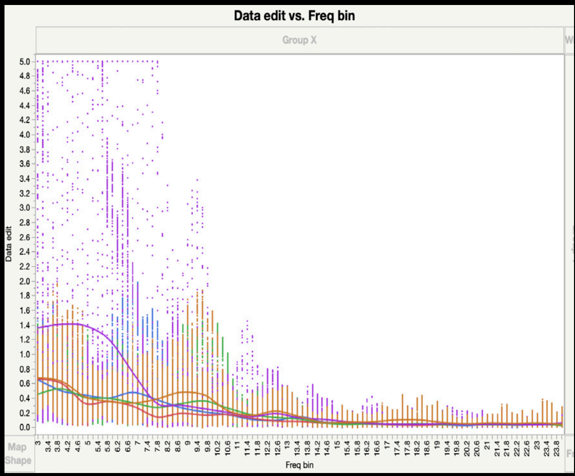


Figure 51: The participant's experimental data, showing responses to audio stimuli between 8 and 12 Hz.

simply passive brain activity.

Looking at the resonance scores produced by my system sheds some light on this issue. Comparing 10Hz and 12Hz stimulus responses again (Figure 53), the 10Hz response seems to be stronger overall. This is because the resonance scores — i.e. increase in neural activity compared to the participant's baseline — clearly peak around 10Hz during the 10Hz stimulus period. In comparison, there is a small peak around 12Hz during the 12Hz stimulus period, but this is accompanied by several other comparable peaks across the spectrum, which suggests a less coherent response.

As a final check, I ran an ordinal fit model on the experimental data. The confusion matrix of this model (Figure 54) shows a relatively good level of predictability, meaning the data can be taken as representative of the neural responses described above. Some of the overlap in predictions between neighbouring frequencies could be attributed to a more distributed neural response, i.e. in a range centred around the stimulus frequency.

4.4.3 CONCLUSIONS

Referring to my assessment goals:

- Overall, the **character of the response data was more complex** than in previous protocols. Resonance phenomena were not as pronounced as before, with neural activity more evenly **spread across a range of frequencies**.
- However, some form of response at the stimulus frequency was visible during 10Hz and 12Hz stimulus periods. After examining the data more closely and comparing resonance scores, it was found that the **resonance response to the 10Hz stimulus** was stronger overall.

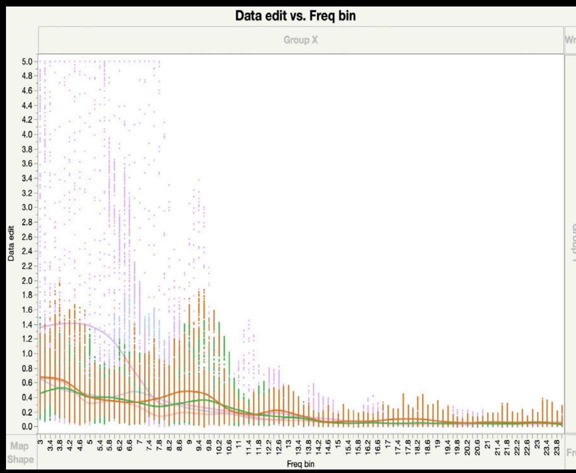


Figure 52: Highlighting the responses at 10Hz and 12Hz, we can see they are more typical of neural resonance than the other stimulus responses.

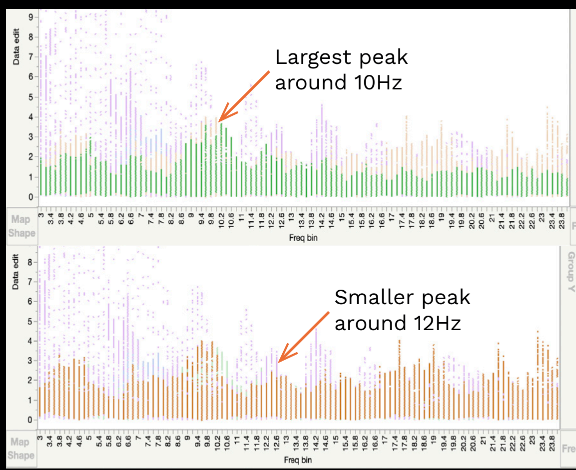


Figure 53: The peak in resonance score at the stimulus frequency is more pronounced, relative to neural activity as a whole, during the 10Hz period (top) than the 12Hz period (bottom).

Training

Actual Stimulus frequency (Hz)	Predicted Count 8	9	10	11	12
8	461	96	9	0	0
9	54	424	127	6	0
10	0	120	394	105	3
11	1	7	133	313	40
12	0	0	2	73	326

Figure 54: Confusion matrix of the response data, showing a good level of predictability.

- This is in line with previous protocols, where frequencies close to the participant's **peak baseline alpha** (in this case, 9.6Hz) produced **stronger resonance responses**.

Despite some apparent evidence of resonance in my results, I was intrigued by the very different nature of experimental data I had gathered compared to my experiments with flicker. Returning to neuroscience literature on the topic of music cognition helped to clarify this difference.

Although neural responses to simple audio stimuli (such as those used in this protocol) are documented in literature, researchers have also observed variability in the strength and nature of these responses, depending on the way they are measured and the analysis techniques applied to the experimental data. In particular, the placement of electrodes and **spatio-temporal analysis** of data, as opposed to averaging over electrodes, are key considerations for future experiments.

According to music cognition researchers Will and Makeig, EEG responses to audio signals (such as music) are far more spatially distributed across the brain than other oscillatory stimuli, such as flicker[26]. Although averaging neural response over a recording — such as aggregating data by frequency bin, as in my system — is **ideal for simple auditory responses**, it becomes less meaningful as audio signals and brain response alike become more **complex and three-dimensional**[26]. This suggests that, although my system is indeed able to detect neural resonance produced by simple audio stimuli, changes may need to be made as these stimuli are developed aesthetically.

4.5 CONCLUSIONS

4.5.1 GENERAL CONCLUSIONS

Carrying out the three protocols — Flicker, Play and Sound — gave me valuable insights into the accuracy and reliability of my resonance metric, and the efficacy of different stimuli. My main conclusions were as follows:

- My system is **able to detect and measure neural resonance** with a good degree of accuracy. It gives reasonably reliable results across different protocols and stimuli.
- The chosen **resonance metric** — proportional increase in spectral density **represents the equivalent neural phenomena**, as shown in comparisons between the live plots of this metric and live spectrograms of the raw EEG.
- The system enables me to elicit resonance responses in a more **organic and personalised** manner through its live visualisations, which are sufficiently **accurate and responsive** to changing stimuli. This can be conceptualised as a human-controlled version of a typical hill-climbing algorithm.

4.5.2 FROM DATA TO DESIGN

Producing resonance through a hill-climbing approach is particularly significant in terms of **experiential design**. This approach showed me that I could infer a probable resonant frequency from a person's baseline peak alpha, and that I could elicit resonance at a number of frequencies in a range centred around it.

This means that, in future experiential prototypes using my system, it may be possible to **compose a neurally resonant experience around a person's peak alpha** and generate audiovisual components using frequencies around this peak alpha. Such an experience would be inherently temporal, evolving over time but unified structurally through the central peak — much like music, where structure gives intelligibility, whilst variation creates space for emotional expression and sensory delight. Emotion, meaning and sensory pleasure: all essential components of aesthetic resonance.

A key question then arose:

how might neurally resonant stimuli be transformed into an aesthetically resonant experience?

5

DATA & DESIGN

This chapter translates the findings of the previous chapter into design requirements for an aesthetic experience driven by my neural resonance system. It defines a general concept for this experience, alongside specific design parameters, and details exploration of the concept through an interactive prototype.

5.1 DESIGN VISION

5.1.1 DESIGN REQUIREMENTS

By carrying out various tests with my resonance metric, as detailed in the previous chapter, I was able to validate my approach for measuring and representing neural resonance. The next step was to consider the experiential aspects of neurally resonant stimuli in more detail — and how to move from traditional stimuli, such as flickering light and sine waves — to a more aesthetically meaningful experience.

Referring back to my initial literature review, I discussed a model of aesthetic experience in neuroaesthetics literature known as the aesthetic triad[19]. The triad consists of three system pairs: emotion-valuation, meaning-understanding, and sensory-motor. Each system underpins the cognition and perception of an aesthetic experience; when all three are fulfilled, aesthetic resonance can occur. These three system pairs therefore formed the basis of my experiential design requirements, as follows.

The experience should:

- hold **emotional value**, either directly or indirectly, for the participant;
- give **interpretable cues** about the relationship between the **designed environment** and the **participant('s data)**;
- provide **sensory interest and pleasure**.

5.1.2 INTERACTION VISION

An interaction vision is a technique for representing the intended interaction qualities of a design[27] in a metaphorical way, giving a reference point for the assessment of concepts and prototypes. The first step is to (re-)state the overarching design goal:

> **to create a personalised, engaging, multi-sensory experience that is driven by resonance.**

The next step is to construct a vision that encapsulates the intended qualities of the design. A common way of building an interaction vision is through the pairing of intended qualities and related affordances Considering the above general design requirements and design goal, my intended qualities and affordances are shown below. From these pairs, a vision is produced: **being on the front row at a concert** (Figure 55).

Quality	Affordance
Immersive	Proximity to performers
Personal	Connection to music and culture
Ephemeral	A unique, one-off event
Dynamic	Changing sounds and environment

Table 1: Qualities and affordances of my interaction vision.

Figure 55: My interaction vision: being on the front row at a concert. (This particular image shows a Talking Heads gig — a personal favourite.)

5.2 CONCEPT

5.2.1 CONCEPT DEFINITION

As explored in the previous chapters, audio-visual stimuli are commonly used when investigating neural responses, due to the relative predictability of response (at least with simple stimuli). Because of this, the design concept is envisaged as an audio-visual experience. Constraining the experience gives greater scope for exploration and meaningful personalisation. Considering my design goal, interaction vision and design parameters, I defined my general design concept as follows:

a platform for measuring and creating neural and aesthetic resonance through a data-driven, audiovisual experience.

This platform should include not only controllable audiovisual components, but interpretable, real-time information about the degree of neural and aesthetic resonance a participant is experiencing. This will allow the designer to iteratively optimise the audiovisual experience, checking for changes in the resonance data as they adjust the audiovisual parameters (Figure 56).

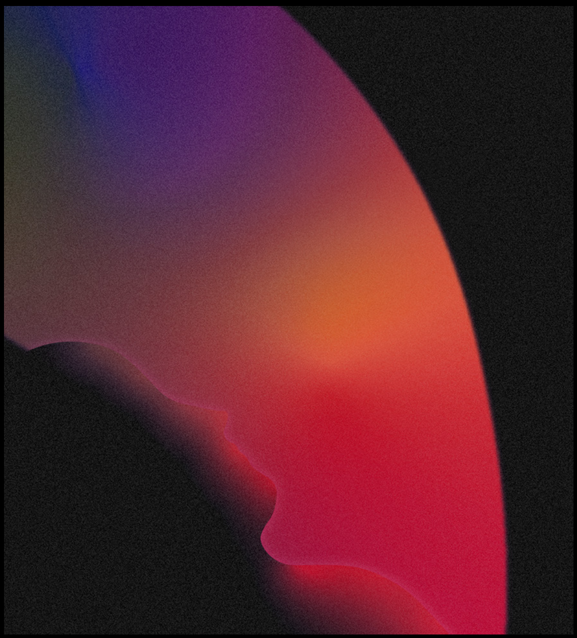


Figure 56: An initial concept sketch: the participant is completely enveloped by light and sound, which morphs and evolves with their EEG to optimise resonance.

5.2.2 DESIGN PARAMETERS

Both light and sound have numerous properties that can be manipulated to create any number of unique audiovisual experiences, each with a particular atmosphere. To give shape to the design space, I defined the main properties of light and sound I wanted to investigate in my experiential prototypes, along with questions to incorporate into user tests.

LIGHT

Property	Question
Brightness	What is the trade-off between comfort and strength of neural response?

Property	Question
Colour	How do associations with colour affect experience?
Saturation	Does saturation have psychological associations?
Abstraction	How do abstract vs. figurative forms affect experience?
No. of instances	Does layering affect neural and aesthetic response? How?

SOUND

Property	Question
Volume	What is the trade-off between comfort and strength of neural response?
Pitch	How do associations with pitch affect experience?
Timbre	How do associations with timbre affect experience?
Tempo	What is the trade-off between frequency representation and aesthetic pleasure?
No. of instances	Does layering affect neural and aesthetic response? How?
Abstraction	How melodic and structured should the sound be, vs. how abstract and organic?

Tables 2+3: Possible audiovisual properties of the design concept and related questions to explore.

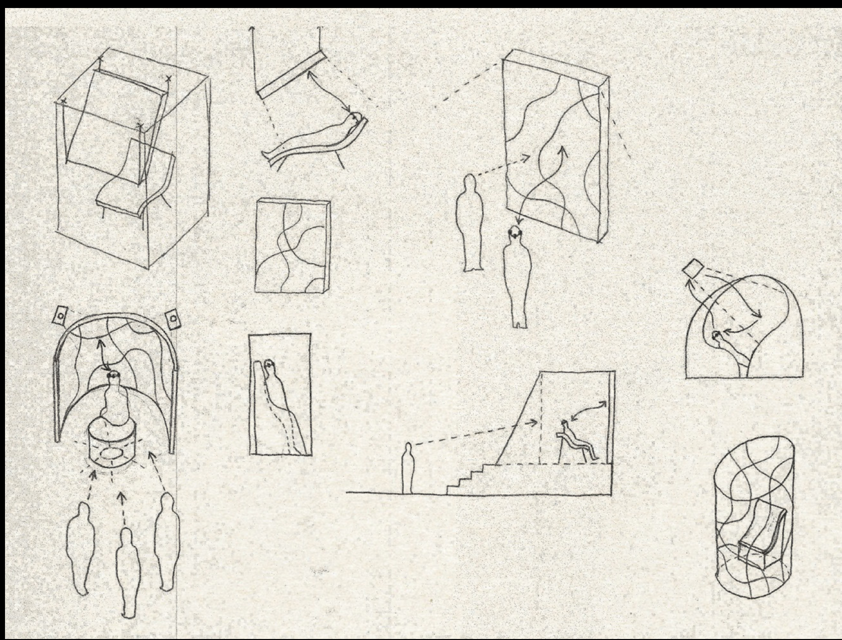


Figure 57: Sketches exploring different possible spatial configurations. In some, the experience is entirely secluded and visible only to the participant, whereas in others, partial visibility turns it into an exhibition piece.

Figure 58: Conceptual storyboard showing the participant's journey from approach to immersion. The approach is particularly important: building interest and priming the participant to be open and inquisitive.

5.3 PROTOTYPE 1: MOLTEN

5.3.1 PROPERTIES & GOALS

Prototype Design

My first prototype, *Molten*, focuses on establishing a relationship between live neural resonance and a visualisation.

A dynamic visualisation (Figure 59) was made using WebGL shaders in p5, a browser-based JavaScript library. The visualisation was kept purposely simple and abstract, focusing mainly on changes in colour, saturation and movement. It was projected on a plain, white wall using a standard LED projector.

The visualisation was paired with audio in the form of an amplitude-modulated sine oscillator. Using Processing, the oscillator (a 400Hz carrier wave) was modulated between 8-12Hz with a digital slider. Participants' live EEG data was processed, logged and plotted as in the previous chapter, with audio being adjusted in real-time (as in Protocol 2) to optimise for neural resonance. The current peak resonance score in the alpha range was then mapped to the saturation of the visualisation via OSC (Figure 60).

Testing Goals

The questions I wanted to answer with this prototype were as follows:

Light

- How does **colour** affect subjective experience?
- Do changes in **saturation** convey changes in the participant's EEG?

Sound

- How do participants experience an auditory **sine wave**?
- Are changes in **frequency** perceptible?

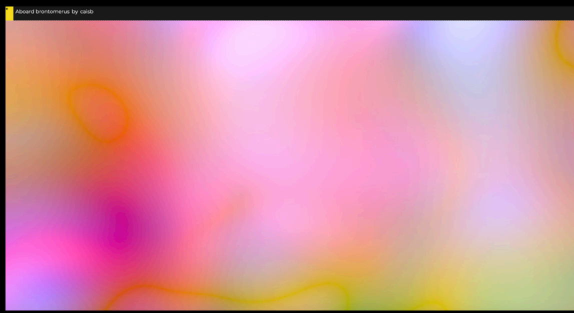


Figure 59: p5 sketch used as the visual component of my first prototype. The colours become more saturated as neural resonance increases, whilst the "blob" forms gently morph over time.

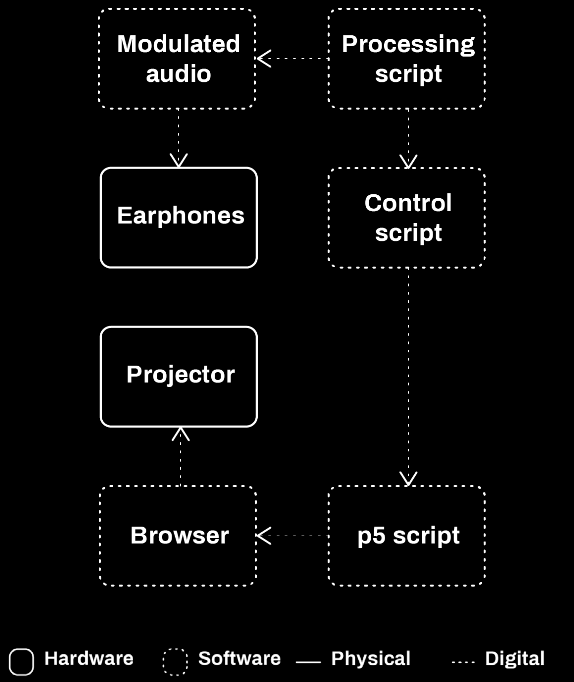


Figure 60: Information flow between the hardware and software used to control the stimuli.

5.2.2 USER TESTING

Method

1. Participants (n=4, 3 female) were recruited using convenience sampling. All participants were students at TU Delft's Industrial Design Engineering faculty. This demographic was also advantageous in that, as fellow designers, they would be more likely than average to feel comfortable reporting their subjective experience. All participants were screened for any health conditions that could make exposure to oscillatory stimuli problematic for them.
2. Participants were fitted with an Enobio 8-channel device (channels P7, PO3, Oz, PO4, P8, Pz, C3 and C4).
3. Participants were seated in front of the projection, wearing earphones connected to a nearby PC.
4. For the first 30 seconds of the experience, baseline EEG was collected and processed as before. This was followed by a 5-minute session in which I changed the audio modulation frequency.
5. Using the live plot and Processing interface, I performed an approximate hill-climbing approach, starting the stimulus frequency at around the participant's baseline peak alpha and exploring the space around it to optimise for resonance response.
6. Each participant was asked to verbally report their experience, remarking on the three components of the aesthetic triad: understanding and meaning of the experience (i.e. what they were seeing and hearing represented), emotions and valuation (i.e. if any feelings arose in relation to the experience), and sensory aspects (i.e. whether the experience was sensorially pleasurable or not, and why).

Results & Analysis

I began by organising the qualitative data collected from each participant into statement cards (Figure 61). Statement cards consist of a quote from a participant and an abstraction of that quote, i.e. a statement that expresses the underlying meaning of the quote[28]. Once statement cards had been made for each participant, I clustered these cards into thematic groups. Six themes emerged in total:

1. **visual form;**
2. **colour;**
3. **meaning;**
4. **purpose;**
5. **feeling;**
6. **sensing**.

Each statement card was also tagged with one of the three components of the aesthetic triad[19] — emotion/valuation, meaning/understanding and sensory/motor (Figure 62). Although there was some semantic overlap between these components and the six clusters, I found that for most clusters, multiple components were represented. This suggests that different aspects of the prototyped experience have differing significance in terms of the three components. It would also then follow that a form of balance is required across these aspects to in turn create balance between the aesthetic components, and therefore evoke aesthetic resonance. (For an overview of the statement card clusters, see Appendix B.)

Considering the statement cards and aesthetic component distribution in each thematic cluster, I drew a series of conclusions regarding my first prototype. Notably, there was significant overlap and interplay between different clusters in terms of emotions, senses and meaning-making. This is in line with the aesthetic triad[19], which models how the cognitive

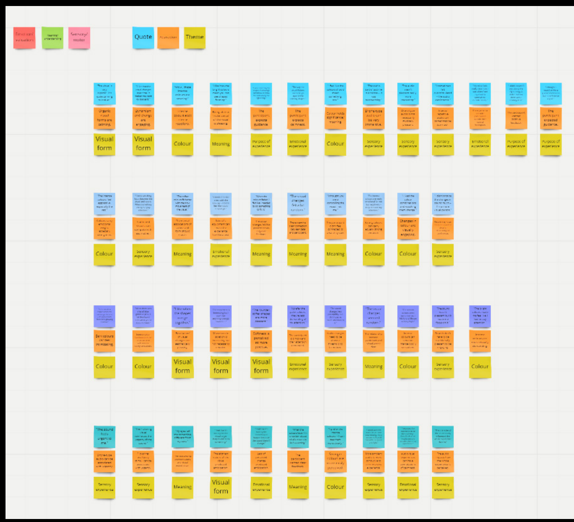


Figure 61: Statement cards produced from the gathered qualitative data, organised by participant.

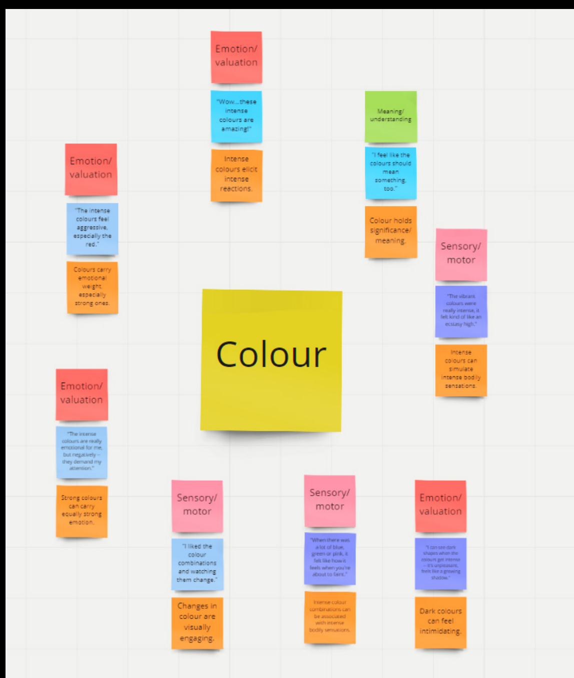


Figure 62: An example of thematic clustering. This cluster contains statement cards pertaining to the perception of colour.

systems behind these three dimensions all influence each other during an aesthetic experience. The clusters helped me to tie this theory to tangible aspects of my audiovisual design:

1. **Visual form** has strong influence over the emotional perception of the experience, with some impact on sensory perception and understanding.
2. **Colour** also has strong influence over the emotional perception of the experience, in addition to strong influence over sensory perception and some impact on understanding.
3. **Meaning** is a significant factor in the overall subjective experience. Participants look for and expect some kind of symbolic representation, even in abstract forms.
4. The **purpose** of the experience, and the framing thereof, is crucial to how the experience is subsequently perceived.
5. The **feelings** evoked by the experience are complex and influenced by both the senses and the perceived meaning of what is seen or heard.
6. Likewise, the **sensory** dimension of the experience involves both perceptual and emotional processes.

I also drew some more general conclusions in relation to the questions I posed prior to testing regarding light and sound:

Light

- **Colour** influences subjective experience greatly, with some trends between participants but also a good degree of individual variability. Colour is seen as symbolic and changes in colour provoke interest.
- Changes in **saturation** evoke emotional responses, but did not convey the intended

meaning in this prototype. Saturation was sometimes perceived as a form of feedback, however.

Sound

- The amplitude-modulated **sine wave** was often perceived as interesting, even “mesmerising”, but not especially pleasant. It evoked urgency to some, a trance state to others.
- The **character of the audio** significantly influenced participants’ overall attitude towards the experience; it commanded their attention.
- Small steps in **frequency change** (e.g. 0.5Hz) were not perceptible, but larger ones (e.g. 3Hz) were.

5.2.3 NEXT STEPS

In light of the conclusions drawn from my user testing, I formulated recommendations for the development of my next prototype.

Firstly, the next prototype should aim to convey a **more complete narrative** of the experience, so that participants’ expectations are in line with the intended effects. The experience is not necessarily meant to be calming or soothing; rather, it should be engaging and dynamic. Intensity is a natural part of this, but needs to be carefully managed so that the experience is still positive.

Secondly, the repetitive and high-contrast nature of simple oscillatory stimuli (such as the audio used in this prototype) can negatively influence the overall perception of the experience. However, audio is clearly a powerful way to **shape the aesthetic perception** of an experience and can capture participants’ attention well. The next prototype should explore ways of delivering **oscillatory audio** in a **more nuanced and changeable** way to deliver aesthetic value.

Thirdly, visualisations carry **expectations of symbolic meaning**. This can be leveraged to convey the relationship between the participant's neural activity and their environment, but the next prototype should investigate whether visualisation is the best format for expressing this relationship and if doing so meaningfully contributes to the **aesthetic value** of the experience.

A final and particularly important point that arose through testing was that of **measurement**. Although the verbal feedback participants gave was certainly useful for investigating the aesthetic properties of the audiovisual design, it was not "real-time" in the way my neural resonance metric was. This meant that it was more difficult to associate the participants' aesthetic experience with changes in the stimuli and would make optimising for aesthetic resonance challenging. Additionally, the fact that the participants were describing their experience verbally meant that there was significant **variation** in terms of the language used to report their aesthetic response. As previously detailed, post-experience semantic analysis was needed to properly understand and compare the participants' subjective experiences.

Considering the limitations described above, I concluded that before developing and testing further prototypes, I needed to create a **consistent, real-time metric of aesthetic experience** with which to assess and optimise them.

6

METRICS OF EXPERIENCE

This chapter reviews literature on aesthetic emotions and their measurement, then details the development of two assessment protocols for aesthetic emotions during and after an aesthetic experience.

6.1 QUANTIFYING EXPERIENCE

6.1.1 EMPIRICAL AESTHETICS

My first prototyping cycle provided me with a range of insights relating to audiovisual experience design. However, a key observation was that a consistent, real-time measure of aesthetic experience was needed to properly compare neural and aesthetic response, and to optimise for both in a responsive manner.

Aesthetic experiences are inherently personal and subjective, which may make them seem difficult to measure in a quantifiable way. The field of empirical aesthetics explores this tension between subjectivity and measurability. According to the International Association of Empirical Aesthetics (IAEA), the field's primary aim is to “use scientific methods to investigate aesthetic experience and aesthetic behaviour”[29]. Psychologists, neuroscientists, artists and many others contribute to this investigation.

A contemporary challenge in empirical aesthetics is the understanding and modelling of aesthetic emotions[30]. It is an obvious thought that aesthetic objects or experiences inspire emotion, but defining and measuring these emotions is another matter entirely. There has been much debate as to whether and how aesthetic emotions may differ from the typical emotions felt in everyday life, but it is generally agreed upon that aesthetic emotions are the result of the cognitive appraisal our minds carry out when confronted with an aesthetic entity[31]. In this way, aesthetic emotions are an expression of subjective aesthetic experience. Measuring aesthetic emotions can therefore provide empirical insight into aesthetic experiences.

6.1.2 AESTHETIC EMOTIONS

Aesthetic emotions are described as such because they are evoked by an object or environment with aesthetic qualities. They differ from utilitarian emotions (i.e. emotions related to goal achievement) in that they arise purely as a result of the aesthetic appraisal of an artefact. Importantly, aesthetic emotions are felt by the beholder as opposed to “represented, expressed or alluded to in the respective stimuli” [32]. This means that, for example, a painting causes us to feel joy, as opposed to us recognising a joyous scene represented in its image.

Aesthetic emotions can be split into three categories: **pleasing, epistemic and prototypical**[32].

Pleasing emotions relate to emotional valence, i.e. how liked or disliked an artefact is. This is usually linked to some form of pleasing sensory stimulation. They can be broadly categorised into the following themes: joy, humour, vitality, relaxation and energy[32]. It is important to note that arousal — typically partnered with valence in assessing emotional responses — is part of these emotions, but does not necessarily correspond to valence, in that an emotion can be low arousal and positive valence (e.g. relaxation).

Epistemic emotions, on the other hand, relate to the search for meaning in an artefact. They can be categorised with the following themes: surprise, interest, intellectual challenge and insight[32].

Prototypical emotions are those that are associated with aesthetic evaluation[32], such as captivation, awe, attraction and a feeling of beauty. These emotions describe appreciation for an artefact irrespective of any emotional valence it may elicit. For example, a painting can evoke sadness (negative emotional valence) but be simultaneously perceived as beautiful. Such emotions are often complex, which can make them difficult to express — as Kant puts it, beauty is felt rather than known[33].

Considering the aesthetic triad of cognitive processes that underlie aesthetic experience — emotion, meaning and the senses[19] — we can see some overlap with the types of aesthetic emotions described above.

All aesthetic emotions naturally relate to emotional cognitive processes, but pleasing and epistemic emotions appear to correspond more strongly with sensory and meaning processes respectively. Pleasing emotions, according to Schindler et al., are evoked in response to sensory input (for example, feeling energised by bright colours or loud music), whereas epistemic emotions are evoked in response to perceived meaning and understanding[32]. Prototypical emotions are more abstract — described in literature as self-transcendental[32] — and as such may involve all three triad components in some form (Figure 63).

If all three triad components are required to elicit aesthetic resonance, then all three types of aesthetic emotion can contribute to this resonance. Measuring the presence of these aesthetic emotions can therefore act as a metric of whether aesthetic resonance is being achieved, and to what extent.

Figure 63: The three categories of aesthetic emotions, according to Schindler et al[32], overlaid on the aesthetic triad from Chatterjee and Vartanian[19].

Key takeaways:

- **Aesthetic emotions are an expression of subjective aesthetic experience. They are evoked by a stimulus, as opposed to represented by it.**
- **Aesthetic emotions can be categorised as pleasing, epistemic or prototypical.**
- **The three categories of aesthetic emotions can be related to the aesthetic triad from neuroaesthetics literature.**
- **Measuring aesthetic emotions can therefore also measure aesthetic resonance.**

6.2 MEASURING EMOTIONS

6.2.1 AESTHEMOS

Understanding the emotional component of aesthetic experiences is of importance to design, as this understanding can inform designers in creating artefacts that evoke a specific emotional response. There are a great number of different emotions that might be felt in response to an artefact — and an equally great number of theories seeking to classify them. This is compounded by the fact that, across relevant domains such as music, art and design, the context and characterisation of aesthetic emotions can vary significantly[30].

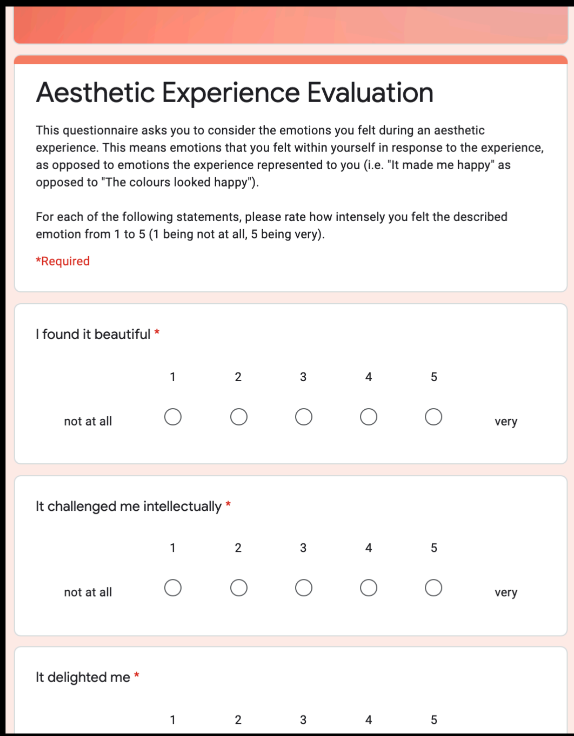
To tackle this lack of consensus, researchers Schindler et al. assessed a number of existing models of aesthetic emotions to synthesise a unified system of assessment. They noted that, typically, researchers have focused on general dimensions of emotion (such as valence or arousal) as opposed to emotions that are specific to aesthetic experiences[32]. This can be problematic in that aesthetic emotions are often complex and occur in combinations that contradict such general scales — for example, a sad song might feel both melancholy and cathartic.

Through their analysis, Schindler et al. produced AESTHEMOS (Aesthetic Emotions Scale), a comprehensive self-report questionnaire with a number of items relating to 21 subscales. Each subscale represents an emotional dimension — for example, relaxation or nostalgia — that together cover a wide range of pleasing, epistemic and prototypical aesthetic emotions. Each questionnaire item is formulated as a statement with which the participant can agree or disagree to a varying extent, using a typical Likert scale construction. In this way, AESTHEMOS gives quantifiable and nuanced insight into the emotional component of aesthetic experiences. I therefore reproduced the AESTHEMOS questionnaire in the form of an online survey (Figure 64), slightly adapting language to make it more accessible to nonnative speakers of English (in response to initial user testing). The AESTHEMOS could then be administered after testing a designed experience with a participant, to get a retrospective impression of its emotional impact, and therefore the degree of aesthetic resonance achieved as a whole. (The adapted survey in full can be viewed in Appendix C.) This information would help me to compare emotional responses across participants and iterate upon my design accordingly.

6.2.2 REAL-TIME REPORTING

Although AESTHEMOS could give me valuable retrospective information about the aesthetic emotions evoked by my design, it was not suitable for providing the real-time, interpretable participant feedback needed to optimise the experience dynamically. However, as previously discussed, aesthetic emotions are varied and often happen simultaneously. This meant that I needed to construct a multi-dimensional metric of aesthetic emotion: simplified enough to aid interpretability and comparison between participants, but nuanced enough to guide optimisation meaningfully.

As previously discussed, aesthetic emotions can be split into three categories: pleasing, epistemic and prototypical. Pleasing emotions relate to (sensory) pleasure, whilst epistemic emotions relate to meaning-finding. Prototypical emotions relate to a more general aesthetic appraisal[32]. As a result, they can be seen as less event-oriented than pleasing and epistemic emotions, and more tied to an experience as a whole (where "event" refers to a change in the aesthetic properties of an artefact) (Figure 65). The real-time metric would be used to adjust aesthetic properties of the experience throughout its duration, with each change producing a perceptual event. This meant that pleasing and epistemic emotions would be more helpful for optimising the experience for aesthetic resonance through these changes,


Aesthetic Experience Evaluation

This questionnaire asks you to consider the emotions you felt during an aesthetic experience. This means emotions that you felt within yourself in response to the experience, as opposed to emotions the experience represented to you (i.e. "It made me happy" as opposed to "The colours looked happy").

For each of the following statements, please rate how intensely you felt the described emotion from 1 to 5 (1 being not at all, 5 being very).

*Required

I found it beautiful *

	1	2	3	4	5	
not at all	○	○	○	○	○	very

It challenged me intellectually *

	1	2	3	4	5	
not at all	○	○	○	○	○	very

It delighted me *

	1	2	3	4	5	

Figure 64: An excerpt from the adapted version of AESTHEMOS I produced for retrospective analysis of my designed experience. The introduction to the survey highlights the distinction between represented and evoked emotions.

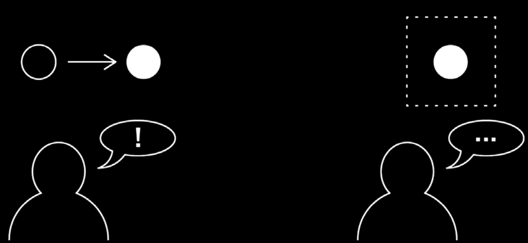


Figure 65: Pleasing and epistemic emotions are event-based (left), whereas prototypical emotions are reflective of a whole experience (right).

whilst prototypical emotions could be assessed using AESTHEMOS to inform future iterations of the overall experience design.

To construct the metric, I abstracted pleasing emotions to a scale of pleasantness (i.e. from unpleasant to pleasant), and epistemic emotions to a scale of engagement (i.e. unappealing to engaging). These two scales were combined to form a response grid with four quadrants. Although the grid does not allow for the expression of specific emotions, it enables a participant to indicate the strength of pleasing and epistemic emotions currently being felt. By using this metric to optimise for both, in addition to AESTHEMOS responses, it would then be possible to optimise for all three categories of aesthetic emotions and achieve aesthetic resonance as a result.

The metric was constructed using TouchOSC, a design platform for simple touchscreen interfaces with OSC (open sound protocol) communication. The TouchOSC interface (Figure 66) allows the participant to indicate their current aesthetic emotional state by moving a cursor around a grid space, with X and Y axes representing pleasantness and engagement, as explained above. The interface is designed to be operable without looking at the screen, so that a participant can focus on their audiovisual experience and thus report their response more accurately and responsively.

The current cursor position is reported with two coordinates from a range of -1 to 1, representing arbitrary scores for pleasing (X axis) and epistemic (Y axis) emotions. These coordinates are sent via OSC to my system control script, allowing them to be logged alongside other significant data — namely, properties of the audiovisual experience and metrics of neural resonance.

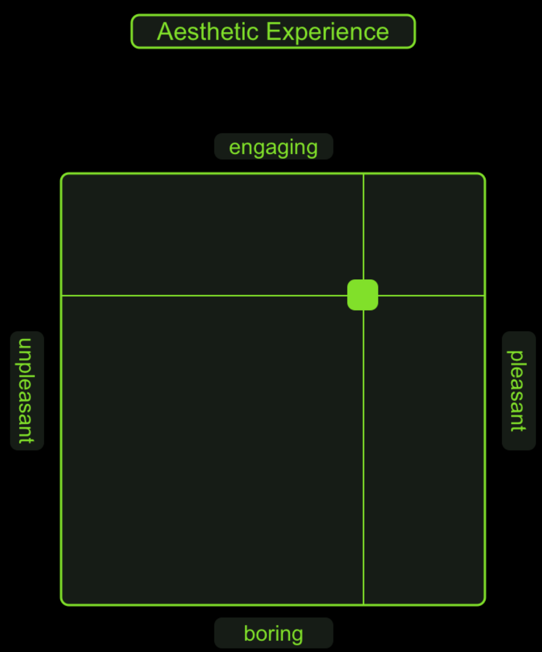


Figure 66: The TouchOSC interface created for simple, real-time measurement of participants' aesthetic emotions. The cursor position shown indicates presence of epistemic and pleasing emotions.

7

DESIGNING EXPERIENCE

This chapter recaps the insights gained from the previous chapter, setting out goals for the next design iteration. Some further literature is reviewed to guide the development of the second prototype, which is then described. User testing of the prototype is reported, with results and conclusions to carry forward into the final design.

7.1 ITERATION GOALS

7.1.1 INSIGHTS FROM PROTOTYPE 1

Having solidified my metrics of aesthetic experience, I returned to the insights gained from my first audiovisual prototype to guide my direction for the next major design iteration.

In my first prototype, I found that the narrative and framing of the experience greatly affected participants' perceptions and enjoyment of it. Both audio and visual components contributed to this narrative. As the complexity of a component increased, participants expected and looked for a greater degree of symbolism or meaning in the component. This presented a challenge in that (personal) meaning is essential to achieve aesthetic resonance, but what is meaningful can vary significantly between individuals. I therefore needed to develop an audiovisual experience that was considered in its **degree and presence of symbolism**, yet **ambiguous** enough to allow **individual interpretations**.

Participant feedback also showed that there was a tension of sorts between the audio and visual components of the experience. Participants noticed changes in the visualisation and reported emotional responses to these changes, but noted that the drone-like character of the audio made it quite demanding of their attention. They thus found themselves **switching their attention** between the two. This switching also seemed to be **event-related**, in that a change of the aesthetic properties of either the visual or audio prompted participants to transfer the majority of their attention to it. If the two were perceived as in competition with each other — that is, equally demanding of attention — some participants reported a feeling of overstimulation, which was described as a negative state.

This is significant in terms of experience design — should the audio or visual component be dominant? How does this influence the aesthetic experience of the design?

7.1.2 AESTHETIC ATTENTION

Research in perceptual psychology shows us that attention plays a major role in aesthetic experiences[34]. In particular, the complex nature of an aesthetic experience means that our attention is often distributed across its many properties, judging and weighing them to appraise the experience as a whole[34].

Aesthetics scholar Nanay posits that aesthetic attention may be either focused or distributed. Moreover, attention can be applied on an object or property level; that is, attention to a specific object compared to other objects, or attention to the aesthetic properties of any number of objects[34]. For example, looking at a meadow of flowers and noticing they are all the same colour demonstrates distributed object-level and focused property-level attention. In contrast, noticing the colour, texture and number of petals of a single flower shows focused object-level and distributed property-level attention. Nanay argues that this second example can be considered an aesthetic experience: a minimal number of aesthetic artefacts with rich and diverse aesthetic properties (Figure 67).

My first prototype showed that oscillatory audio captured the attention of participants and had significant impacts on their subjective experience. Sound — particularly ambient sound — can be at once highly symbolic and open to interpretation: an important characteristic for achieving aesthetic resonance, as discussed in the previous section. With this in mind and considering the insights gained from my first prototype, I decided to prioritise the audio component of my designed experience.

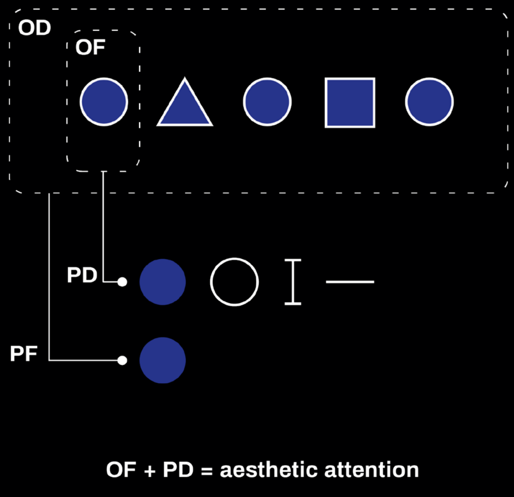


Figure 67: When attention is focused at the object level (OF) and distributed at the property level (PD), it can be considered aesthetic[34].

7.1.3 DESIGN FOCUS

As a result of my findings from my first prototype and from literature, I defined the scope of my second prototype as follows:

> **an ambient soundscape with an adjustable oscillatory component that aims to produce both neural and aesthetic resonance.**

To achieve this, the soundscape needed to have the following three features:

1. **Layered, changeable properties**, to produce aesthetic attention;
2. **controllable sound dimensions**, to optimise for aesthetic resonance;
3. a **controllable frequency component**, to optimise for neural resonance.

7.2 PROTOTYPE 2: DRONE

7.2.1 PROPERTIES AND GOALS

Prototype Design

My second prototype, *Drone*, is a generative ambient soundscape that is designed to explore the possibilities of neural and aesthetic resonance.

The soundscape is constructed in MAX/MSP, using a number of sine wave synthesisers and various audio effects to create a layered, textural sound quality (Figure 68). The input frequencies for the synthesisers are conversions of musical notes, organised in 3-note chords by key. When controlling the sound, one can select a key (for example, E minor) that triggers the system to randomly select a chord to feed to the synthesisers. Each synthesiser then selects a note from this chord to play as a frequency. By adjusting the volume of the synthesisers individually and in groups, the tone and texture of the soundscape can be controlled. This combination of multiple synthesisers is known in music as an “additive synth”.

The additive synth is accompanied by an abstract melody, composed of randomly selected notes from the current musical key. Each note is played for a random number of seconds, but with equal attack, sustain and decay periods. This mean that each note fades in and out smoothly regardless of its duration. Other background effects can also be controlled, such as white and pink noise, to adjust the character of the sound. The soundscape is thus designed to have a **layered, changeable and controllable character**, as outlined in the previous section.

Overlaid on these musical elements is an amplitude modulated tone, as used in my first prototype. The tone consists of a sine wave carrier tone (at 400Hz), modulated in a range of 5-40Hz. The current modulation frequency can be controlled using a slider. The modulated tone acts as an entrainment stimulus and

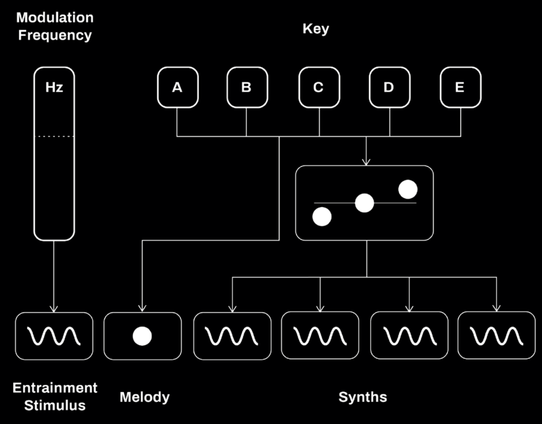


Figure 68: A simplified control diagram of my generative ambient soundscape.

can be adjusted according to the participant's neural activity to **evoke neural resonance**. The tone also pans from left to right as it fades in and out, giving the soundscape a sense of movement and dimension.

As in my first prototype, my neural resonance system would be used to optimise for neural response in real-time. I adjusted this system and the data display to include a live plot of the aesthetic emotion metric I had developed (Figure 69), to give an overview of both the neural and aesthetic impact of the soundscape, and to help me optimise both (Figure 70).

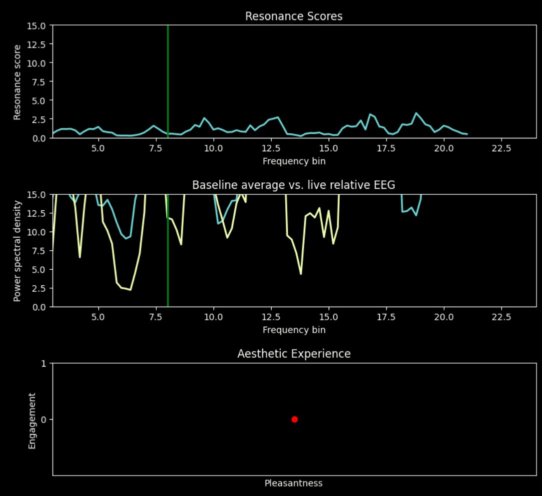


Figure 69: The updated data display for my resonance measurement system, including my new metric of aesthetic experience (the bottom graph).

<u>**Testing Goals**</u>

My primary goal for this user test was to explore whether it was possible to evoke neural and aesthetic resonance with my soundscape. More specifically, my research questions were:

1. Does a **simple oscillatory audio** stimulus still produce **neural resonance** when embedded in a soundscape?
2. Can the **designed soundscape** be optimised for **aesthetic resonance**?
3. Can the soundscape evoke **neural and aesthetic resonance simultaneously**?

7.2.2 USER TESTING

<u>**Method**</u>

4. Participants (n=5, 5 female) were recruited using convenience sampling. All participants were students at TU Delft's Industrial Design Engineering faculty. All participants were screened for any health conditions that could make exposure to oscillatory stimuli problematic for them.
5. Participants were fitted with an Enobio 8-channel device (channels P7, PO3, Oz, PO4, P8, Pz, C3 and C4).
6. Participants were seated, wearing earphones connected to a nearby PC. They were familiarised with the purpose of the test and

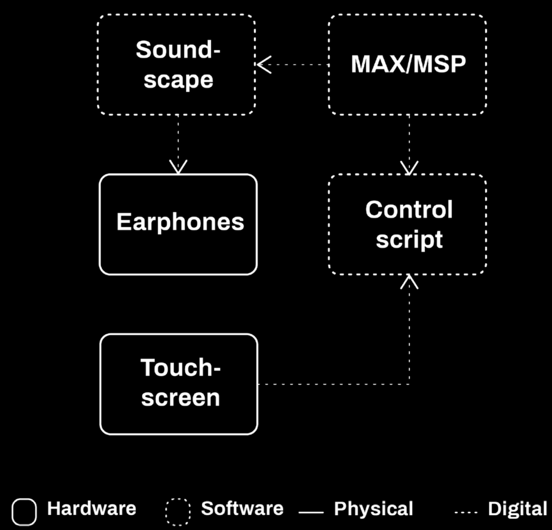


Figure 70: Information flow between the hardware and software used to control the stimuli and log resonance data (both neural and aesthetic).

the TouchOSC interface.

7. For the first minute of the experience, baseline EEG was collected and processed as before. No sound was played during this time and participants' eyes were closed.
8. A 3 minute listening session was conducted. Using the live plot and Processing interface, I performed an approximate hill-climbing approach for both neural and aesthetic resonance, adjusting the amplitude modulation frequency and sound properties respectively.
9. Participants listened to the soundscape for one minute without providing aesthetic data to familiarise themselves.
10. For the following two minutes, each participant was asked to continuously report their aesthetic experience using the TouchOSC interface, keeping their eyes closed as much as possible.
11. After the listening session had concluded, each participant completed my adapted version of AESTHEMOS. We then briefly discussed their experience.

Results & Analysis

As there were several data types to explore in my results, I structured my analysis around the three research questions I composed for this test.

1. **Does the amplitude modulated tone produce an entrainment effect?**

To investigate this, I compared baseline and experimental data for each participant, looking firstly for the participant's baseline peak alpha, and then examining a range around this in the experimental data. Some participants' data was broadly inconclusive in this respect, whilst others' appeared to show entrainment effects when the modulation frequency was close to their baseline peak alpha. For example,

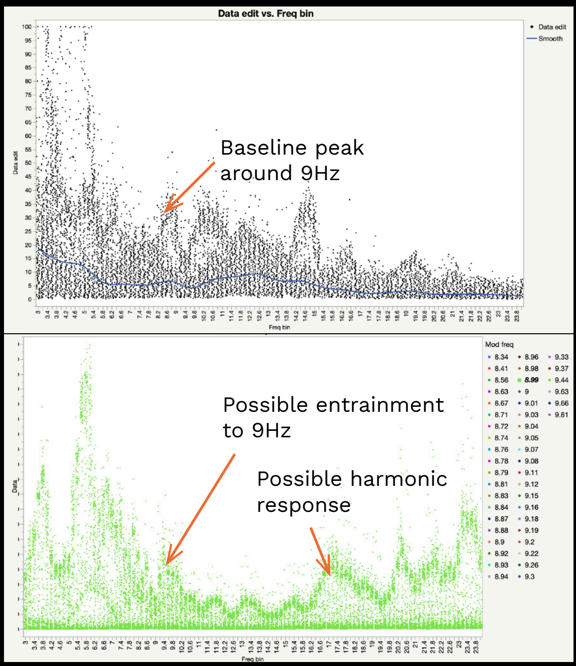


Figure 71: Baseline (top) and experimental (bottom) neural response for one participant.

Figure 71 shows one participant's baseline and experimental data (top and bottom graphs respectively). In the top graph, we can see a clear baseline peak in the region of 9Hz. In the bottom graph, we also see a peak in this region when a modulation frequency of approximately 9Hz is applied. There is also the greatest number of datapoints at this modulation frequency, with the datapoints themselves showing increased neural activity across all frequency bins. This is reflective of the hill-climbing approach I took to optimising for neural resonance: I explored a range around 9Hz and found a peak response within this, then kept the modulation frequency the same for the rest of the session to maintain the resonance response. Similar results can be seen in Figure 72, showing the baseline and experimental data of a second participant.

Overall, the participants' neural data suggested that:

- The entrainment stimulus embedded in the soundscape **could induce an entrainment effect**, and additionally that **optimising** its frequency to baseline peak alpha could produce **neural resonance**.

However, the limited number of participants and presence of inconclusive data meant that further testing would be needed to confirm this.

2. Can the soundscape be optimised for aesthetic resonance?

As expected, the aesthetic data for each participant was highly individualised. Some participants' data showed strong positive correlation between pleasantness and engagement (e.g. Figure 73), whereas others' were more inconclusive(e.g. Figure 74). This suggests that, although it is possible to optimise for pleasantness and engagement in the same audio design, what increases one does

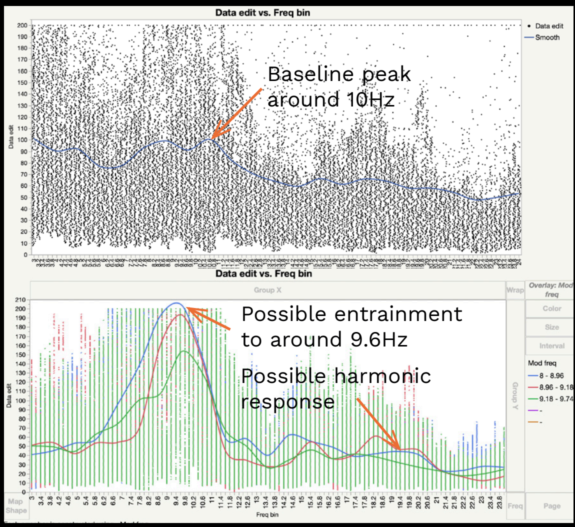


Figure 72: Baseline (top) and experimental (bottom) neural response for another participant.

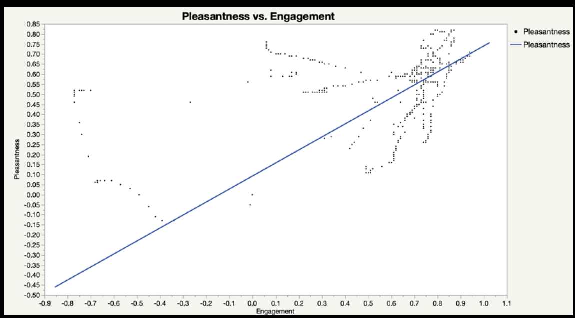


Figure 73: Positive correlation between pleasantness and engagement scores of one participant. In this case, the points in the top right of the graph show aesthetic optimisation.

not necessarily increase the other (and vice versa). The data did generally show, however, that steep peaks and troughs in the aesthetic data usually coincided with a change in the soundscape — either the modulation frequency or a musical feature, such as key (see Figure 75).

From this data, it is possible to (tentatively) make two interim conclusions:

- The **controllable parameters** in the soundscape had **measurable effects** on participants' aesthetic experience;
- The **real-time aesthetic metric** is sufficiently **responsive** to show how changes in these parameters affect aesthetic experience.

To get a better overall understanding of the participants' aesthetic experience, I analysed their AESTHEMOS responses (Figure 76). I grouped their responses to each item and categorised them by the type of aesthetic emotion represented (pleasing, epistemic or prototypical). All three would need to be scored highly to constitute aesthetic resonance. (Each item was scored with a rating of 1-5.)

The most highly rated (i.e. most strongly felt) emotions were:

- relaxation;
- calm;
- liking;
- mental engagement;
- delight;
- interest.

These statements all received average scores of 4 or higher. Additionally, the top three emotions (relaxation, calm and liking) all had ranges of 1, meaning the scores given for these emotions were highly consistent across

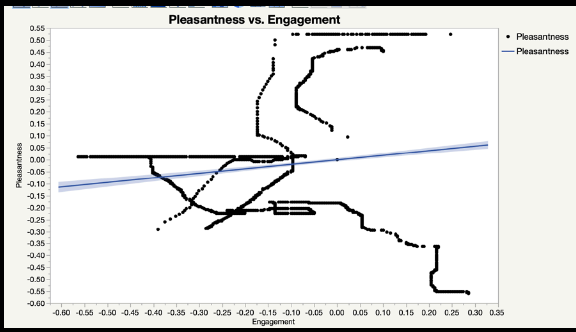


Figure 74: Slight positive correlation between another participant's pleasantness and engagement scores.

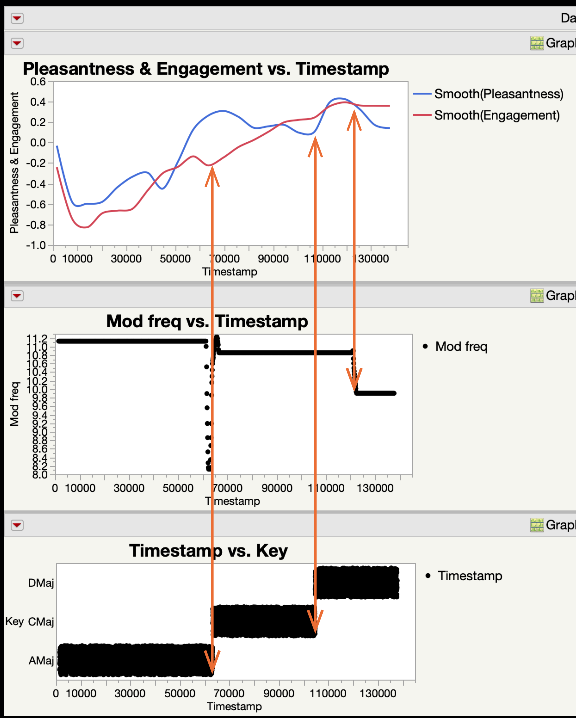


Figure 75: Sudden changes in pleasantness and engagement appear to be prompted by changes in audio properties.

participants. In terms of emotion types, the top statements included 3 pleasing, 2 epistemic and 1 prototypical. This suggests that:

- **the experience was able to elicit a form of aesthetic resonance** as it fulfilled all three emotion categories.

Despite this, pleasing and epistemic emotions were felt more strongly, leaving room for improvement in the prototypical category (e.g. beauty).

It was also interesting to note that the experience was consistently characterised as both relaxing and engaging. This might be compared to a meditative practice, in which the mind is focused but in a state of low arousal.

The lowest rated (i.e. least strongly felt) emotions were:

- worry;
- aggression;
- anger;
- sadness;
- distaste;
- ugliness;
- unsettledness.

These statements all received average scores of 1.5 or lower. All of the lowest-rated statements were in the AESTHEMOS category of negative emotions.

Additionally, the bottom three statements (worry, aggression and anger) all had ranges of 1, meaning scores were relatively consistent between participants. This is a **positive indication of the experience quality**, as it means that the experience did not strongly evoke negative emotions in participants, but did strongly evoke a range of aesthetic emotions

Statement	Average score	Range		
It relaxed me	4.8	1		negative
It calmed me	4.6	1		misc
I was mentally engaged	4.2	3		prototypical
I liked it	4.2	1		pleasing
It sparked my interest	4	3		epistemic
It delighted me	4	2		
It made me curious	3.8	3		
I was impressed by it	3.8	2		
I was enchanted	3.6	4		
I found it beautiful	3.6	2		
I found it sublime	3.6	1		
It made me happy	3.4	3		
I felt moved	3.4	2		
It made me feel melancholic	3.4	2		
I sensed a deeper meaning	3.4	1		
It made me feel sentimental	3.4	1		
It touched me	3.4	1		
It fascinated me	3.2	3		
It made me feel wonder	3	4		
It invigorated me	3	3		
It challenged me intellectually	2.8	3		
It made me feel nostalgic	2.8	3		
It surprised me	2.8	3		

Figure 76: An excerpt of AESTHEMOS response analysis, showing a range of different aesthetic emotions present in the experience.

with positive affect (i.e. prototypical, pleasing and epistemic).

3. **Can the soundscape evoke neural and aesthetic resonance simultaneously?**

Although the soundscape was able to evoke both neural and aesthetic resonance, whether they consistently occurred simultaneously was less clear. Comparing neural response generally to aesthetic scores was not particularly helpful as neural activation could be indicative of many things, depending on the frequency bin in question. Because of this, I restricted neural response data to a range of 1Hz either side of the participant's baseline peak alpha. This would enable me to compare resonance activity with the aesthetic data.

Figure 77 shows one participant's neural and aesthetic data, plotted against time. Although the data appears somewhat inconclusive, we can see a period of heightened neural resonance that aligns with an increase in both pleasantness and engagement scores, and the changing of the modulation frequency to around the participant's baseline peak alpha (11Hz). Although this is only one example and may not be representative of any relationship between the three, it at least suggests that:

- It is **possible to produce neural and aesthetic resonance simultaneously** using the designed soundscape.

7.2.3 NEXT STEPS

Overall, my user testing suggested that my generative soundscape was **able to produce both neural and aesthetic resonance**, and was generally perceived as a **positive and engaging experience** by my participants. My real-time metric of aesthetic response also functioned well and, along with my neural resonance system, enabled me to optimise the

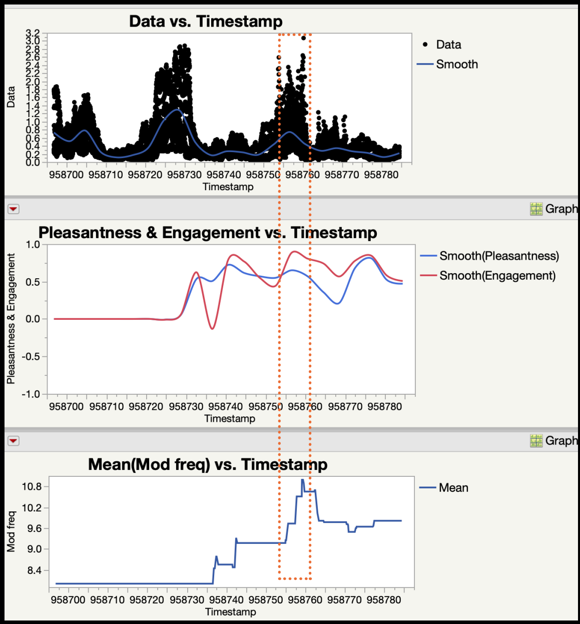


Figure 77: Neural and aesthetic data for one participant, plus modulation frequency, plotted against time. The neural data was restricted to a small range around their peak alpha to represent resonance. Some possible overlap between neural and aesthetic resonance can be seen.

soundscape on an individual basis.

Conversations with the participants post-testing were also illuminating in terms of next steps for design. Each participant had different mental associations with the soundscape, but they saw its interpretability as a strength — the ambiguous, changeable nature of the soundscape encouraged their **imagination and curiosity**. Additionally, the overlapping tones, randomised timing and panning effects were all reported as highly positive elements. According to the participants, they created a **powerful sense of space**. The only downside to the soundscape was its **limited range of chords**, which could result in a drop in engagement over time.

I also asked the participants whether they would want to have a visual component incorporated into the experience. Although the reaction to this suggestion was positive, the participants perceived the soundscape as quite complex and said they would **want the visualisation to be a secondary, complementary element**. They thought it could heighten the aesthetics of the experience but should not be demanding of their attention.

With this feedback and my user testing in mind, I set out the following design recommendations for my final design iteration:

- The **soundscape** should retain its general musical character, but be **expanded** with more musical keys and more noticeable changes in its sound components over time.
- A **complementary visualisation** should be designed to **amplify the soundscape's effects** and bring its spatial quality into a physical dimension.
- Although the **data collection** systems appear to work well, more thought should be given to the **participant's experience** of them and how this can be designed.

8

FINAL DESIGN

This chapter details the final design, developed as a result of previous explorations. It documents the building of a functional final prototype and the testing thereof with participants.

8.1 INSTALLATION DESIGN

8.1.1 SOUNDSCAPE

Through my second prototype, I was able to create a generative soundscape that could be optimised for both neural and aesthetic resonance. My user testing suggested that I should maintain the character of the soundscape and focus on expanding its range with additional musical keys and background elements.

I added a variety of music keys, both major and minor, to the MAX/MSP controls for the soundscape. Additionally, I added more chords to each key, as well as implementing some simple selection rules for key changes based on the circle of fifths.

Finally, I expanded the range of properties logged to increase the granularity of collected data and to allow for multivariate correlation analysis between these audio properties and resonance data in future.

8.1.2 VISUALISATION

Participants who tested my second prototype suggested that a complementary visual element could amplify the aesthetic effects of the soundscape. When asked to describe what this visualisation might look like for them, participants tended to describe abstract forms and geometry, with some movement to reflect changes in the soundscape, but not so much as to become distracting.

I then considered how the visualisation could physically manifest whilst staying secondary to the soundscape. A screen or projection would not necessarily be suitable, as these forms have very direct modes of interaction; we expect to watch them and receive information. Instead, I considered creating a physical light source (Figure 78). Light is atmospheric, changeable and aesthetically powerful, but can easily recede into the background when other senses are engaged.

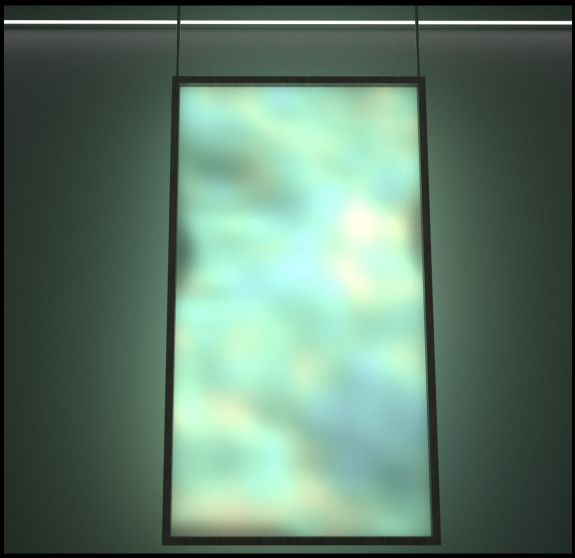


Figure 78: Rendered model of the designed light source. A coded visualisation is mapped to a matrix of LEDs, diffused by acrylic.

However, the light source would still need to be linked to the soundscape in some way to complement it and translate its character to a visual form. To achieve this, I decided to create an abstract screen-based visualisation that could be mapped to a matrix of LEDs. These LEDs would be mounted in a frame that could be covered with diffusive material, resulting in an atmospheric and subtly evolving light source.

The visualisation, made using p5 (a browser-based Javascript environment), consists of a particle field (Figure 79). This is essentially a simulation of how physical particles behave — each coded particle moves closer to or further from its neighbours in an organic way. This movement is controlled by Perlin noise, an algorithm that simulates natural variation and grouping behaviours. The speed at which these particles move is controlled by the current modulation frequency in the soundscape, whilst the saturation of the overall visualisation increases and decreases with neural resonance scores. The particles also change colour according to the musical key of the soundscape. As a result, the visualisation is abstract but inherently tied to the participant's experience of resonance, and an expression of resonance in physical form.

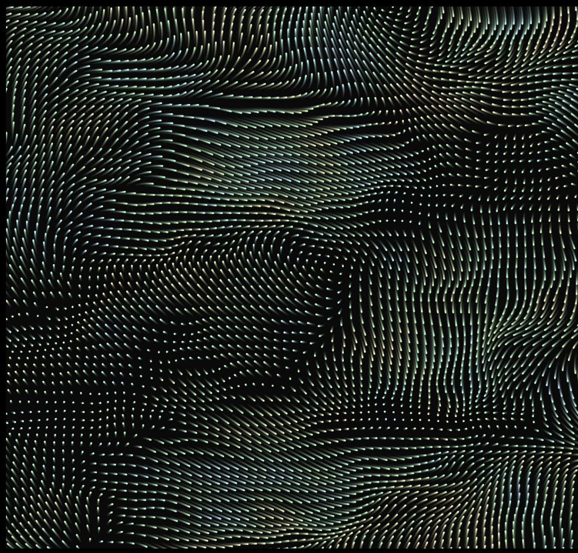


Figure 79: An organic, abstract visual undulates gently in response to both the soundscape and the participant's resonance data.

8.1.3 SPACE

The physical installation is split into three stages, with three corresponding spaces. The first is a reception space, where the designer receives participants and briefs them on the installation experience (Figures 80, 83). The space also contains some textual information giving context of the installation and motivations behind it.

The second space is an antechamber of sorts. In this room, lighting is used to create an illumination level somewhere between the bright openness of the reception space and the darkness of the third space beyond it (Figures 81, 84). In this space, the participant is fitted with the EEG headset and earphones by the designer, and given a touchscreen device on which to use the TouchOSC interface for aesthetic ratings. The designer explains this interface and then leaves the space. This intermediate stage is intended to sensitise the participant and prepare them for the resonance experience, whilst giving the designer an opportunity to check that all technical system components are working correctly, and to calibrate the EEG data collection.

Finally, the participant moves into the third space: the 'resonance chamber' (Figures 82, 85). This room is dark save for the installation itself, which begins as a plain white monolith. The participant sits in front of it and their baseline EEG is recorded for one minute whilst their eyes are closed. When the baseline period is concluded, the monolith comes to life, with colours and abstract shapes slowly filling the white space. At the same time, the soundscape fades in through the earphones, gently easing the participant into the audiovisual experience. Over the course of the following five minutes, the participant and designer co-compose the audiovisual experience through a data feedback loop. The space is purposely dark and modest in size, to maximise the impact of the audiovisual components and create a private, protected atmosphere that encourages the participant to fully immerse themselves in the experience.

Once the resonance experience has concluded, the monolith and soundscape slowly fade. The participant is received by the designer again in the antechamber space, returns the various hardware (EEG headset, earphones and touchscreen device), and is debriefed by the designer, who administers the AESTHEMOS questionnaire.

Figure 80: In the first room, the participant is briefed on the experience.

Figure 81: As the participant enters the second room, they are fitted with the EEG headset and earphones, and given the TouchOSC interface, which is then explained to them.

Figure 82: The final room is a 'resonance chamber' — a space to experience resonance through body and mind.

Figure 83: The first space of the installation journey, in which participants are received and sensitised.

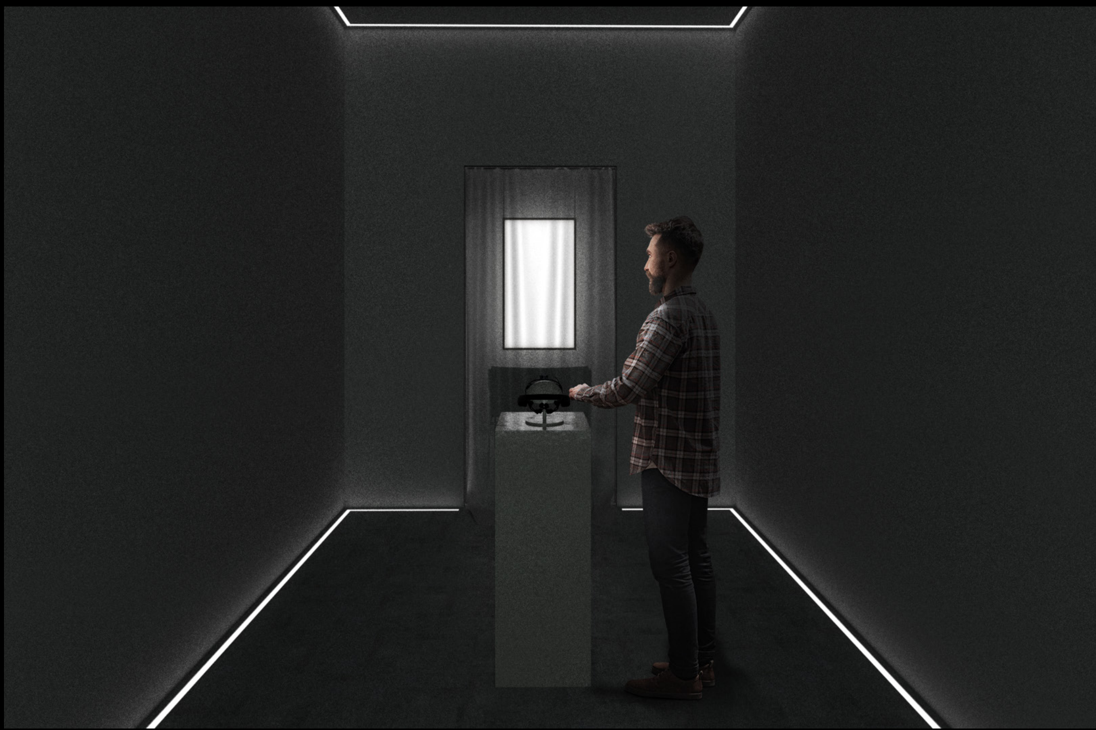


Figure 84: The second space of the installation, in which a participant is fitted with the EEG cap and briefed on the experience.

Figure 85: In the third and final space, the participant is surrounded by sound and light.

8.2 FINAL PROTOTYPE

8.2.1 SPECIFICATIONS

To evaluate my final design, I needed to create a physical prototype that would recreate the envisioned exhibition experience as well as possible within the scope of the project. The scope of this prototype was heavily influenced by the limitations of COVID-19; although I had originally planned to use a public exhibition space, I was restricted to the space and resources available at my faculty. I decided to then focus on producing the audiovisual components of my design to the highest fidelity possible in my time frame, so that the prototype would create an impactful experience regardless of its location.

My prototype would therefore consist of a light source and a soundscape. For the **light source**, my specifications were as follows:

- **controllable and addressable**, to translate the visualisation into light;
- **diffused**, to soften shapes and movements;
- **self-contained**, to allow portability.

For the **soundscape**, I set the following specifications:

- **responsive**, to allow for real-time optimisation;
- **connected**, to allow transmission of data to the visualisation and real-time data display.

8.2.2 BUILD PROCESS

Based on the specifications identified above, I designed and built a physical light source, consisting of a supporting frame, diffusion material and a matrix of addressable LEDs (Figure 87). The LEDs are connected via a FadeCandy microcontroller to a PC, which maps the p5 visualisation (as previously described) to the LED matrix, controlling their colour and brightness. This means that changes in the visualisation that are linked to the soundscape are also expressed in real-time through the physical light source (Figures 89, 90, 91). The light source is powered by a 5V supply that can be connected to mains electricity using a standard wall plug (Figure 88). As a result, the whole system is relatively portable and simple to adapt once constructed: with a few lines of code, any kind of visualisation in any programming language can be mapped to the LED matrix.

Key information about the current soundscape is sent directly to the Python control script via OSC, as are aesthetic resonance scores (engagement and pleasantness) from the TouchOSC interface (Figure 86). This makes data collection simple and centralised — in principle, any number of data sources could be connected to the system in this way. As a result, the final prototype can be used in a number of ways to test the aesthetic and neural resonance embodied by audiovisual designs.

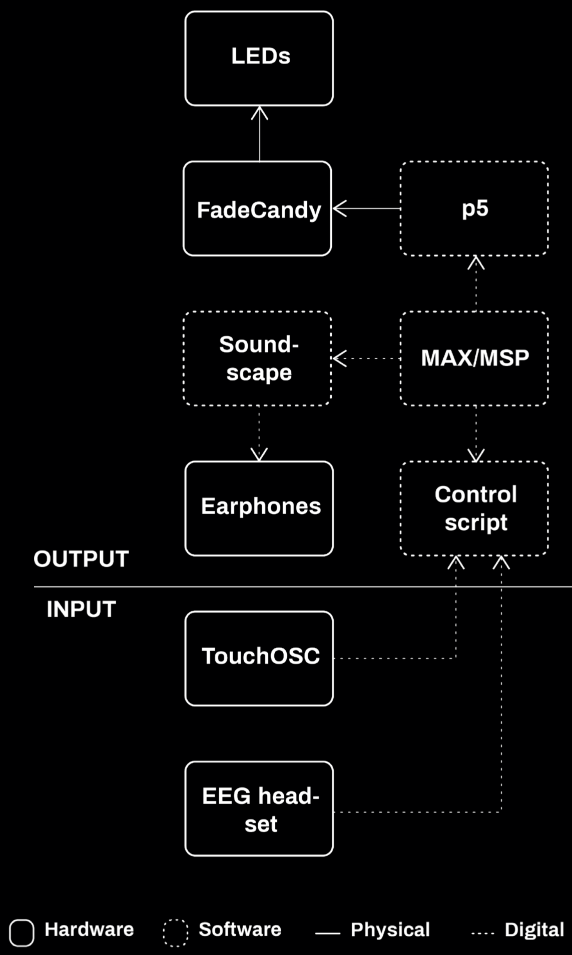
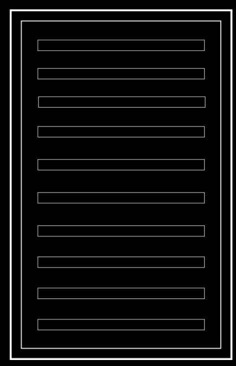


Figure 86: Information flows in the final prototype for controlling the audiovisual outputs.

A BACKING BOARD
B LED STRIPS (X 10)
C FRAME
D DIFFUSION MATERIAL



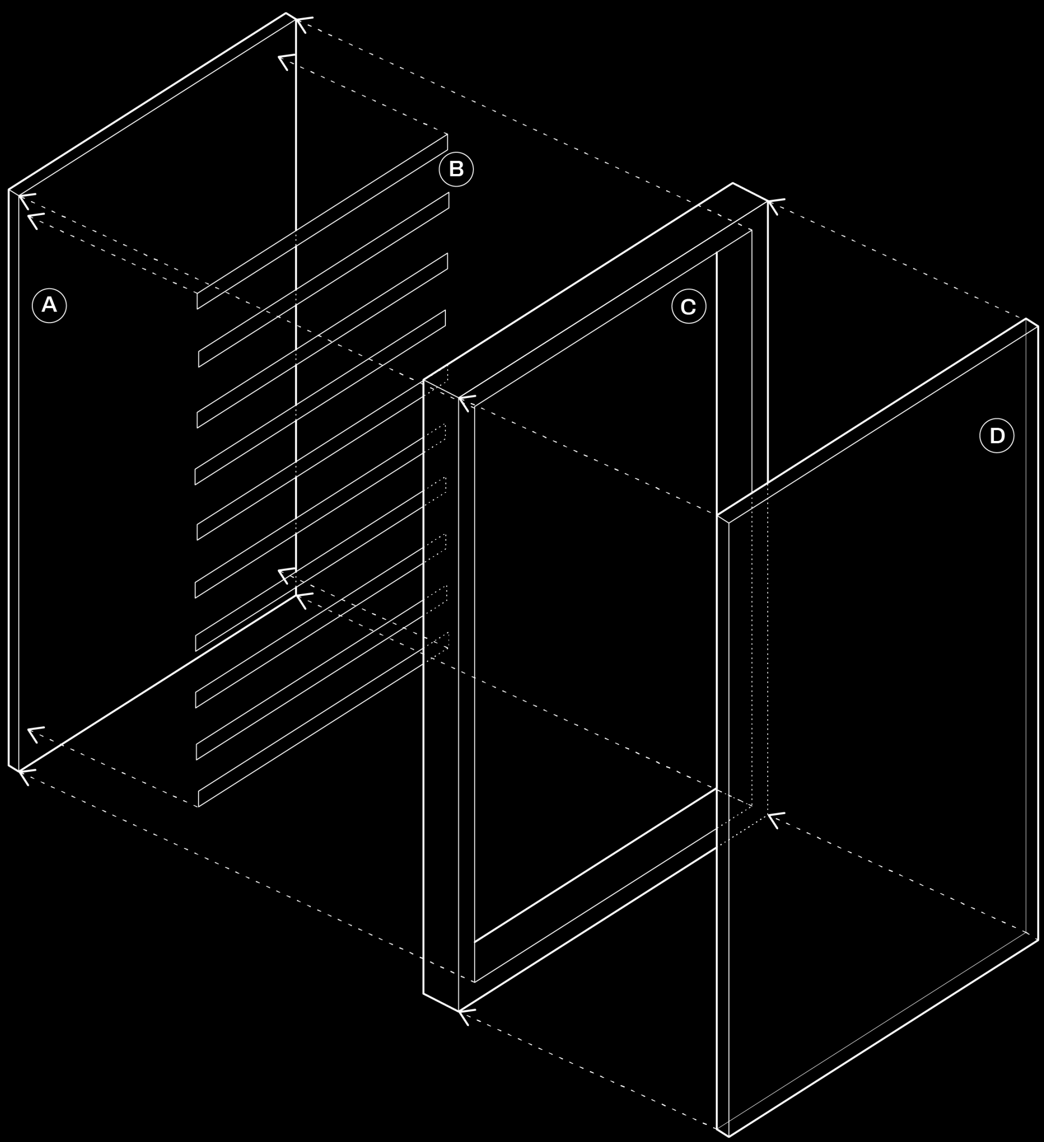


Figure 87: Schematic of the final physical prototype. The frame holds a matrix of addressable LEDs, diffused by acrylic, that together create an atmospheric light source.

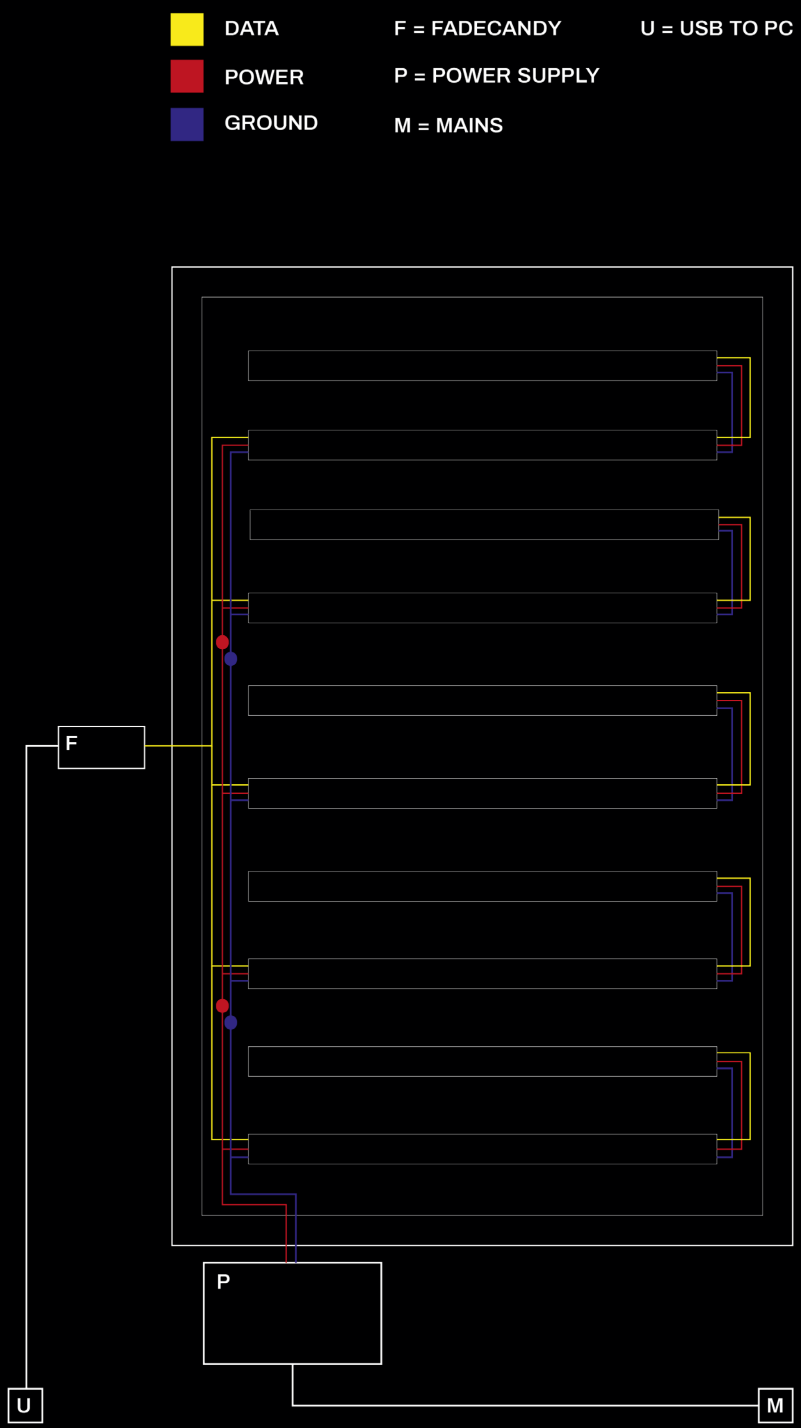
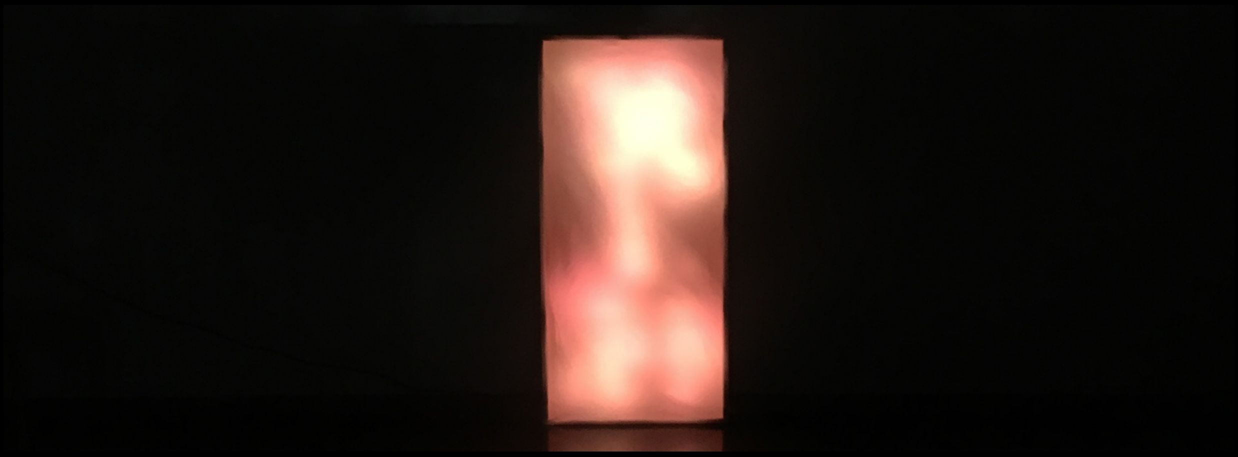


Figure 88: Wiring diagram of the final prototype. Data from a computer via USB is sent to a FadeCandy board, which distributes this to the LEDs. Power and ground are supplied by a 5V power supply.

Figures 89, 90, 91: Photos of the final prototype. A FadeCandy board is connected to a p5 sketch and maps this sketch to the LED matrix. The LEDs change colour with the key of the soundscape.



8.3 FINAL USER TEST

8.3.1 SETUP & GOALS

Once my final prototype was complete, I prepared it for user testing. Due to COVID-19 restrictions I was unable to test within a gallery setting as originally intended, so I instead used studio space available to me at my faculty (Figure 92). The space was sufficiently unembellished for the prototype to be experienced properly, although all three spaces in the exhibition design (as outlined earlier in this chapter) naturally had to be recreated in the same environment.

My final user test was designed to evaluate my prototype, and by extension my final design concept, in relation to my hypothesis that I set out at the beginning of the project. To reiterate, my hypothesis was defined as follows:

It is possible to design an experience that simultaneously elicits neural and aesthetic resonance.

I then defined three test-specific research questions with which to approach this hypothesis:

1. Does the designed experience **produce neural resonance**, and to what extent?
2. Does the designed experience **produce aesthetic resonance**, and to what extent?
3. How successfully does the design concept **enable simultaneous optimisation** for both forms of resonance?

8.3.2 METHOD

1. Participants (n=5, 3 female) were recruited using convenience sampling. All participants were students at TU Delft's Industrial Design Engineering faculty. All participants were screened for any health conditions that could make exposure to oscillatory stimuli problematic for them.

Figure 92: The final user test setup. The prototype was displayed in a suitably plain and dark space to allow the prototype itself to create the atmosphere.

Figure 93: A participant indicating their aesthetic experience using the TouchOSC interface, whilst their neural response is recorded using the EEG headset.

2. Participants were fitted with an Enobio 8-channel device (channels O1, O2, P3, P4, Pz, C3, C4 and Cz).
3. Participants were seated in front of the light source. They were familiarised with the nature of the experience and the TouchOSC interface.
4. For the first minute of the experience, baseline EEG was collected and processed as before. No sound was played during this time and participants' eyes were closed. The light source was set to white.
5. The light source and soundscape were then activated and played for 4 minutes. Participants listened to the soundscape and watched the light source, indicating their aesthetic experience using the TouchOSC interface (Figure 93).
6. Using the live plot and controls for my generative ambient music, I performed an approximate hill-climbing approach to optimise for both neural and aesthetic resonance, adjusting the amplitude modulation frequency, sound properties and visualisation (Figure 94).
7. After the session had concluded, each participant completed my adapted version of AESTHEMOS. We then briefly discussed their experience.

8.3.3 RESULTS & ANALYSIS

As might be expected, results varied significantly on an individual basis, from neural response to aesthetic preference.

Neural Resonance

Overall, the experience was **successfully optimised for neural resonance** for four out of the five participants. There was individual variability in terms of the particular resonant frequencies and the number of these frequencies at which resonance occurred.

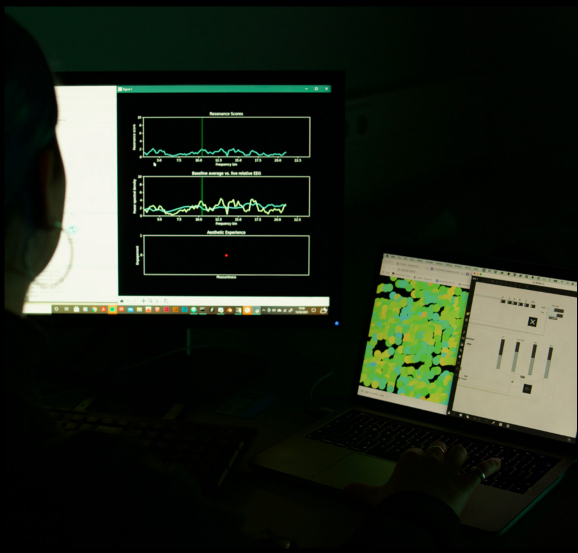


Figure 94: The soundscape is adapted using live controls in MAX/MSP, which in turn control the colour and movement of the light source.

For example, the first participant of the four only exhibited resonance at one frequency (11Hz) (Figure 95), whereas the other three participants showed resonance at two frequencies (Figure 96). In all cases these frequencies were either represented as peaks in their baseline activity, or fell within a small range (±1Hz) of peak baseline activity. For each of the four participants a noticeable response was present at the fundamental (same as stimulus) frequency, but the strength of response at the first harmonic (double stimulus frequency) varied. These results suggest that **targeting a small range around peak (alpha) activity in a person's baseline** EEG is a good technique for optimising for neural resonance.

The real-time aesthetic scores were plotted against stimulus frequency to see if there was a relationship between the two on an individual and general basis. The first participant's scores showed positive correlation between aesthetic scores and stimulus frequency (Figure 97), with the most consistently high scores given at around their resonant frequency (10.5Hz). However, the other participants' data showed either negative correlation or no discernible correlation at all. Additionally, there was **no clear indication of aesthetic preference for neurally resonant frequencies** and the range of aesthetic scores was large for all stimulus frequencies. From this information it seems reasonable to conclude that there is not a clear-cut relationship between stimulus frequency and aesthetic experience — or at least not one that can be observed in the current data.

However, two of the five participants' data showed clear **alignment between peaks in neural resonance and aesthetic resonance** over time. Figure 98 shows one of the two participants' aesthetic scores plotted with their neural resonance scores at the first harmonic (i.e. a measure of the strength of their neural resonance response). The majority of peaks and

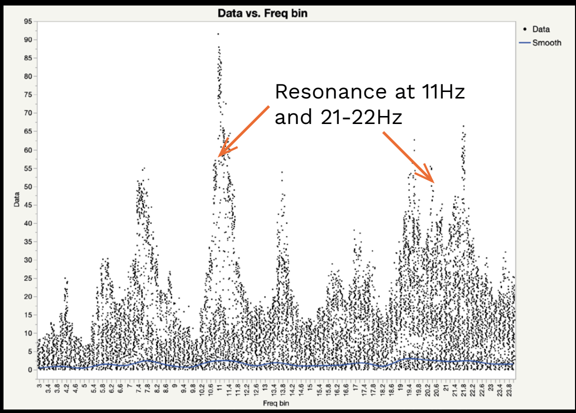


Figure 95: The first participant's neural resonance scores, showing a peak around 11Hz evoked by a 10.5Hz stimulus. Some activity is also visible at the first harmonic (21-22Hz).

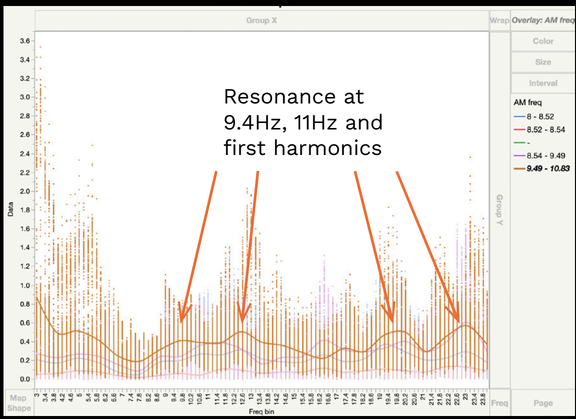


Figure 96: The fifth participant showed neural resonance responses at both approximately 9.4Hz and 11Hz, with first harmonic responses also present for both frequencies.

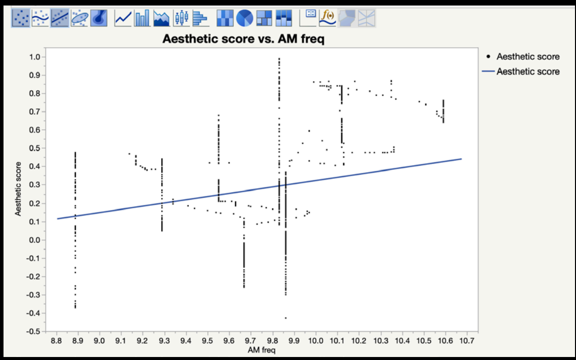


Figure 97: The first participant's data showed some positive correlation between aesthetic scores and stimulus frequency.

troughs in the two plots are closely aligned. This is intriguing as it suggests that the two might be linked in some way — perhaps neural resonance positively affects our aesthetic perception, or aesthetic resonance produces a heightened brain response. In any case, more data is needed to explore this further.

Aesthetic Resonance

The real-time aesthetic scores naturally varied a great deal depending on the individual and the current experiential conditions. However, it was possible to elicit and maintain high scores for both engagement and pleasantness through the design. As the experience is inherently temporal and changeable, averaging these scores is less helpful for examining the optimisation process. Even so, **average scores were positive for all participants**, which indicates that the designed experience was generally more aesthetically resonant (pleasant and engaging) than dissonant (unpleasant and boring).

Results from the AESTHEMOS questionnaire administered after the experience give more insight into this. Responses from the five participants were compiled and averaged per emotional statement, giving an average score from 1 to 5 (1 indicating the emotion was not felt at all, 5 indicating it was felt strongly).

The five most consistently, strongly felt emotions (Figure 99) were as follows:

- **Calmness**;
- **Liking**;
- **Relaxation**;
- **Beauty**;
- **Mental engagement**.

The statements all received an average score of at least 4 out of 5, with ranges of 1. These statements represent all three forms of aesthetic emotions: pleasing (calmness and

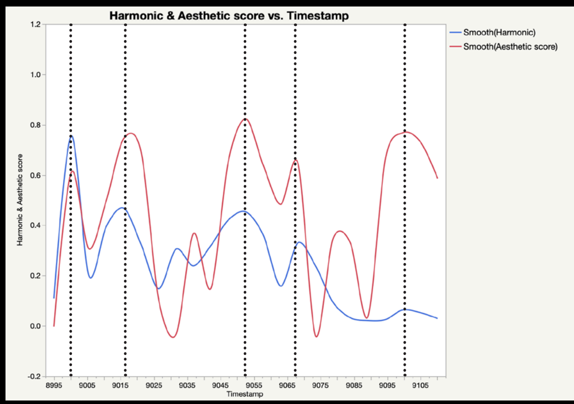


Figure 98: Data from two of the participants shows alignment between peaks in harmonic scores (i.e. neural resonance) and aesthetic scores (i.e. aesthetic resonance).

Statement	Average score	Range	
It calmed me	4.8	1	pleasing
I liked it	4.4	1	epistemic
It relaxed me	4.4	1	prototypical
I found it beautiful	4.2	1	misc
I was mentally engaged	4	1	negative

Figure 99: The five most consistently, strongly felt emotions from the AESTHEMOS responses indicate that the design evoked aesthetic resonance for all participants.

relaxation), epistemic (mental engagement) and prototypical (liking and beauty). From these results it can be concluded that the **design evoked aesthetic resonance consistently across the participants.**

The five most consistently, least strongly felt emotions (Figure 100) were as follows:

- **Aggression**;
- **Sadness**;
- **Anger**;
- **Distaste**;
- **Worry**.

The statements all received an average score of less than 1.5, with ranges of 0 or 1. All of these emotions are categorised as negative according to the AESTHEMOS framework, which suggests that the **experience was consistently perceived as positive and enjoyable** by the participants.

8.3.4 CONCLUSIONS

To conclude, I referred back to my three test-specific research questions to assess the outcomes of the final design.

1. **Does the designed experience produce neural resonance, and to what extent?**

From the results and analysis discussed in the previous section, it can be said that **the final design can successfully optimise for and produce neural resonance**. The live data display enables the designer to explore a range of potential resonant frequencies in an adaptive and iterative manner. The degree of neural resonance experienced may vary between participants, but generally there are clear responses at both the fundamental and first harmonic frequencies.

It worried me	1.4	1
I found it distasteful	1.4	1
It made me angry	1	0
It made me sad	1	0
It made me feel aggressive	1	0

Figure 100: The five most consistently, least strongly felt emotions are all negative, which indicates that the experience was positive and enjoyable overall.

2. **Does the designed experience produce aesthetic resonance, and to what extent?**

Both the real-time aesthetic scores and AESTHEMOS responses indicate that **the design consistently evoked aesthetic resonance across participants**, both during the experience and in retrospect. The live data display also enabled me to identify specific aesthetic preferences for some of the participants, such as light colour, musical key or pitch. This was done intuitively by exploring the audiovisual design space and noting real-time changes in the participant's aesthetic response. This also suggests that the platform I have created is **generative for designers** in rapidly testing aesthetic responses to experience designs.

3. **How successfully does the design concept enable simultaneous optimisation for both forms of resonance?**

It is clear from the results discussed above that **the final design is capable of evoking both neural and aesthetic resonance through the same audiovisual design**. However, the relationship between neural and aesthetic resonance is not clear from the data collected. The temporal synchronisation of neural and aesthetic resonance is not straightforward to determine, as the factors influencing both measures are not necessarily the same. For example, there was no consistent correlation found between aesthetic scores and stimulus frequency, which suggests that what causes neural resonance may not simultaneously cause aesthetic resonance — or indeed have any effect on conscious aesthetic appraisal.

There may, however, be statistical relationships between neural and aesthetic resonance scores present in the collected data that are simply not interpretable using typical methods. As the complexity of stimuli increases and so too does the granularity of responses, it will be necessary to implement more statistically

robust techniques for analysing the relationship between neural and aesthetic resonance.
A possible example could be **canonical correlation analysis (CCA)**, which identifies characteristics of multivariate data and finds the degree of correlation between them. This could help to better understand the complex relationship between the various components of the design space and the resonance response data.

9

PROJECT EVALUATION

This chapter evaluates the final design against my research questions and design goals, as defined in the first chapter. It discusses limitations of the work and opportunities for future research, then outlines the implications of the project for design. The chapter concludes with a personal reflection on the project and design process as a whole.

9.1 DESIGN EVALUATION

9.1.1 RESEARCH QUESTIONS

At the beginning of this project, I defined a general hypothesis: that **it is possible to simultaneously evoke neural and aesthetic resonance through a designed experience**. To investigate this hypothesis I defined three overarching research questions.

In order to evaluate the research outcomes of the project, I referred to these questions in turn:

1. **Can neural and aesthetic resonance be evoked simultaneously by periodic stimuli?**

From my final user test, it is clear that **periodic stimuli** — when embedded in an **aesthetically considered experience design** — can successfully evoke **both neural and aesthetic resonance**. This is significant as it suggests that typical periodic stimuli (such as flickering LEDs and droning sounds) can be redesigned to create meaningful and engaging experiences that contribute positively to a participant's general wellbeing beyond the physiological and psychological effects documented in neuroscience literature.

What is less clear is the temporal relationship between neural and aesthetic resonance; i.e. if both forms of resonance occur at the same time and in response to the same characteristics of audiovisual stimuli. Initial analysis from the data collected during the final user test suggests that **peaks in neural and aesthetic resonance can coincide**, but it is still unknown if this is a consistent phenomenon and whether there is a causal relationship between the two. Further data collection and statistical analysis are needed to explore the topic fully.

2. **Does peak neural resonance correspond with peak aesthetic resonance?**

As previously discussed, the relationship between neural and aesthetic resonance remains somewhat unclear, beyond the finding that **both can be evoked by the same designed experience**. Specific resonance frequencies were found, and particular aesthetic preferences were inferred, for the participants in the final test. This demonstrates that **it is possible to identify particular characteristics** — both quantitative and qualitative — of an audiovisual experience **that affect neural and aesthetic resonance**. There was some indicative data to suggest that **peaks in first harmonic response** (i.e. a component of neural resonance) may **align temporally with peaks in aesthetic resonance**. What is still unknown is how these forms of resonance might influence each other. As discussed in the previous chapter, more complex statistical analysis techniques such as CCA may help to investigate this further.

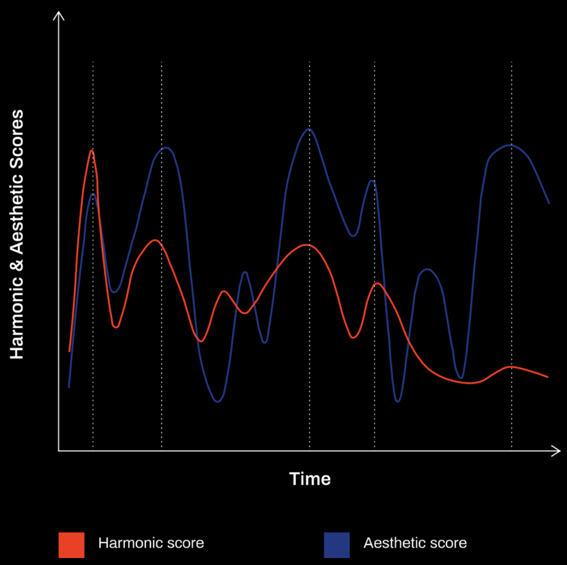


Figure 101: Data from some of the participants in my final user test suggests that peak neural resonance could coincide with peak aesthetic resonance.

3. How can both forms of resonance be embodied in an audiovisual experience design?

Throughout this project, the design process has been characterised by a tension between the requirements for accurate, consistent periodic stimuli and aesthetically pleasing experiences. Having successfully incorporated both into the final design, I have been able to identify some key considerations for designing neurally and aesthetically resonant experiences.

Firstly, the decision to move from visual to audio stimulation opened up the design space considerably. In using synthesisers to deliver my neural resonance stimulus, I was able to manipulate the aesthetic character of the stimulus in a much more nuanced and aesthetically pleasing way. My prototypes demonstrated how **periodic auditory stimuli can generate greater aesthetic engagement and more positive mental associations** than their photic counterparts. This decision also came with some drawbacks: audio stimuli produce much more complex and spatially distributed neural responses than basic flickering LEDs, which presented challenges for my neural resonance metric. However, by preserving the accuracy of my auditory stimulus and instead changing the melodic character of its carrier wave, I was able to evoke some degree of neural resonance whilst creating aesthetic pleasure and interest.

Secondly, my literature review indicated that a significant proportion of aesthetic emotions are triggered by change. This meant that it was essential to produce generative, controllable stimuli that enable full exploration of the design space and encourage aesthetic attention. Striking **a balance between consistent delivery of the neural resonance stimuli and evolution of aesthetic properties over time** is therefore essential. I achieved this in my final design by implementing an **attentional hierarchy**, prioritising the neural resonance stimulus and complementing it with the other audiovisual components. By making the visualisation dependent on and secondary to the soundscape, I was able to maintain a sufficient level of attention to the neural stimulus to produce resonance.

9.1.2 DESIGN GOALS

I defined the scope of this project using three overarching design goals, as follows:

1. Create a **personalised and engaging multi-sensory experience** that is driven by resonance;
2. Design **audiovisual stimuli** that are both **neurally and aesthetically resonant**;
3. Create an accessible system for **measuring and producing resonance** that is **generative for designers**.

I assessed the design outcomes of my work against each of these goals in turn.

1. **Create a personalised and engaging multi-sensory experience that is driven by resonance.**

The audiovisual experience produced as part of the final design is **inherently personalised** in that it is driven by an individual's (neural and aesthetic) data (Figure 101). Their aesthetic preferences are deduced using the real-time data display, which allows the designer to tune properties of the experience to optimise it on a personal level. As both the audio and visualisation are algorithmically generated based on the participant's resonance data, every session is unique to the individual who is experiencing it.

Both the real-time metric of aesthetic resonance and the AESTHEMOS questionnaire used in my final user test include measures of engagement. In both cases, the final design **successfully produced high levels of engagement across all participants**. This shows that the design is engaging during the experience and also perceived as such upon reflection.

2. **Design audiovisual stimuli that are both neurally and aesthetically resonant.**

Through my iterative prototyping process, I was able to develop an approach to audiovisual design that incorporates elements of typical periodic stimuli into a more aesthetically rich and changeable experience. My prototypes demonstrated how using amplitude modulated audio can produce neural resonance whilst evoking a range of aesthetic responses and mental associations.

I developed this further in my final design by embedding amplitude modulated audio in an algorithmically generated soundscape. The modulated audio was kept as the dominant auditory element to encourage attention to it, but was enriched and complemented by

Figure 102: The final design produces a unique, personalised audiovisual experience driven by a participant's resonance data.

textural, ambient sounds. The frequency of this modulated audio, in addition to selected musical properties of the soundscape, were used to control the colour, brightness and movement of an abstract light visualisation. The result was **a customisable, constantly evolving audiovisual experience** (Figure 103) that could be optimised for all participants using my real-time aesthetic metric, and was able to evoke all three forms of aesthetic emotions (pleasing, epistemic and prototypical) according to the AESTHEMOS results. In summary, the audiovisual components I designed were **successfully able to evoke both neural and aesthetic resonance**.

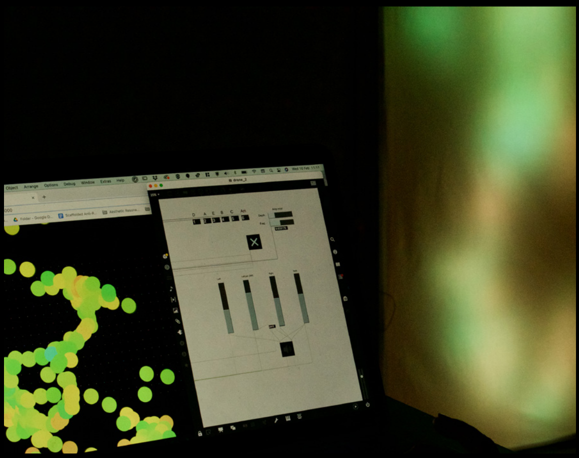


Figure 103: Both audio and visual components are generated algorithmically, diversifying the aesthetic emotions that can be evoked in response.

3. **Create an accessible system for measuring and producing resonance that is generative for designers.**

The final design is built upon a technical framework that collects raw (neural and aesthetic data), interprets it using resonance metrics, and translates it into audiovisual stimuli that can be controlled and optimised by a designer. The system is designed using standardised communication protocols, such as OSC and Lab Streaming Layer, to enable designers to connect the system with their own audiovisual designs. This means that any number of audio or visual sources, in a variety of formats, can be used to further explore resonance as a factor in experience design. As more data is produced using the system, a **more nuanced understanding of how design resonates with our brains and minds** can be developed, which can in turn **inform interaction design practices**.

Additionally, the real-time resonance metrics and audiovisual controls allow designers to **rapidly iterate within the design space**. For example, the system could be used to iterate upon an installation that uses neural entrainment to address sensory overload. The installation could be connected to the system

Figure 104: The real-time data display and audiovisual controls allow rapid, adaptive iteration within the design space.

and assessed using the resonance metrics to optimise both the neural and aesthetic aspects of the design, tuning the audiovisual components in real-time and collecting synchronised data that can provide valuable insight into how these components affect neural and aesthetic outcomes. By **transforming complex raw data into easily interpretable scores** and providing **live visualisations**, the system enables designers to see the results of their iterations immediately and pivot their approach accordingly (Figure 104). In summary, my resonance optimisation system **turns complex, abstract data into an accessible and generative input for experience design** that can be applied across a variety of multi-sensory configurations.

9.1.3 LIMITATIONS & FUTURE WORK

As with any design project, there were a number of limitations that affected the scope and outcomes of my work. One of the most pressing was the ongoing COVID-19 pandemic, which greatly impacted my ability to gather data and test my prototypes. Working with brain data and live aesthetic measures meant that in-person testing was essential to validate my designs and move the project forward. I was thankfully lucky enough to have a small group of fellow students with whom I could safely test, but this naturally resulted in a **small sample size** for all of my tests. Additionally, the fact that all of my participants were designers could easily have affected the aesthetic data I gathered; designers are well acquainted with aesthetics and are perhaps more readily able to self-report on aesthetic experiences than the typical participant. As my work explores fundamental aspects of neuroscience and design, it is important to further validate my initial findings with **larger and more diverse population samples** in future.

Another impact of COVID on the project was the necessity to constantly adapt my design outcomes according to changing conditions. I had originally intended to exhibit my final prototype and gather data in a gallery context, which could have aided in priming participants for an aesthetic experience. I was unfortunately unable to do so, but based on the small-scale testing I carried out in faculty studio spaces, I believe that the project could benefit from **development for an exhibition setting** when conditions allow for it.

Regarding the final design itself, there are several aspects highlighted during the final user test that would benefit from further work. Firstly, the recording sessions were purposely kept relatively short (approximately 5 minutes) to maintain participants' aesthetic attention and ensure that their self-reported aesthetic data was consistently accurate by avoiding fatigue or loss of interest. However, this naturally reduced the amount of neural data collected and thus made it more difficult to make generalisable conclusions. In future, I would like to try **increasing the duration of recording sessions** to investigate the trade-off between generalisability of neural data and quality of aesthetic data. Secondly, the real-time aesthetic measure I implemented was described by a minority of participants as sometimes detracting from the experience. They explained that the character of the audiovisual components made them want to fully immerse themselves in the experience, without having to reflect on their perception of it. As a result, the format of the real-time aesthetic measure should be further developed to **balance accuracy and ease of use**.

9.2 IMPLICATIONS FOR DESIGN

9.2.1 AESTHETIC THEORY

The **real-time aesthetic metric** developed during this project draws upon aesthetic theory to simply and efficiently asses the effect of audiovisual properties, and combinations thereof, on subjective aesthetic experience. This metric enabled me to successfully optimise for aesthetic resonance — operationalised as pleasantness and engagement — and as a result can be seen as a good **representation of aesthetic experience**. The metric, and its use in my final design, demonstrate that it is possible to **measure, iterate upon and optimise aesthetic experiences in real-time**. Additionally, such experiences are not only perceived as aesthetically resonant during the experience, but remembered as such afterwards (as shown by the results of the AESTHEMOS questionnaire).

Although the metric is simplified by necessity and does not contain the granularity of emotional reporting in retrospective tools such as AESTHEMOS, it indicates that real-time aesthetic measurement is both **useful for designers** and a sufficient representation of aesthetic experience to enable optimisation of such experiences. This also suggests that **such measurement tools merit further research**, particularly as real-time aesthetic metrics appear to be far less common in literature compared to their retrospective counterparts.

9.2.2 DESIGNING WITH DATA

My final design demonstrates how **real-time data and metrics can be generative for design** in facilitating a **feedback loop** between a designer and participant or user. This approach enables designers to **rapidly iterate** upon an experience design and quickly gather **synchronised data** that can lead to generalisable conclusions about the influence of various (audiovisual) design factors on subjective experience.

Further to this, the design offers an accessible, adaptable platform for collecting and analysing data regarding the fundamental relationship between our physical and psychological responses to design. Although the current version of the platform focuses on EEG data, other forms of biodata could be incorporated using similarly constructed metrics to gather more comprehensive information about how aesthetic experiences affect our bodies. This could be of great benefit in **design for wellbeing** contexts, where designers require reliable measures to validate the positive outcomes produced by their designs. In the case of EEG data, further applications of my system could include the treatment of conditions related to audiovisual perception, such as sensory overload, through experience design.

Regarding brain-computer interfaces and neurotherapeutics, my design and user test results strongly suggest that it is possible to embed periodic stimuli in positive, aesthetically resonant experiences, without reducing their neural effects. This is significant for BCI design, as it indicates that **the experiential qualities of BCIs can be improved** to create interfaces that are as enjoyable as they are effective — potentially addressing the fatigue effects of BCIs as well. Similarly, nascent clinical treatments in the field of **neurotherapeutics** could be approached from an experience-centred perspective to **deliver treatments in a more holistic way**. In both cases, making the experience of neurally resonant stimuli aesthetically pleasurable seems essential for long-term adoption.

9.2.3 FROM HUMAN TO ARTIFICIAL

The research platform developed during this project addresses an **optimisation problem** regarding neural and aesthetic resonance. Optimisation problems are often examined in a computational context, where digital processing power can search a solution space efficiently.

The **labelled datasets** generated by my platform lend themselves to computational applications, such as **machine learning**. Applying machine learning techniques could help to further explore the statistical relationships between audiovisual properties and the resonance metrics developed during this project. As previously discussed, the final user test provided initial indicative data that neural and aesthetic resonance can be maximised by the same audiovisual stimuli. However, the relationship between the combination of audiovisual properties and both resonance metrics — as well as the influence these metrics may have on each other — does not appear deducible through human information processing.

Machine learning, as with other forms of artificial intelligence, excels in processing large amounts of complex data and finding relationships between variables that are not apparent to the human eye. In this particular case, machine learning could help to **identify which properties of an experience design influence which resonance metrics**, and to what extent. At the same time, humans (in this case, designers) are well-equipped to intuitively optimise aesthetic properties based on both real-time aesthetic data, as demonstrated in this project, and their own experiences. A future iteration of the platform is envisaged in which **human and artificial intelligence can complement each other** to jointly optimise for neural and aesthetic resonance: an example of a **human-centred smart system**[35].

9.3 PERSONAL REFLECTION

9.3.1 PERSONAL GOALS

At the beginning of this project, I set myself some goals for personal and academic development. Firstly, I wanted to further develop my existing technical skills relating to physical and digital prototyping. I can say with certainty that I have been able to do this — almost every day working on this project involved some kind of technical challenge! By adopting a proactive and independent attitude to technology, I was able to consistently find solutions to these challenges. I was determined to make as much as I could from my own knowledge and resources, building my prototypes from the ground up whenever possible. This experience has given me greater confidence in my technical abilities, my patience for seemingly unsolvable problems, and my ability to solve these problems creatively.

Another personal goal was to strengthen my understanding of data analysis and data-informed design. Although it was initially difficult to get to grips with the complexity and arbitrary nature of EEG data, by immersing myself in literature and recreating simple neuroscience experiments I was able to gain a good understanding of how this data can be analysed and used in a design context. Having developed my own metrics and implemented them in an experience design, I see great value in this approach and will continue to explore data-driven design in future.

My final personal goal was to consolidate my project management skills, which was probably the greatest challenge I faced during this project. My project quickly grew in complexity, morphing from a direct healthcare application to a much more fundamental, research-driven project. Balancing the various domains involved — including design, neuroscience and creative technology — was at times almost overwhelming. This meant that even though my experiments and prototypes were relatively structured, the design process often felt quite chaotic. Upon reflection, I think that the project would have benefited from more clearly defined research questions and design goals earlier on in the design process, as these helped me greatly in structuring the final stages of my project.

9.3.2 PERSONAL DEVELOPMENT

Having come to the DfI programme from the architectural industry, I think that I have always struggled to feel as if I "get" design in the same way that my peers with an industrial design background do. My thesis was an opportunity to prove to myself that my perspective on design is not only valid, but can be of value to others, too. In addition to the skills I had gained through the DfI programme, I drew upon the spatial design, modelling and visualisation abilities I developed during my architectural career. In this way, my thesis is a true representation of me as a designer.

I value art and engineering in equal measure and feel that both have been essential in this project. I could not have developed my metrics and data protocols without a logical mindset, but equally could not have translated these into an experiential design without artistic intuition. Above all, my desire to understand things deeply and my awareness of how little I truly know (especially about something as mysterious and complex as the human brain) have propelled me forward even when it felt impossible to reconcile the two. Looking back on the past 6 months, during which I have continuously questioned myself and been questioned in turn, I can say that I am more sure of myself — and of how much there is still to learn — than I have ever been.

REFERENCES

1. Millner, B., Squire, L. R., Kandel, E. R. (1998). Cognitive Neuroscience and the Study of Memory. In *Neuron* 20 (pp. 445-468).
2. Wang, Q., Sourina, O., Nguyen, M. K. (2010). EEG-based “Serious” Games Design for Medical Applications. In Proceedings of the International Conference on Cyberworlds 2010.
3. Brunner, C. et al. (2015). BCNI Horizon 2020: towards a roadmap for the BCI community. In *Brain-Computer Interfaces* 2(1) (pp. 1-10).
4. Nijholt, A. (2019) *Brain Art: Brain-Computer Interfaces for Artistic Expression*. Springer Nature, Switzerland.
5. Sargent, A., Heiman-Patterson, T., Feldman, S., Shewokis, P. A., Ayaz, H. (2018). Mental Fatigue Assessment in Prolonged BCI Use through EEG and fNIRS. In *Neuroergonomics: The Brain at Work and in Everyday Life* (pp. 315-316).
6. Hammond, D.C. (2005). Neurofeedback treatment of depression and anxiety. In *Journal of Adult Development* 12 (pp. 131-137).
7. Frayling, C. (1993). Research in Art and Design. In *Royal College of Art Research Papers* 1 (pp. 1-5).
8. Zimmerman, J., Forlizzi, J., Evenson, S. (2007). Research Through Design as a Method for Interaction Design Research in HCI. In CHI 2007 Proceedings (Design Theory).
9. Teplan, M. (2002). Fundamentals of EEG Measurement. In *Measurement Science Review* 2(2).
10. Gruzelier, J. H. (2014). EEG-neurofeedback for optimising performance. I: A review of cognitive and affective outcome in healthy participants. In *Neuroscience and Biobehavioral Reviews* 44 (pp. 124-141).
11. Herrmann, C. S. (2001). Human EEG responses to 1-100 Hz flicker: resonance phenomena in visual cortex and their

potential correlational to cognitive phenomena. In *Experimental Brain Research* 137 (pp. 346-353).

12. Rapela, J., Gramann, K., Westerfield, M., Townsend, J., Makeig, S. (2012). Brain oscillations in switching vs. focusing audio-visual attention. In Proceedings of 2012 Annual International Conference of the IEEE Engineering in Medicine and Biology Society.

13. Nozaradan, S. (2014). Exploring how musical rhythm entrains brain activity with electroencephalogram frequency-tagging. In *Philosophical Transactions of the Royal Society* 369.

14. Schwarz, D. W. F., Taylor, P. (2004). Human auditory steady state responses to binaural and monaural beats. In *Clinical Neurophysiology* 116 (pp. 658-668).

15. Trost, W.J., Labbé, C., Grandjean, D. (2017). Rhythmic entrainment as a musical affect induction mechanism. In *Neuropsychologia* 96 (pp. 96-110).

16. Clayton, M., Sager, R., Will, U. (2005) In Time with the Music: The Concept of Entrainment and its Significance for Ethnomusicology. In *European Meetings in Ethnomusicology* 11 (pp. 3-76).

17. Basu, S., Banerjee, B. (2020) Prospect of Brainwave Entrainment to Promote Well-Being in Individuals: A Brief Review. In *Psychology Studies* 65(3) (pp. 296-306).

18. Hascher, T. (2008). Quantitative and qualitative research approaches to assess student well-being. In *International Journal of Educational Research* 47(2) (pp. 84-96).

19. Chatterjee, A., Vartanian, O. (2014). Neuroaesthetics. In T*rends in Cognitive Science* 18(7).

20. Krebs, A. (2015). On Aesthetic Resonance. In Proceedings of Bi-annual Conference of the International Society for Research on Emotion, July 8-10 2015.

21. Lewis Brooks, A., Hasselblad, S. (2004). Creating Aesthetically Resonant Environments for the handicapped, elderly and rehabilitation: Sweden. In *International Journal on Disability and Human Development* 4(4).

22. Hummels, C., Ross, P., Overbeeke, K. (2003) In Search of Resonant Human Computer Interaction: Building and Testing Aesthetic Installations. In Proceedings of INTERACT'03.

23. Nan, W., Pedro Rodrigues, J., Ma, J., Qu, X., Wan, F., Mak, P., Vai, M., Rosa, A. (2012) Individual alpha neurofeedback training effect on short term memory. In *International Journal of Psychophysiology* 86(1) (pp. 83-87).

24. Bin, G., Gao, X., Yan, Z., Hong, B., Gao, S. (2009). An online multi-channel SSVEP-based brain-computer interface using a canonical correlation analysis method. In *Journal of Neural Engineering* 6.

25. Korczak, P. A., Smart, J., Delgado, R., Strobel, T. M., Bradford, C. (2012). Auditory steady-state responses. In *Journal of the American Academy of Audiology* 23(3).

26. Will, U., Makeig, S. (2011). EEG Research Methodology and Brainwave Entrainment. In *Music, Science, and the Rhythmic Brain: Cultural and Clinical Implications*. Editor: Berger, J., Turow, G. Routledge, U.K.

27. Pasman, G., Boess, S., Desmet, P. (2011). Interaction Vision: Expressing and Identifying the Qualities of User-Product Interactions. In Proceedings of the 13th International Conference on Engineering and Product Design Education.

28. Sanders, E., Stappers, P. J. (2012). *Convivial Toolbox: Generative Research for the Front End of Design*. BIS, Netherlands.

29. International Association for Empirical Aesthetics. Accessed on: January 10th, 2021. (Online). Available: https://www.science-of-aesthetics.org/

30. Leder, H., Nadal, M. (2014), Ten years of a model of aesthetic appreciation and aesthetic judgements: The aesthetic episode - Developments and challenges in empirical aesthetics. In British Journal of Psychology 105(4) (pp. 443-464).

31. Silvia, P. J. (2006). *Exploring the psychology of interest*. Oxford: Oxford University Press.

32. Schindler, I., Hosoya, G., Menninghaus, W., Beermann, U., Wagner, V., Eid, M., Schere, K. R. (2017). Measuring aesthetic emotions: A review of the literature and a new assessment tool. In PLoS ONE 12(6).

33. Kant, I. (1790). *Critique of the power of judgement*. Editor: Guyer, P. (2000). Cambridge: Cambridge University Press.

34. Nanay, B. (2015). Aesthetic Attention. In *Journal of Consciousness Studies* 22(5-6) (pp. 96-118).

35. Beardow, C., van der Maden, W., Lomas, J. D. (2020). Designing Smart Systems: Reframing Artificial Intelligence for Human-Centred Designers. In Proceedings of International Tools and Methods of Competitive Engineering Symposium 2020.

36. Peters. B. et al. (2020). SSVEP BCI and Eye Tracking Use by Individuals With Late-Stage ALS and Visual Impairments. In *Frontiers in Human Neuroscience* 14.

37. Hummels, C., Ross, P., Overbeeke, K. (2003). In search of resonant human computer interaction: building and testing aesthetic installations. In *Interact '03*. Editors: Rauterberg, M., Menozzi, M., Wesson, J. IOS Press, Amsterdam.

38. Albert, B., Sjaaheim, H., Setchi, R., Velikova, S. (2016). Automatic EEG Processing for the Early Diagnosis of Traumatic Brain Injury. In *Procedia Computer Science*.

APPENDIX A: BRIEF

4480

DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name [redacted]

initials ______ given name [redacted]

student number [redacted]

street & no. [redacted]

zipcode & city [redacted]

country [redacted]

phone [redacted]

email [redacted]

Your master programme (only select the options that apply to you):

IDE master(s): IPD / DfI (selected) / SPD

2nd non-IDE master:

individual programme: - - (give date of approval)

honours programme: Honours Programme Master

specialisation / annotation: Medisign / Tech. in Sustainable Design / Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Dr. J. Derek Lomas — dept. / section: HCD

** mentor: Dr. Elif Ozcan Vieira — dept. / section: HCD

2nd mentor:

organisation:

city: country:

comments (optional): Although my mentor and chair are from the same faculty department, their areas of research do not overlap and are both relevant to my project. Together, they provide a balance of technical and design skills.

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 — Page 1 of 7

Procedural Checks - IDE Master Graduation

TUDelft

APPROVAL PROJECT BRIEF
To be filled in by the chair of the supervisory team.

chair Dr. J. Derek Lomas date 29 08 2020 signature

CHECK STUDY PROGRESS
To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 30 EC

Of which, taking the conditional requirements into account, can be part of the exam programme 30 EC

List of electives obtained before the third semester without approval of the BoE

X YES all 1st year master courses passed

NO missing 1st year master courses are:

name C. van der Bunt date 09 - 10 - 2020 signature

FORMAL APPROVAL GRADUATION PROJECT
To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: V APPROVED NOT APPROVED

Procedure: V APPROVED NOT APPROVED

- separate version with readable planning
-remark: make title more descriptive, express who benefits from the solution and express that it is about the design of an experience

comments

name Monique von Morgen date 27/10/2020 signature MvM

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 Page 2 of 7

Initials & Name Beardow Student number 4915453

Title of Project Aesthetic (Neuro)Resonance

Aesthetic (Neuro)Resonance — project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 15 - 09 - 2020 — 19 - 02 - 2020 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Resonance is a term with diverse meanings. Traditionally, it is a scientific term that refers to the "sympathetic vibration" that occurs when an entity vibrates at the same frequency as a neighbouring sound source in response to their proximity. However, we also use 'resonance' in reference to cultures, people, and works of art. We say that something resonates with us when we feel deeply connected to it. Aesthetic resonance describes an emotional response to our environment in which our behaviour and our environment's response to it feel aesthetically synchronised, and we feel in harmony with it at a result. Although many aspects of this experience are qualitative, the biological systems that allow us to perceive them can provide quantitative insight into the resonance phenomenon.

The design will be developed as a therapeutic experience to address sensorial (and, by extension, psychological) exhaustion and imbalance in a healthcare(-adjacent) context. Healthcare professionals, especially in emergency medicine, can experience physical and mental fatigue due to the high number of audiovisual signals in their vicinity. This fatigue can contribute to error in healthcare workflows, with potential negative impacts for both staff and patients. The project seeks to alleviate this fatigue and reduce workflow errors as a result. Primary stakeholders include healthcare professionals (potentially in the context of Erasmus Medical Centre) and design researchers in related fields. The work of the Critical Alarms Lab, a research lab in the IDE faculty exploring this domain, will be referred to as a contextual knowledge base.

The project also addresses the role of EEG (electroencephalography, AKA brain wave data) in design, and as such is intended to have significance for neuroscience researchers who are interested in how fundamental concepts in their field may be implemented through design, particularly in a wellbeing context. This aspect of the project will be conducted in collaboration with Vibe Research Lab, a design research collective within the IDE faculty with whom I have worked for the past year. Vibe Research Lab explores the relationship between biodata, empirical aesthetics and design. During my project, I aim to demonstrate how this relationship can be expressed through a physical design, and how the data driving this process can be visualised in an accessible and communicative way. I see this aspect as a key contribution of the project -- a human-centred approach to complex data that makes visible the feedback loop between this data and aesthetic experiences.

With these stakeholders and aims in mind, I have identified three primary project outcomes:
1. an art exhibition, in which the final conceptual prototype is demonstrated;
2. a real-time data display that supports human-centred data science;
3. a technical framework for measuring and interpreting neural resonance.

Main opportunities relate to the potential for the project to highlight and generate approaches to design that can improve, even if temporarily, the wellbeing of the target group. Due to the fundamental nature of much of the literature by which this project is informed, there is also an opportunity to demonstrate how design can both facilitate (qualitative and quantitative) research, and translate theoretical knowledge across several disciplines to an experience that is engaging and communicative. Limitations mostly relate to time and resources, particularly in light of the ongoing COVID-19 pandemic. As the project hinges on human participants and physical prototyping -- especially in a healthcare context -- alternative arrangements may need to be explored as the project develops. To mitigate the risks of this, a remote research process and concept will be developed in tandem with the original intended outcomes, such that they can be engaged with at any point in the project if needed.

space available for images / figures on next page

introduction (continued): space for images

TO PLACE YOUR IMAGE IN THIS AREA:
- SAVE THIS DOCUMENT TO YOUR COMPUTER AND OPEN IT IN ADOBE READER
- CLICK AREA TO PLACE IMAGE / FIGURE

PLEASE NOTE:
- IMAGE WILL SCALE TO FIT AUTOMATICALLY
- NATIVE IMAGE RATIO IS 16:10
- IF YOU EXPERIENCE PROBLEMS IN UPLOADING, COVERT IMAGE TO PDF AND TRY AGAIN

image / figure 1:

TO PLACE YOUR IMAGE IN THIS AREA:
- SAVE THIS DOCUMENT TO YOUR COMPUTER AND OPEN IT IN ADOBE READER
- CLICK AREA TO PLACE IMAGE / FIGURE

PLEASE NOTE:
- IMAGE WILL SCALE TO FIT AUTOMATICALLY
- NATIVE IMAGE RATIO IS 16:10
- IF YOU EXPERIENCE PROBLEMS IN UPLOADING, COVERT IMAGE TO PDF AND TRY AGAIN

image / figure 2:

Personal Project Brief - IDE Master Graduation

TU Delft

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Although relatively well-established concepts in literature, resonance and entrainment are not often explored in a design context. Their potential for driving therapeutic experiences is not fully utilised as a result. A design perspective -- understanding what is engaging, meaningful and enjoyable -- is essential for implementing these concepts successfully outside of a lab environment, particularly for therapeutic purposes.

Now more than ever, healthcare professionals carry a significant burden of physical and psychological stress. A portion of this stress can be attributed to, or otherwise aggravated by, the overwhelming number of concurrent sounds, lights and other sensory stimuli that are used to communicate messages in a clinical environment. Particularly in emergency and critical care environments, simultaneously parsing these messages can cause healthcare professionals to become sensorially overstimulated. The resulting fatigue can in turn cause human errors in the healthcare workflow, with negative impacts for staff and patients alike.

There is potential for the concepts of resonance and entrainment to address the issue of sensorial overstimulation, through a personalised and scientifically informed experience that brings sensory systems into harmony with the designed environment, created specifically to encourage physiological and psychological balance.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

The envisioned design consists of a personalised, aesthetically engaging therapeutic experience, that is both quantitatively and qualitatively resonant. The experience is driven by an individual's EEG data and uses the concept of "neural resonance" to generate audiovisual stimuli that are attuned to the individual's bodily state and designed to faciliate a restorative, meditative experience. The design will physically manifest as a spatial installation.

This project aims to explore how biodata (more specifically, EEG) can be used to create personalised, and potentially therapeutic, aesthetic experiences. The envisioned design includes a closed loop system, in which an individual's "neural resonance profile" is determined from live EEG data, and is used as input for real-time, iterative audiovisual and tactile stimuli. In this context, resonance is used to describe the degree to which the frequencies represented by stimuli provoke neural response at corresponding (harmonic) frequencies in a person's EEG. Machine Learning techniques will likely be used to optimise for neural response, interpreting EEG data and processing it as input for audiovisual stimuli.

The primary goal of the designed experience is to facilitate a 'reset' of overstimulated healthcare professionals' mental wellbeing, via a personalised multi-sensory experience. Consequently, stimuli will be developed through iterative testing with participants (ideally from the target group, or adjacent groups) to determine what is qualitatively and quantitatively perceived as restful, harmonious, and healing.

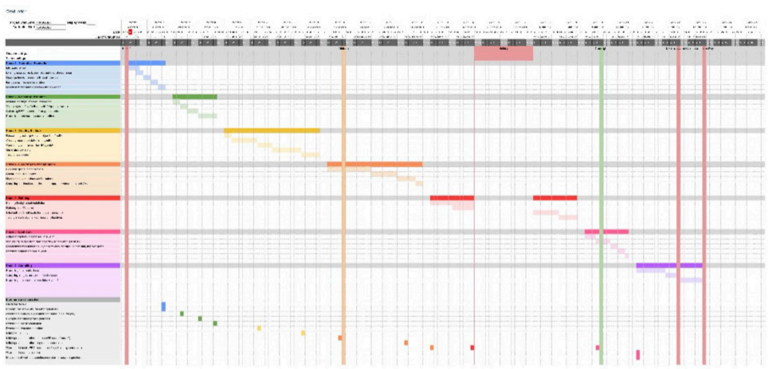
Personal Project Brief - IDE Master Graduation

TUDelft

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 15 - 9 - 2020 19 - 2 - 2020 end date



My approach in the above Gantt chart involves seven phases that begin with initial research and concept definition, followed by three phases of technical and design exploration, culminating with a refined final concept and physical prototype. Two shorter phases of evaluation and compilation of materials follow this 'making' period, and bring the project to a close. During the 'making' phases (3-5), I will follow the weekly prototyping cycles as taught in the Interactive Technology Design course. This consists of an orientation at the beginning of the week where I will set key goals, then several days of prototype building, followed by an end-of-week testing day that is closed off with reflections and improvements to be carried forward to the following week. I have used this rapid cycle approach in much of my prototyping work previously and have found it to suit me well. It allows me to maximise my time and resources, focusing on insights over perfection in the initial stages, and then refining a concept to an exhibition-ready level for final testing.

IDE TU Delft - E&SA Department /// Graduation project brief & study overview /// 2018-01 v30 Page 6 of 7

Initials & Name [redacted] Student number [redacted]

Title of Project Aesthetic (Neuro)Resonance

Personal Project Brief - IDE Master Graduation

TU Delft

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

Throughout the second year of my MSc, I have been an active member of a research collective in the faculty. As part of my research, I have done experimental work, created interactive prototypes, and published an academic paper on topics related to this graduation project (namely, empirical aesthetics and technology for wellbeing). I feel that this project proposal is a natural culmination of both my research work and my design interests. I have gained proprietary experience and education in Machine Learning techniques during my 3rd semester electives, which I am keen to explore further and implement in a creative setting during this project. I also have a background in architecture, having studied and worked in the industry for several years before coming to Delft. This project proposal gives me the opportunity to draw upon my spatial design skills, thus combining the competences in research, prototyping and design I have developed over the course of my education and professional career.

My primary self-development goals for this project are:

- Further develop my existing technical skills (both digital and physical) through rapid prototyping cycles.
- Strengthen my understanding of data analysis and data-informed design.
- Build a professional network in the Netherlands, both inside and outside TU Delft.
- Consolidate my project management skills in a design context.

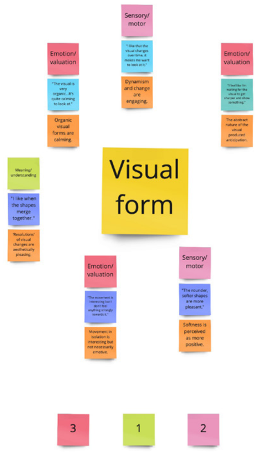
FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Initials & Name [redacted] Student number [redacted]

Title of Project Aesthetic (Neuro)Resonance

APPENDIX B: P1 CLUSTERS



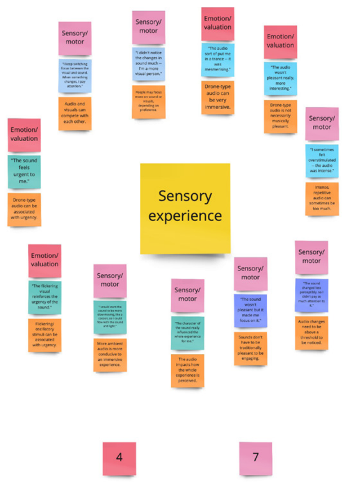
Visual form has strong influence on emotional experience, some influence on sensory experience and some influence on understanding.

Colour has strong influence on emotional experience, strong influence on sensory experience and some influence on understanding.

Meaning is a significant part of the experience -- participants look for symbolism and representation.

The purpose of the experience is a key consideration and needs to be framed narratively.

Emotional value, sensory experience and meaning all influence the emotional impact of the experience.



Sensory experience involves both perceptual and emotional processes.

APPENDIX C: AESTHEMOS

Item no.	Statement
1	I found it beautiful
2	It challenged me intellectually
3	It delighted me
4	It calmed me
5	It made me curious
6	I liked it
7	It fascinated me
8	It made me feel wonder
9	It invigorated me
10	I was mentally engaged
11	It baffled me
12	I found it ugly
13	I sensed a deeper meaning
14	I felt moved
15	It made me feel melancholic
16	It energised me
17	It made me angry
18	I was enchanted
19	It bored me
20	It relaxed me
21	I felt that I gained insight from it
22	It amused me
23	It made me sad
24	I felt confused
25	It made me feel aggressive
26	It made me feel sentimental
27	It worried me
28	It made me feel nostalgic
29	It surprised me

Item no.	Statement
30	It felt oppressive
31	I felt connected to it
32	It motivated me
33	I felt indifferent to it
34	I was impressed by it
35	I found it distasteful
36	It touched me
37	I found it unsettling
38	It sparked my interest
39	It made me happy
40	I felt awe
41	I found it humorous
42	It made me want to do something

APPENDIX D: SAMPLE DATA

Sample baseline EEG data, organised by frequency bin per timestamp

Timestamp	3	3.2	3.4	3.6	3.8	4	4.2	4.4
8940.74	77.21	55.42	41.44	26.69	23.63	38.12	33.36	36.22
8940.8	97.27	55.95	56.49	32.84	27.78	26.04	23.87	28.47
8940.85	103.54	56.24	70.53	40.67	30.06	26.6	21.15	23.52
8940.89	95.45	55.18	73.77	43.3	28.14	32.53	24.61	27.24
8940.94	76.72	53.53	61.11	37.67	24.43	32.81	32.21	39.16
8940.99	53.07	54.28	47.36	31.39	21.34	37.08	45.98	45.95
8941.04	37.46	54.96	42.9	31.01	21.09	44.98	49.38	38.82
8941.07	26.46	54.53	44.72	36.7	24.88	49.31	38.74	26.2
8941.13	30.54	55.03	41.8	41.27	37.3	36.26	27.27	24.58
8941.18	40.89	60.38	40.25	45.09	50.86	28.62	25.82	23.52
8941.22	55.95	68.41	45.19	48.86	58.39	29.9	28.68	21.46
8941.27	71.62	64.58	66.85	39.91	25.36	37.91	28.28	26.82
8941.37	61.75	52.97	59.79	30.79	22.98	36.63	30.78	30.09
8941.41	36.67	46.79	35.95	35.27	57.39	36.27	35.89	27.61

Sample experimental data, showing audio properties and neural resonance scores by frequency bin

Timestamp	AM freq	Key val	3	3.2	3.4	3.6
8995.02	10.69	1	0.26	0.23	0.12	0.26
8995.05	10.69	1	0.25	0.24	0.11	0.22
8995.11	10.69	1	0.23	0.22	0.1	0.19
8995.15	10.69	1	0.22	0.2	0.09	0.17
8995.21	10.69	1	0.24	0.25	0.1	0.13
8995.25	10.69	1	0.22	0.25	0.12	0.13
8995.3	10.69	1	0.17	0.22	0.14	0.16
8995.34	10.69	1	0.12	0.16	0.15	0.19

Sample experimental data, showing neural resonance scores, first harmonic score and aesthetic scores

23.6	23.8	24	Harmonic	Pleasantness	Engagement
0.3	0.28	0.44	0.14	-0.01	0.03
0.3	0.3	0.42	0.18	-0.01	0.03
0.28	0.29	0.45	0.17	-0.01	0.03
0.3	0.28	0.43	0.14	-0.01	0.03
0.33	0.34	0.49	0.1	-0.01	0.03
0.3	0.33	0.45	0.11	-0.01	0.03
0.34	0.35	0.37	0.19	-0.01	0.03
0.28	0.28	0.48	0.11	-0.01	0.03