Visualizing psychophysiological responses to music stimuli

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Abstract

Music and emotion are deeply connected in the human experience. From the physiological realm to the cultural perspective, music is known for its capability to modify and drive human emotions, mood and movement. Thereby, music, in combination with technology, can effectively supply powerful tools to raise awareness of internal processes, and provide access to physiological data. This thesis explores the main physiological responses to musical sounds, with a special focus on the breathing mechanisms. The first part contains a literature review of relevant research on human psychophysiological responses to different types of music, and how these responses relate to attributes of the auditory stimuli. The second part presents a prototype design of a visual interactive application based on the user's respiration response to music. The visualizations generated by the application *Breath Painting* have the potential to feature music apps focused on relaxation and wellness. It integrates gamification tools for mental health support applications. It can also be utilized for educational purposes by raising awareness of the importance of music and respiration for the human mental health. The prototype shows how it is possible to make physiological data and musical features accessible to the general public in a visually appealing design.

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Contents

Chapter 1

Introduction

The world is going through a global mental health crisis [58], although the traditional pharmaceutical drugs available can be effective and are an important support for people with mental disorders, they often impinge harmful side effects on the patients making use of it. However, some alternative methods and tools can help support treatments in the mental health field. Not excluding the importance of the classic pharmacological medicines, music can be a powerful tool and serve as means to diminish the dependence, volume of use, and therefore side-effects [53] of such medicine. From the physiological realm to the cultural perspective, research show that music has the capability to modify and drive human emotions, mood, and movement [28], [76], [38], and [59]. Following these lines, music technology can be effective at supporting mental health and well-being. Music can induce down-regulation of the nervous system, providing relaxation, and in combination with technology, music technology has the potential to supply powerful tools to promote not only better mental health, but also raise awareness of internal bodily processes, supplying access to physiological data that can be valuable to manage psychophysiological processes.

1.1 Motivation

Throughout my entire life, music has been an essential support to deal with traumatic events and difficult emotions. Since I was young, I found music a safe space where I can express myself and let emotions flow through. Later on, when I decided to do a bachelor's degree in Graphic Design, I started to develop a professional path where I could associate creative work with technology, and inevitably music has always been present in the large majority of the projects that I developed during the program. During this period I realized how music is deeply associated with visual representations in my perception, and that seeded my interest in creating immersive visual and musical interactive experiences, which brought my focus to *Interaction Design* within the graphic design field.

Recently in my adulthood, I started to deal with and recognize strong symptoms of post-traumatic stress disorder (PTSD) as a consequence of acute traumatic events categorized as *"Big T Trauma"*, being diagnosed later on with *complex PTSD*. Initially, I did not know how to deal with these symptoms, and it took me years of struggle, self-medicating, moreover trying classic pharmacological antidepressants until I started to self-study the subject which led me to develop coping methods and find professional assistance that gave me a proper diagnosis and support. My experience with antidepressants was briefly positive, and it quickly started to be negative. When I decided to quit it, I had a terrible time, which made me invest more in investigating several alternative methods that I have been learning during my healing process and self-studies.

The process of trying to understand my condition, dealing with issues regarding that, and looking for solutions has been going on for years, but it had culminated during my studies in the present master's program in Music, Communication, and Technology. During this intense healing process (which is still going on while I am writing it), I started searching for my purpose, and I knew that it would be deeply aligned with music somehow. That is when I realized that my purpose was born from and within my pain. I felt the first sign of passion for this path when I had the opportunity to use music technology for a health matter, in one of the projects developed in the master's program. That was the first sign, a click, poking me to realize that health would be the matter of my thesis project among so many other appealing fields.

As a person that plays and composes music, music has been always an important part of my well-being and expression as a human, but only in the recent years, during this master's program, I have found out the healing music of great composers such as *Hiroshi Yoshimura*, *Brian Eno*, *Jon Hopkins*, *Harold Budd*, and many others which has opened up a new world for me. I have been using this type of *ambient music*, or *healing music*, in my self-work and it has shown me clear benefits and potential out of my own experience. That led me to connect my purpose with my passion for music, and so I decided to investigate how music can be beneficial for mental health through the lenses of science.

1.2 Aim

The present thesis aims to investigate how music affect human psychophysiology and the potential uses of music in combination with technology to benefit the mental-health and well-being of individuals. It does so by studying the key physiological responses to musical sounds, with a focus on the breathing mechanisms, since respiration is considered the main component of the physiological functions capable of modifying and down-regulate the autonomic nervous system.

The prototype proposed further on in this project aims to raise awareness of the capability of music as a tool to modify physiological patterns and consequently regulate an individual's autonomic nervous system. Music technology can support health care and psycho-therapeutic treatments, helping to prevent mental disorders such as anxiety, depression, stress, and bipolar disorder. Altogether, the combination of a biofeedback interactive system, with gamification techniques and conscious breathing can be a powerful tool to support mental health and wellness, and this project will describe how.

Starting by doing a literature review with relevant scientific papers, the present project observes human psychophysiological responses under the influence of different types of music, relating the attributes of the auditory stimuli to the characteristics of these responses. In this way, this research intents to understand the main physiological mechanisms involving the correlation between sound stimuli and the autonomic nervous system, providing valuable information about applications and ways in which music can be used for the regulation of the autonomic nervous system. After analysing the efficacy of a few applications of music in combination with respiration, we go to the second step of this project which is the creation of means to inform and engage individuals about their physiological adaptations in interaction with music.

The last step of this project is a prototype design of an interactive application that creates a biofeedback system based on the respiration response to music. This interactive process derives data from the respiratory behavior of a listener while listening to music, showing the breathing transformations under the influence of different types of musical sounds. To do that, data visualization techniques will be used to create artistically appealing graphics representing and correlating the breathing data to the musical data during the listening experience, making it accessible and understandable for a broad audience.

These visualizations, which I am calling *Breath Painting*", have the potential to feature music apps focused on relaxation and wellness, integrating gamification tools for mental health support applications, or educational purposes by raising awareness of the importance of music and respiration for the human mental health. It also can be used for the practice of resonance frequency breathing, which is proven to be an efficient technique used for regulating the autonomic nervous system.

1.3 Research questions

In sum, the goal of this project is to combine music and technology as a tool for supporting mental health. Therefore, this project aims to answer the following questions:

- RQ1: Does music affect an individual's psychophysiological responses?
- RQ2: Can music change breathing patterns?
- RQ3: How can music be combined with technology to support mental health?

Before moving on, it may be worth defining some of the core terminology used in the thesis. By human physiology, I mean body functions responsible for keeping a human alive, such as respiration, heart rate, blood pressure, body temperature, nervous system activation, and hormone release among others.

When I refer to physiological data, I mean the body's physiological responses mentioned above that are fetched by sensors that send the measurement of such bodily responses as digital information to devices able to convey this information as numbers or any other type of data communication.

Musical features in this matter, are characteristics of the musical sounds such as amplitude, pitch, tone, timbre and overtones, melody, rhythm, and other characteristics of musical performance and expression such as staccato and texture, instance.

To induce relaxation in the context of this project, means to down-regulate the nervous system of an individual, providing low arousal and a calm emotional state. When I say that music can drive human emotion from the physiological realm to the cultural perspective, I mean that not only music is a powerful tool when it comes to affecting a person's reality and emotion within a culture and personal experiences, but it also has the direct effect on human physiological processes.

By "biofeedback system" I mean a system where an individual is connected to a sensor and a device that show physiological information in real-time, creating an interactive experience capable of providing awareness and agency of the user's bodily processes.

1.4 Scope

This study investigates the potential of music influence on key physiological functions that have the capability to support achieving relaxed states for an individual to help with stress and anxiety management. It does so by analysing the current scientific literature covering psychophysiological responses to music, and the data available. Among several psychophysiological responses involved on human relaxation and music listening, I chose to focus on the respiration, as it is proven to be highly effective at inducing down-regulation of the nervous system. This study also aims to create a prototype which shows breathing and music data in interaction, forming artistic and unique pictures that can engage and inform individuals about their breath transformations while listening to music.

The population studied in the literature reviewed is broad and differs according to the specific approach of each research, studying music's impact on psychophysiological behavior of non-musicians, musicians, westerns, and isolated tribes, among other variations in totally distinct geographical locations.

The sample chosen to be explored on the prototype developed within this project is a group of 42 participants studied in the experiment "Headphones/speakers Experiment, 2018" [67] at the University of Oslo, Norway. These participants could not present any type of hearing impairment or neurological disorders. 25 of the participants informed having some type of experience in music, either professionally or self-taught.

1.5 Limitations

During the idealization phase of this project, I had big ambitions. The first plan I had would start with an experiment investigating which specific features of musical sound trigger specific responses in human physiology. Initially, I aimed to contribute to the currently available research in the field, helping to consolidate the notion that music can be used as medicine with a scientific basis.

This aim came from both my wish to design my research and discoveries and also from the literature review process, where I saw the need to add to the studies on how music affects emotions and physiological processes. That would work in an ideal scenario, but I had to prioritize what to approach, due to a lack of time to develop all the ideas proposed for this project.

Conducting such an experiment would reinforce the importance of this project, and support discoveries regarding the potential of music for mental health with new data regarding this matter.

Moreover, the prototype would ideally be an app that takes real-time physiological data (such as the breath) from a sensor connected to the device in use and translate it into art during the music listening experience. The app could be integrated with other music streaming apps, so it would receive the internal audio of the device as input for the music data to be interacting with the breath data, for instance.

However, delimiting and focusing the work was also important to achieve meaningful and clear results. By having to define priorities, I realized how respiration can be highlighted as a key element on the human relaxation mechanisms and how it interacts with the experience of listening to music. Hence, delimiting it to breath, shaped not only decisions within this project, but also made me focus on creating engagement to how music and respiration are related to a listener's relaxation and how they interact dynamically.

Therefore, this study does not cover which specific features of sound trigger changes in the respiration patterns, but it shows an overview of the breath data behavior while listening to different types of music, also displaying characteristics of the audio in time, providing some insights of how the music listened influenced the breath behavior during the listening experience.

1.6 Overview of thesis

The first chapter is an introduction where I explain the topic, the goals, the motivation, limitations, and the research questions of this thesis. In the second chapter, I do a literature review, in which I start by explaining key concepts and definitions of technical terms explored in this thesis.

Continuing the same chapter, I do a review of relevant research organized by topics in music and psychophysiology. Moving forward, in the third chapter I break down the development of the prototype proposed in this project. In this chapter, I start by explaining the aims of the prototype, why it is relevant, and how I built it. Continuing, I do product research where I review relevant work that served as a reference for the prototype. Moreover, I explain the data used for this project and the sensor utilized for collecting this data. Furthermore, I go through the iterative process of designing and programming the prototype, finishing with an evaluation of the results. Finally, in the last chapter, I answer the research questions proposed in the introduction, followed by a discussion about the results and possible improvements for the prototype. Finishing the thesis, I explore ideas for implementing the prototype for health and educational applications as future work.

Chapter 2

Literature review

In this chapter, important concepts and technical terms will be explained based on research directly related to the present project. As it is a multidisciplinary project that involves music, health, and technology - different fields, from medicine to interaction design will be explored with the objective not only to clarify relevant concepts but also to support the potentials of the idea explored during the development of this project.

2.1 Biofeedback and Healthcare

The purpose of this project is to use music and technology combined to support mental health treatment and maintenance. Biofeedback is a technological component that fits the purpose, helping to bridge the gap between internal physiological processes and the patient's perception of these processes, which creates a vast number possibilities. The use of biofeedback in gamification systems for example, can help patients to be aware of their own physiological internal state, while engaging on activities that can help to regulate their autonomic nervous system's activity. It can be specially interesting for children, but not only children, studies show that adult individuals also benefit from the effectiveness of the use of these tools.

Biofeedback is a type of *connected mental health*, a term that describes technological solutions applied for mental health care and therapeutic purposes [2]. In this context, biofeedback is a tool that potentially facilitates the visualization of psychological and physiological processes of a patient, improving the understanding and management of anxiety treatments. It also can make interventions and results more effective when applied appropriately to the patient's needs.

According to the article "What is Biofeedback?" [22], biofeedback is the technical use of measuring instruments to inform one about a physiologic process occurring under the autonomic nervous system control despite not being consciously perceived. The measurement is made in real-time, and it has the objective to support a patient to develop agency regarding their own healing process. This type of practice also embodies the learning experience enhancing the way in which an individual acquires new abilities

[25].

2.1.1 Biofeedback and music applied for mental health

Since when the aforementioned article [22] was written until the actual days, many applications of biofeedback were developed. From motor rehabilitation to anxiety control, and athletic performance, biofeedback has been showing effective ways to support health recovery and education, and arousal reduction.

Another interesting application of biofeedback is the combination of biofeedback and music. Considering the powerful influence that music potentially has on individuals, the study presented in the article "Using music as a signal for biofeedback" [4], aims to answer the question of how the combination between music and biofeedback perform compared to the use of these individually.

The results of the experiment [4] pointed that musical and sonification biofeedback had similar effectiveness modulating physiological arousal on the participants (24 young adults). Interestingly, when it comes to regulating physiological arousal, the study showed that the use of biofeedback reflected much greater efficacy than listening to music alone by evaluating the participant's heart rate and respiration rate. This conclusion points out possibilities using biofeedback systems to enhance the effects of music with the goal to modulate arousal.

2.1.2 Biofeedback and gamification

Gamification is a technique that utilizes features of the gaming experience in non-gaming contexts [18]. It is widely used to provide users engagement with a product, and it is effective for educative purposes. Studies observed that gamification techniques have great potential in stimulating individuals for the accomplishment of tasks. In the article "User-Centred Design and Usability Evaluation of a Heart Rate Variability Biofeedback Game" [86], results validate this hypothesis, showing that visualization techniques in a gamification context were effective in creating engagement for specific applications such as heart rate variability biofeedback training.

Healthcare and well-being can benefit from the use of gamification and biofeedback since these are tools that potentially support maintaining the physiological system working in balance. The paper "Help me Relax! Biofeedback and Gamification to improve interaction design in healthcare", analyses the user experience by utilizing the combination of biofeedback and gamification for well-being purposes. The former demonstrated to be an efficient tool to provide joy and engagement to healthcare applications [78]. Spillers and Asimakopoulos also explore the practice of meditation training combined with biofeedback to help support restorative goals. They mention the article "Total engagement: How games and virtual worlds are changing the way people work and businesses compete" [66], pointing that this combination has the potential to improve healthcare games, making it more efficient [66].

The article [86] points out that reduced heart rate variability (HRV) is associated with diseases, depression, bad health conditions, and aging. It is likely to be associated with a disorder on the ANS. Hence, the study suggests HRV biofeedback as a method to establish the equilibrium of the autonomic nervous system by raising the heart rate variability [86].

This study takes into consideration an HRV biofeedback system that induces the individual's respiration (and consequently HRV) through a method defined as "resonant frequency breathing". This is a process based on the individual's breath rate, where the resonant frequency creates a loop between the respiration rate and the physiological feedback responsible to manage the blood pressure. This process has the potential to lower or increase the heart rate accordingly to the blood pressure, and consequentially enhance the HRV of the individual [86], [44], and [46].

2.1.3 Coherence and Resonance Frequency Breathing

Coherence is another interesting concept that helps to understand how training an individual's respiration rhythmic patterns can be beneficial to improving health quality. The article "Coherence: bridging personal, social and global health", explores how *coherence* is widely present in different instances of nature, from the synchronization of oscillatory systems to emotional systems [54].

There is a vast number of research pointing out that emotions modify the heart's rhythm patterns and modulate the activity of physiological systems. Following these lines, physiological coherence stands for the extent to which rhythmic activities present stability and consonance over time inside live organisms [81]. Therefore, psychophysiological coherence designates a continual state of positive emotions that produces a smooth sine-wave-type in the heart rhythm patterns [17].

This concept leads us to a technique called *Resonance Frequency Breathing* (RFB), which is a way of slow breathing that is proven to be effective for regulating the autonomic nervous system, and therefore provides several benefits for treating stress, and other emotional disorders [7]. This technique is studied in the article "The effect of resonance frequency breathing when used as a preparatory exercise in music psychotherapy: A single-case experimental study of a client with anxiety disorder", which describes (RFB) as a "slow, paced breathing at around six breaths/min, with the actual optimal speed needing to be determined on an individual basis" [7, p.8].

That generates physiological responses and adjustments such as the rhythmic synchronization of respiration, heart rate, and blood pressure [84], and increases the heart rate variability among other benefits. Hence, resonance frequency breathing has a central role in a heart rate variability biofeedback system [45]. It also effectively switches the autonomic nervous system from sympathetic activation to parasympathetic dominance, inducing an individual to a state of calm alertness [24]. By putting in charge the parasympathetic nervous system and combining relaxation to energised alertness, resonance frequency breathing stands out among other relaxation techniques [77].

The resonance breathing technique has established its value improving general health and stress reduction [63], emotional regulation [55], cognitive performance [62], sports performance [60], and dance and artistic performance [64]. It also has demonstrated effectiveness treating physical disorders like asthma [43], hypertension [47], chronic muscle pain [29], and emotional disorders like anxiety [68], and depression [39]. Therefore, RFB in combination with music therapy have a great potential supporting mental health [8] and [7].

2.1.4 Resonance Frequency Breathing and Heart Rate Variability

The article "A Practical Guide to Resonance Frequency Assessment for Heart Rate Variability Biofeedback" [74] explores protocols for conducting, and adjusting an individual's respiration rhythm to find their resonance frequency of breathing, and combined with their heart rate variability, activate the autonomic nervous system to attain positive outcomes for emotional, cognitive, and cardiovascular functions. The authors base the study on the postulation that every adult individual has their personal fixed resonance frequency, therefore activation in frequencies close to the resonance frequency, provide blood pressure oscillations that are beneficial for the *baroreflex* function (more information about the baroreflex mechanism.

2.1.5 Physiological responses

Physiological responses are autonomic bodily reactions to stimuli. These reactions can be valuable information for psychophysiological measurement [72]. The most classic type of measurement takes into consideration the activity of the autonomic nervous system (ANS), a part of the nervous system responsible for the activity of the heart, blood vessels, sweat glands, and digestive organs. It is possible to relate emotion activity in opposite directions to two of the autonomic nervous systems instances. The sympathetic nervous system is one of them, which prepares the body to respond to danger (commonly known as fight-flight-freeze reactions) by managing different resources such as heart rate, and respiration. The parasympathetic nervous system is the other branch of the ANS, which is responsible for down-regulating the heart rate when the arterial pressure exceeds optimal levels [26], and also performs digestive functions [72].

Thus, the parasympathetic system is the one in charge of down-regulating the nervous system and consequently leads one to a calm emotional state. Along these lines, it is possible to use specific physiological responses to acknowledge the activity of the autonomic nervous system. Since the ANS is responsible to manage physiological features that are directly related to emotion activity, its activity can help a medical doctor identify the emotional state of an individual at a determined moment. People who have anxiety experiences, for instance, tend to have increased heart rates and hand sweating as two common physiological indicators [72].

As mentioned, internal activity can indicate emotional activation. The heart rate is an important component responsible for and affected by the regulation of the nervous system. That also means that the heart rate can be voluntarily and involuntarily changed (e.g. by changing respiration rhythm and intensity), therefore it can be a key element to be used for downregulation of the nervous system in case one has the objective for example to calm down, deactivating the sympathetic nervous system and activating the parasympathetic nervous system.

There are also many ways to induce changes in the nervous system voluntarily. Heavy and fast breathing, emotions like stress and anger, or the use of substances like caffeine and other drugs, can increase a person's heart rate quickly. On the other hand, activities like meditation and slow deep breathing can be highly efficient to decrease heart rate, therefore downregulating one's nervous system.

2.1.6 Psychophysiological responses

Psychophysiological is relatively new in the field of brain science. In the book "Psychophysiology: The Mind-body Perspective", Hugdahl (1995) uses the term "affective neuroscience" to define it. According to Hugdahl, psychophysiology explores cognition and emotion through the perspective of the physiological mechanisms, and a body-mind approach. Psychophysiology assumes that cognitive, emotional, social, and behavioral occurrences are reflected in physiological activity. Moreover, psychophysiology investigates how thoughts and feelings relate to and impact internal processes of the body [33].

2.1.7 Universal Psychophysiological responses to music

The study "Music induces universal emotion-related psychophysiological responses: comparing Canadian listeners to Congolese Pygmies." [16] compares two very distinct culturally groups of listeners, to observe if music induces universal psychophisiological emotional responses among the completely non-related groups. The same experiment, utilizing 19 music sections in randomized order, was conducted with an isolated Mebenzélé Pygmies community in a Congolese rain-forest, in comparison to a group of western music listeners from Canada with no contact to the Congolese music. The experiment measured subjective feeling (valence and arousal), physiological activation, and facial expression. Results of the study indicate that emotional valence, which is a subjective value, is influenced by cultural background, while arousal responses are universally influenced by sound characteristics.

2.1.8 Baroreflex

The previews mentioned article "A Practical Guide to Resonance Frequency Assessment for Heart Rate Variability Biofeedback" also explains the *baroreflex* operation and its importance for generating the necessary physiological changes that trigger parasympathetic activation in the autonomic nervous system. The baroreflex is a homeostatic system responsible to regulate blood pressure, interacting with multiple regulatory systems in combination with respiration and heart rate variability. [74].

2.1.9 Heart Rate, Heart Rate Variability, and Respiration Rate

As defined on the paper "User-Centred Design and Usability Evaluation of a Heart Rate Variability Biofeedback Game": "Heart rate variability (HRV) refers to the variability of the intervals between consecutive heart beats." [86].

In the paper "Interaction between Heart Rate and Heart Rate Variability" [69], Sacha Jerzy analyses the associations between heart rate (HR), heart rate variability (HRV), and respiration rate (RR). Heart rate and heart rate variability are intrinsically associated, where HRV contains information that indicates the HR and its variability. Jerzy also points that this correlation is not only a physiological process but a mathematical phenomenon as well. The physiological part of this process is directed by the autonomic nervous system and it involves the HRV relation to the HR. "The higher parasympathetic nervous system activity, the slower HR and higher HRV" [69, p.207].

The mathematical part of this process consists of the nonlinear interaction between the respiration rate and the heart rate, which can help to predict critical cardiovascular events [69].

2.1.10 Entrainment in music

In the paper "What is Entrainment? Definition and applications in musical research" [14], Martin Clayton defines the entrainment theory as "the process of interaction between independent rhythmical processes". When it comes to entrainment in music, the researcher points out that entrainment is a recursive process, where "individuals perceive and generate hierarchical temporal structures" [14, p.52].

Entrainment is a relevant concept to the matter of this project, since the process of alignment and synchronization of a listener's breath pace and heart rate to the audio stimulus reproduced, can have characteristics of entrainment. More of this process will be explored in the section about background and literature further below.

2.2 Music and psychophysiology

Since ancient societies, music has been used as medicine through different generations and cultures [32]. Despite the positive outcomes of music therapy in clinical settings, this is a field that still lacks enough evidence-based research to become established in the scientific realm. In recent years, music and its psychophysiological effects on humans have been studied by neuroscience and other fields of science which is providing a promising future for music therapy as a science-based knowledge [30]. Despite the ongoing evolution of the scientific research in the field, music therapy is well established as a support for mental health, showing effective improvement in individual's well-being [53], [48], and [52].

The current literature present a considerable number of researches exploring how music affects different physiological functions in the human body such as breath, heart rate, and other instances of the nervous system mechanisms that have the potential to provide relaxation. It is still a vast field to explore, and many specific targets can be more investigated, especially targeting how music affects human respiration - making direct correlations between musical features and respiration changes in pattern.

2.2.1 Respiration adaptations to music

In their doctoral thesis "Detecting the Adaptation of Listeners' Respiration to Heard Music" [83], Upham explores when and how the experience of hearing music might produce stimulus-synchronous. These phenomena are studied through Repeated Response Case Studies, gathering participants' respiratory sequences during repeated listening to recorded music, and through Audience Response Experiments.

Looking at Upham's research, it is possible to assume that several specific characteristics are necessary to create respiratory phase alignment [Phase alignment connotes an agreement on the position in the phase cycle] between the listener and the music heard. Different types of music will deliver different results. For example, songs with voice will be more likely to provide alignment, even when the respiratory queues are not audible.

One of the findings of Upham's study is that respiratory phase alignment is not a stable process, it appears to arise in an inconstant manner, and rarely lasts more than one cycle of breath. It is also sensitive to certain elements, not responding to all types of music, indicating its conditionality to different variables that the study did not measure with sufficient control for statistical purposes.

Another discovery from this process was the propensity of sounds of respiration to generate respiration alignment. Evidence of respiration such as perceivable respiration sounds, songs with singing voices, or speech, appear to facilitate the influence on the listener's respiration and phase alignment. Nevertheless, respiratory phase alignment can arise not only in the conditions previously mentioned but also in music without perceptible inspirations and sounds originating from actions impelled by respiration.

Familiarity is also prone to influence on the respiration phase alignment. Although it is not consistent enough to be decisive in the process, it does not impede the alignment. At least one of the selected songs by the participants induced respiratory alignment in the vast majority of cases, showing that despite the non-guaranteed result, it has a reliable influence on the listener's respiration along with liking and pleasure.

Rhythmic complexity and groove are also musical characteristics that have a strong impact on the respiratory alignment, but this time in a relatively negative way. Songs with a lot of rhythmic nuances can drive physical responses that mask the signals favorable for phase alignment. The excitement and arousal provided by complex grooves activate different muscles and other physiological responses which create an impact on the timing of respiratory phases and consequential less coordination. Meaning that songs with simpler rhythms will be more likely to generate phase alignment.

In addition to the observations above, this respiratory system presents other influential variables that affect the rate of respiration. For instance, when you have cues repeating more frequently than every 10 seconds, the phase alignment turns out to be ineffective.

On the other hand, the performer's respiration exerts a positive influence on the alignment process. By considering the embodied perception of musical cues, Upham observes that not only the performer's respiration but also musical actions will have a considerable impact on the synchronicity of the listener's respiration. When the listener can imagine musical actions that match the song, more alignment occurrences are detected. Unexpected events in music will also cause responses that positively impact the expiration and breath-holding timing alignment. Adding to that, structural hierarchy possibly contributes to which beats are prioritized for breathing along, while emotional content affects how respiration is controlled, possibly impacting the listener's openness to be influenced by the music playing.

The heart rate variability also can provide relevant data when associated with the respiratory cycle. Studies found that music can sometimes increase the HRV during listening and music production ([56]; [85]; [35]; [40]).

Moreover, to annotate the timing and intervals for stimuli like audible breaths and motivic structures, Upham utilized an open-source application called Sonic Visualiser [10]. The stimuli used in the experiment were evaluated by the following criteria:

- Evidence of respiration
- Motivic structure
- Voicing complexity
- Timing flexibility

Concluding Upham's study, it is possible to observe that the respiratory system is largely complex and sensitive to many variables, which means that several factors will have an impact on the listener's respiration. That makes it difficult to have direct conclusions from research with natural stimuli to respiration. The mind is a strong component of that equation, meaning that the listener's thoughts and where the listener's focus is on the musical piece can imprint a great impact on the experience.

Not mentioning the natural unpredictable variability of the respiratory rhythm. These characteristics make it difficult to isolate and analyze specific feedback of the respiratory operation, although this is possible to do by identifying and distinguishing the patterns of respiratory response that are reliably prompted by segments of music and associating them with evident cues.

2.2.2 Bodily responses to music

In the article "Bodily responses to music, The Oxford handbook of music psychology" [31], , Hodges explores bodily and behavioral responses to music, dividing it into physiological and physical responses. Hodges observes that bodily responses are largely peculiar, as the music-listening experience is shaped by the unique perspective of the listener.

A great part of the physiological processes involved on music listening and the autonomic nervous system's regulation happen internally in the body. Therefore, most of the times a proper measurement tool is required to monitoring the data conveyed by these internal processes, even though these activities are detectable visually at times [31]. In their study, Hodges states that physiological responses are influenced by the experience of music listening. Hodges points that this affirmation is supported by a great volume of studies, although the proposition that sedative music can down-regulate the nervous system, and stimulative music can increase physiological responses, is controversial. This is due to the fact that emotions are strongly related to meaning, which is a concept developed individually according to one's personal experience, cultural background, and technical musical knowledge for example. Also the individual's personal preference adds to the complexity of this analyses. [31] As cited by Hodges, Frijda's (1988, p.349) "Law of Situational Meaning" refers to that context with stating that "emotions arise in response to the meaning structures of a given situation; different emotions arise in response to different meaning structures."

Hodges concludes his study by observing that research validate massively the influence of music listening on physiological responses. He goes further, pointing out that personal preferences impinge a strong influence on the results of studies on whether or not sedative music directly decreases physiological responses and stimulative music increases these responses. The latter idea is generally endorsed by the research reviewed, although not unanimously due to the personal preferences influence mentioned previously.

Despite of that, Hodges research review show lack of evidence on how the personal preference affects the physiological responses to music. Moreover, different studies showed conflicting results when it comes to personal preferences. Iwanaga and Moroki [36] point that the type of music, either stimulative or calming provided diverge responses on heart rate, respiration rate, and blood pressure, while music preference did not show evident influence. Yet, established medical treatment protocols largely support the influence of personal preferences, utilizing music that takes in consideration such idea, for example when utilizing music for pain and anxiety treatments [79].

Hodges explores the cultural, and contextual aspects of the personal experience while listening to music on the following lines:

> Music listening experiences are highly idiosyncratic, as each person possesses an individual history (e.g., amount of musical training) and personality, and each listening experience occurs in varying situations. One of Frijda's (1988) laws of emotion is the Law of Situational Meaning: emotions arise in response to the meaning structures of a given situation; different emotions arise in response to different meaning structures (p. 349). Imagine, then, that one hears the same piece of music, say the slow movement of Bach's Concerto for Two Violins in d minor, BWV 1043, performed at a funeral and then a few weeks later at a wedding. Undoubtedly, the reactions would be significantly different. [31, p.189]

Hodges continues by questioning the meaning of such physiological changes in response to music stimuli. After proving that music modulates physiological processes, he suggests a qualitative analysis of such changes. Exemplifying his inquiry, Hodges questions if a raise in heart rate would suggest positive or negative implications. He states that the attempts to correlate particular physiological activities directly to specific emotions have not presented successful results. Music-induced activation of facial muscles, such as increased smile activity in response to happy music in contrast to sad music (Lundqvist et al. 2000), is an example of effectively correlating the physiological responses to emotions, although there are not many other cases in research. Hodges finishes stating that by taking into account individuals' preferences and idiosyncrasies when designing studies, one may be able to gain greater insight into the influence of music on physiology. Music medicine is currently leading the most advanced research on this matter. [31, p.190]

2.2.3 The effects of music on heart or pulse rate

Moreover Hodges investigates heart or pulse rate responses to music, pointing that although some studies suggest that any type of music tend to increase the heart rate in comparison to silence (Krumhansl 1997; Rickard 2004), substantially, music with stimulative attributes like fast beats/tempo, loud passages, and staccato progression, tend to increase the heart rate, while sedative music characterized by slow tempo, soft passages, with legato progressions tend to cause a decrease in heart rate. The idea that the music listening experience has the capability to modify heart rate in opposite ways (either by raising or lowering it) is endorsed by a relevant number of research (e.g. [5]; [6]; [71]).

2.2.4 The effects of music on blood pressure

When it comes to the effects of music on blood pressure, music tends to show similar behavior to the observed on the pulse rate. For instance, Hodges points contradictory results from different research. While some studies observed increased blood pressure over the listening of stimulative music [5], [42] and [61], other studies showed that music decreased blood pressure not only over sedative music, but also some stimulative music had the same effect on the listeners. ([50], [71]). Also, context and meaning seem to be important variables on how music affects physiological responses, while self-selected music proved to be effective in lowering blood pressure ([23]; [57]; [82]), music students under the expectation of a graded performance had an increase in blood pressure while listening to music [1].

2.2.5 The effects of music on respiration

Hodges also analyses the effects of music on respiration, showing that various studies indicated a rise in breathing rate ([6] and [36]). Ries (1969) showed increases in breathing rate related to music preference. Haas et al. (1986) found that musical rhythm can generate an entrainment process on breathing rates. In the article "Physiologic responses of coronary care patients to selected music" [15], Davis observed that respiration rate decreased to sedative music but did not change with stimulative music.

In the article "Effect of music on blood pressure, pulse rate and respiratory rate of asymptomatic individuals: A randomized controlled trial" [75], a study was conducted observing cardio respiratory responses while listening to Indian classical music were compared to staying still in silence. Relevant reductions of systolic [the maximum pressure in the arteries when the heart is contracting [12]] and diastolic [the arterial pressure when the heart reposes in between beats [3]] blood pressure, pulse rate and respiratory rate were observed immediately after listening to Indian classical music, while no significant change was detected when staying still in silence. This way, the invasive methods for reducing cardiovascular diseases can give place to a more acceptable approach using music. Therefore music can be used as a supportive and economically accessible tool for preventing cardio vascular diseases.

In the study "Passive music listening spontaneously engages limbic and paralimbic systems" [9], Brown observed responses in the limbic and paralimbic systems of non-musicians listening to unknown instrumental music. By opting for comparing results to unfamiliar music, the study aimed to investigate how the listener's emotions would respond to music when they did not have experienced the music before, therefore excluding expectations associated with the song selected. That can help assess if there are direct responses related to the sound stimuli, in spite of cultural background and personal music experience. The study revealed that unfamiliar musical stimuli without a specific intention can generate intense positive feelings with activation in the limbic and paralimbic systems [the limbic system processes memory, emotions, and behavior (especially the survival-related behaviors) [34]]. It appears that aesthetic responses follow a direct pathway, which may be used as a foundation for determining our preferences and how we use music in different social contexts and entertainment [9].

Moreover, the study "The effect of music listening on physiological responses of premature infants in the NICU" [11] tested the effects of music in low birth-weight infants who had to be oxygenated in a Neonatal Intensive Care Unit. They were 20 subjects in total, where 10 of them listened to lullabies and the other 10 were control subjects. All of the subjects had their auditory system tested (auditory brainstem response) to certify that all infants had a consistent audiological response, therefore normal hearing. The experiment measured heart rate, respiratory rate, oxygen saturation, and apnea/bradycardia episodes during treatment. The conclusion of the experiment pointed out that music impacted positively oxygen saturation, heart rate, and respiratory rate, with no rise in apnea/bradycardia episodes.

In the research "Effects of perceived musical rhythm on respiratory patterns" [27], Haas, Distenfeld, and Axen collected data from two groups of 10 people, in which one is formed by individuals with no musical training, and the other is formed by trained subjects. The subjects tapped to both, musical parts and a metronome alone, and half of each group also listened to the segments without tapping. After measuring the breath period, beat period, and phase coupling on the last 20 breaths of the interaction with the segments, the data showed relevant decrease in the coefficient of variation to the breath period in all participants, while listening and tapping had the biggest decrease showing 10%, and 15% when only listening, compared to the 23% base line). The experiment results show also relevant indication of entrainment between rhythm and breath period. Among the conclusions out of this study, the following is worth highlighting for this matter:

> These data advance the following hypothesis: musical rhythm can be a zeitgeber (i.e., pacemaker), with its ability to entrain respiration dependent on the strength of its signal relative to spurious signals from the higher neural centers that introduce noise into the central pattern generator. Tapping reinforces the zeitgeber, increasing its signal-to-noise ratio and thereby promoting entrainment. [27, p.1185].

By using the term "zeitgeber", the author means that the musical rhythm has the ability to prompt the circadian rhythms of an individual's body [87]. Considering this affirmation, one can conclude that rhythm can induce the respiration pace in order to achieve down-regulation of the nervous system.

Chapter 3

Breath Painting: A biofeedback based data visualization tool

Biofeedback and data representation techniques are not a new technology in our time, the term "biofeedback" has been explored since the late 60's [70], while the first heart rate data sonification device, a room-sized machine called *electrocardiograph*, has been in use since 1902 [21]. The same applies to data visualization techniques, they have been around with well-developed cartography since the 16th-century [19] and [20]. On the other hand, the combination of all these techniques together, with modern technology and advanced apparatus, opens up a whole universe of possibilities.

The possibilities provided by data representation techniques such as data visualization and data sonification are appealing to me. The fact that we can visualize the internal bodily process, and listen to alterations regarding an individual's psychophysiological activity sparkle endless creative solutions that can be at the same time, effective for medical use, and artistically instigating.

This is the reason why the idea for this prototype was born. By combining such techniques, it is possible to create an interactive system that receives biofeedback input from the user's respiration data and translates it into graphic information. The idea is to raise awareness and induce people to breathe mindfully and with quality. That process can be supported by data sonification, where sounds indicate when the user's breath is in resonance and stable, or when it is too fast and unstable.

3.1 Prototyping Process

The objective of this prototype is to provide unique visualizations of the correlation between breath data and music data from an individual's music listening experience. The prototype takes numbers as input and translates them into dynamic geometric shapes and colors, as means to convey information about the synchronization in behavior between the two types of data. For this project, the objective of the visualization is to display technical data with an artistically engaging approach. In sum, people from any educational background will be able to visualize how different types of music modulate different breathing patterns. That is why the prototype was named *Breath Painting*. The challenge here lies in how to process this data, and implement meaningful mappings with clear outputs that can be understood by the general public.

3.2 Product Research

Moving forward, I initiated the creative process, by performing product research with the goal to collect references and investigate similar existent products. This research was a valuable source for identifying unattended needs, gaps, also common issues, and surely an inspiration. Amongst many interesting references found, some of them present key similarities regarding goals and functions that are worth be investigated in the present project.

With similar characteristics and goals to this project, *heart/work* (figure 3.1) is an iOS app that uses health information data output fetched from the Apple Watch to generative interactive artworks. The app was developed by a group of students (Marco Falanga, Ottavio Gelone, Baldev Ghelani, Giselle Katics, Mikey T. Krieger) at the Apple Developer Academy in Napoli, Italy, with the goal to improve the user's health quality and stress management by decreasing the user's heart rate [65]. It also interacts with meditative breathing exercises and environmental information, measuring the progression through guided breathing exercises. The input data (figure 3.2) was translated into visual interactive elements such as colours and shapes, which communicate different types of information about the data according to a visual language (figure 3.3) created by the group of students.

Another relevant reference for this project is "*Respire:* Virtual Reality Art with Musical Agent Guided by Respiratory Interaction" (figure 3.4). Respire combines breathing interaction (with a breathing sensor) and musical feedback in an immersive virtual reality (VR) environment to provide an augmented breathing experience [80]. Respire utilizes mappings (figure 3.5) from breathing data to visual and sonic responses to provide an immersive breathing experience. In this platform, the user is able to explore over or under ocean perspectives by using the breath through the breathing sensor to control the vertical position in the VR environment. Also, the breathing data patterns modulate the arousal of the musical agent and the intensity of the waves of the virtual ocean. The user's breathing frequency and patterns are measured by the thoracic and abdominal sensors that send it to the system which does appealing mappings to enhance the gamified experience. As mentioned, when breathing in, the user moves vertically, first rising and then slowly sinking underwater, while they move slowly across the virtual environment when the user breaths out. The breathing frequencies are also processed into the musical agent (figure 3.6), which correlates the frequency of the breath to the eventfulness of the audio generated in real-time. Also, the speed of the breath determines the unpredictability and quality of the visual elements displayed in the virtual environ-

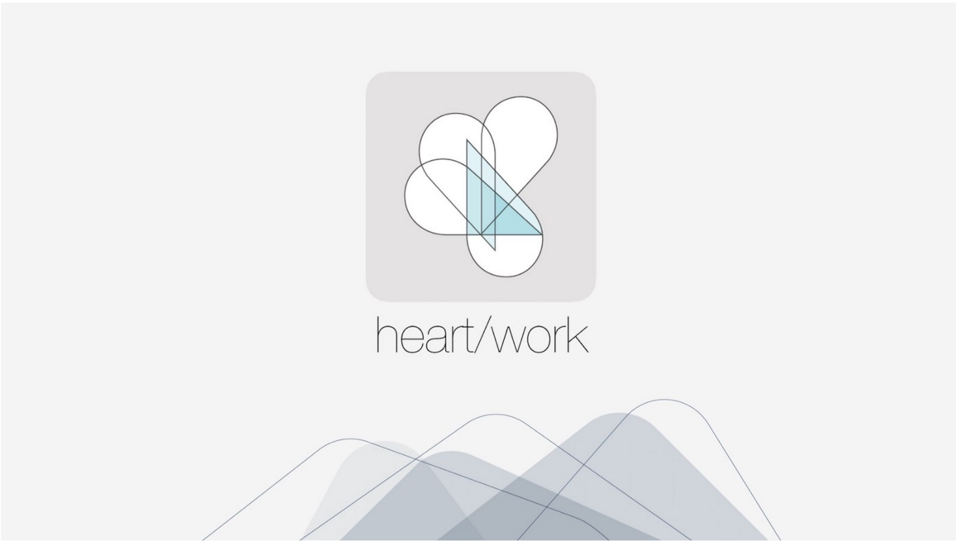

Figure 3.1: heart/work App - Identity
Source:
https://moritzrecke.com/generative-art-created-by-heart-work-ios-app/

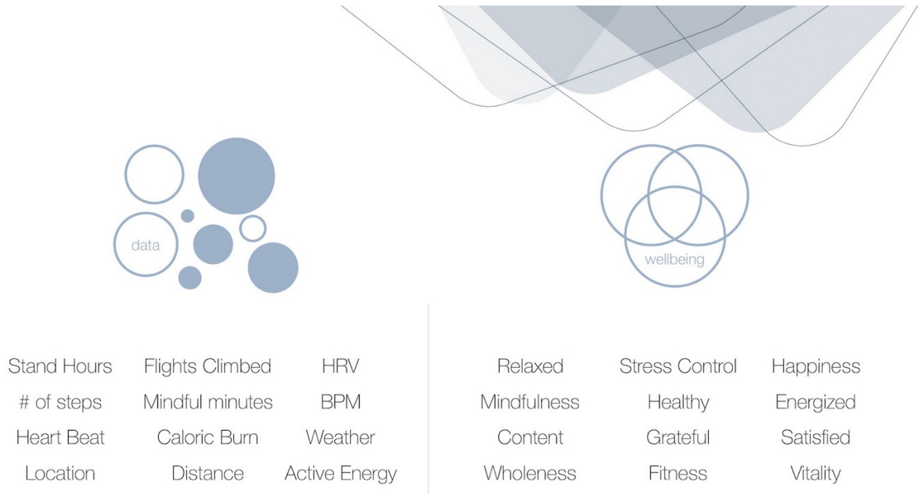

Figure 3.2: heart/work App - Data conceptualization approach

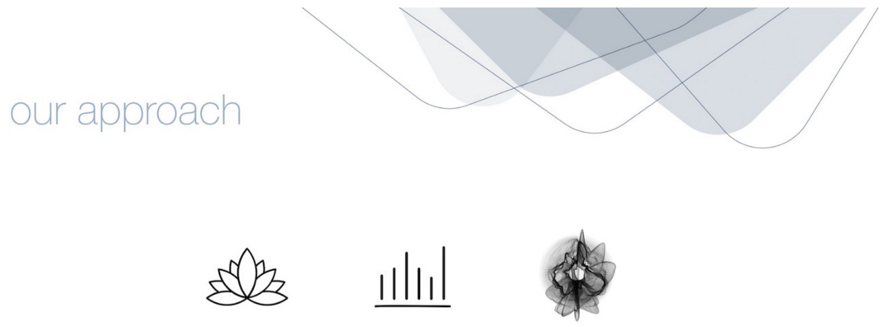

Figure 3.3: heart/work App - Visual language

ment, meaning that when the breath is fast the elements will be more unpredictable and induce an uneasy mood, while slow breathing makes the environment stable and peaceful. Also, sustained breaths allow the user to stay still in place, contrasting with fast and strong breaths that turn the movements turbulent.

Also aiming for the combination between art and health, *GANspire* (figure 3.7) is a deep learning tool developed by a multidisciplinary team of artists, designers, researchers, and clinicians. GANspire produces breathing pressure waveforms (figure 3.9) through a generative model (figure 3.7), and can be used for medical purposes and artistic applications. GANspire's interface design (figure 3.8) aims to provide an easy way for the user to adjust the generative model and modulate the breathing expressiveness. Among other goals, GANSpire aims to provide empathetic interactions between patients and soft breathing objects in clinical settings as means to support patients with respiratory diseases [73].

3.3 Programming Language

During the product research process, I started searching in parallel for a suitable programming language in the context of visual arts. Amongst several options, highlighting Pyhton, JavaScript, and Processing, I concluded that JavaScript was the most convenient programming language, using the library p5.js and the p5 web editor as the framework. This choice was taken considering economical accessibility, time frame, features, experience with coding languages, and open knowledge available.

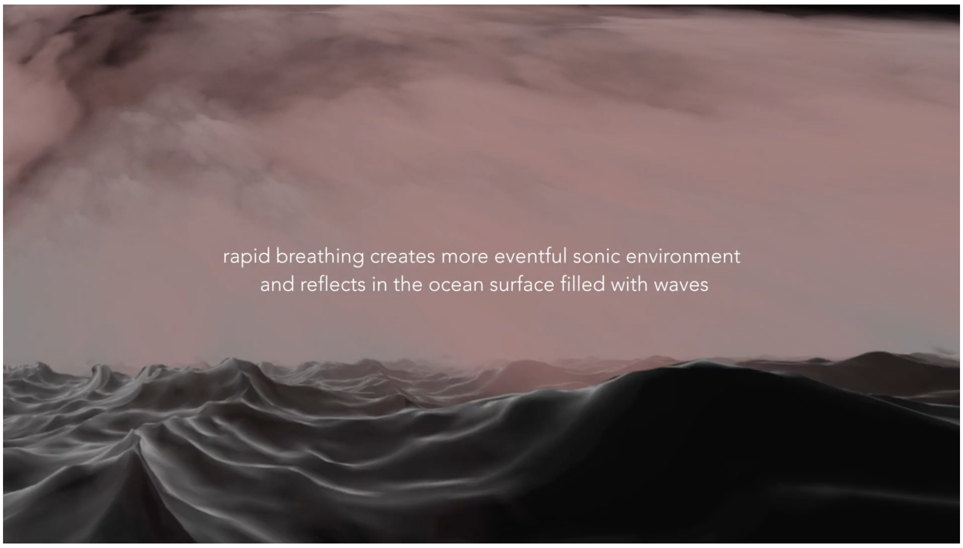

Figure 3.4: Respire - Virtual environment visuals
Source: https://kivanctatar.com/Respire

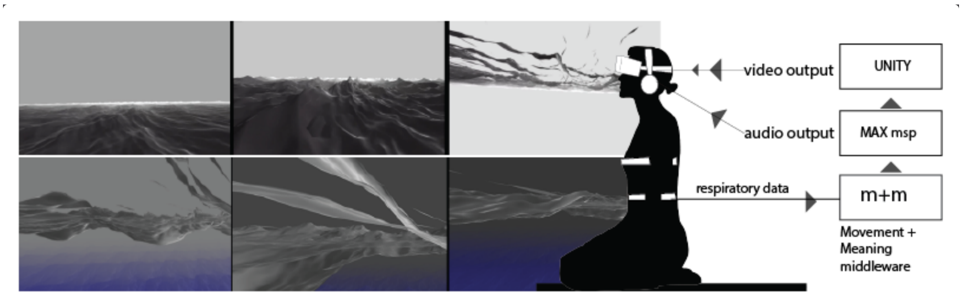

Figure 3.5: Respire - System Design

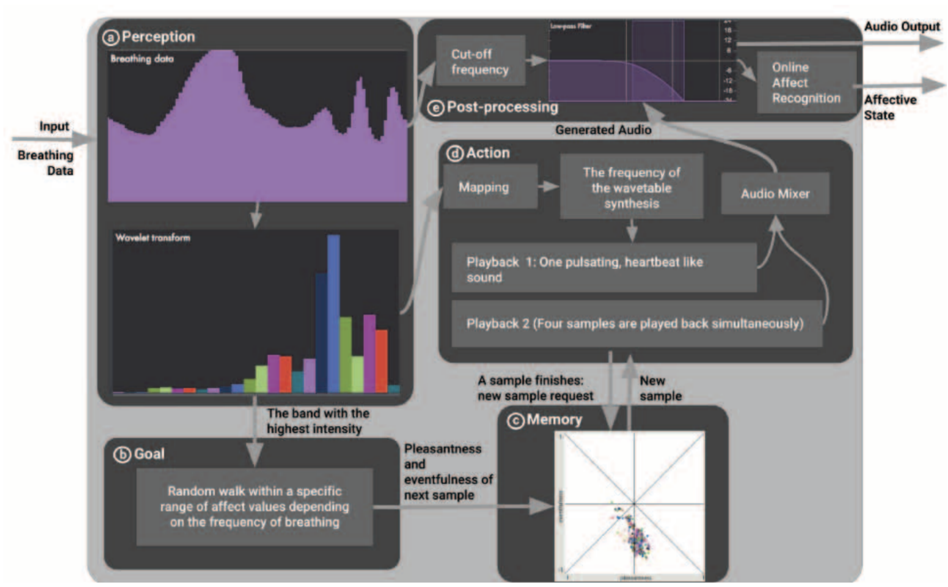

Figure 3.6: Respire - Musical Agent

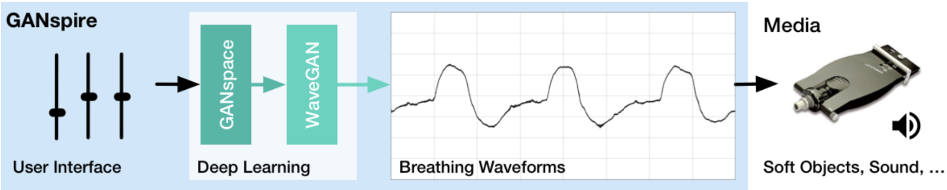

Figure 3.7: GANspire - System
Source: https://hugoscurto.com/portfolio/ganspire/

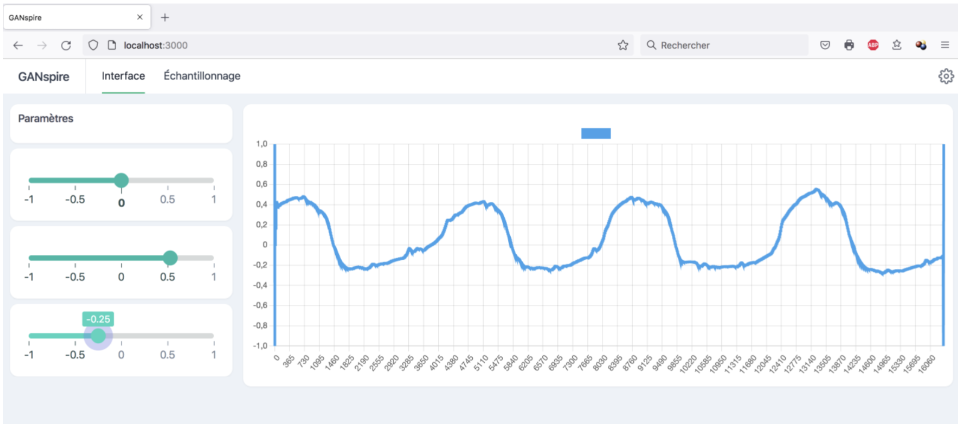

Figure 3.8: GANspire - Interface

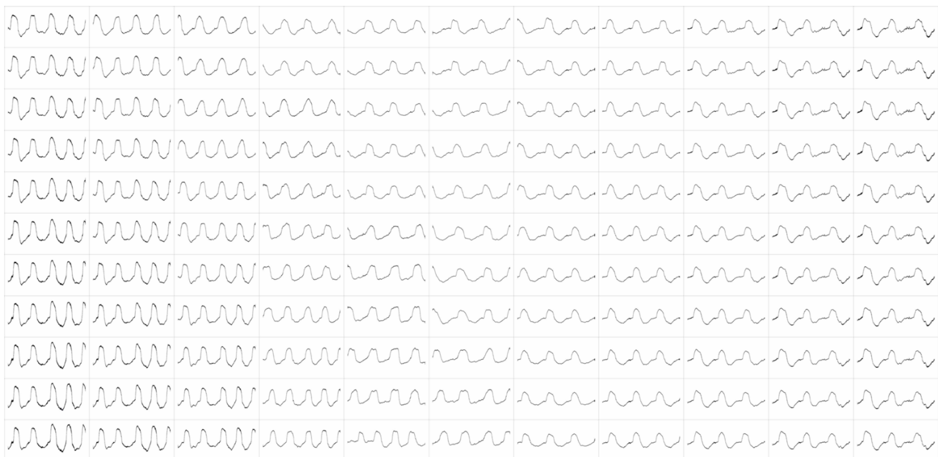

Figure 3.9: GANspire - Sample breathing waveforms generated by the generative model

3.4 Data

The data that will be used in this project is the first and most important component starting the development of the prototype. The breath and music data inputs used in this project were collected from the experiment "Headphones/speakers Experiment, 2018" [67] at the University of Oslo, part of the "MICRO - Human Bodily Micromotion in Music Perception and Interaction" project [37], which studied how music and rhythm influence the human body motion. The goal of the "Headphones/speakers Experiment, 2018" experiment was to analyse the body motion and rhythm entrainment while listening to music, exploring how the motor responses would differ if the listener were using headphones or speakers.

The participants were 42 persons signed up at the University of Oslo, without any impairments or medical conditions that would impact the results of the study. All the subjects listened to the same audio sample through headphones and speakers with systematic variation of the order of the samples and the listening device used. Every session starts with 30 seconds of silence, and presents the audio stimulus (45 seconds each) in different orders, having a 30 seconds interval between each song, and at the end. Different measurements of the participants movements were fetched, one of them being the breathing movement. The data set package provided came with a table called "Stimulus order hp-sp", which presents the order in which the audio stimulus were played for each participant's session. The table also provides a list of the audio stimulus named and numbered for identification as following:

- 1-Andre (EDM track with a low level of complexity)
- 2-Metronome (Metronome track based on a drum sample)
- 3-Neelix 1 (Trance track with complex rhythmic structure)
- 4-Neelix 2 (Same as Neelix 1 track but different section: a rhythmic and glissando build up)
- 5-Pysh (Deep house track with a steady, but slightly laid-back beat)
- 6-Rhythm (Simple two-measure drum pattern)

It is important to consider the differences between the musical stimulus, being it a song, metronome, or rhythm patterns. Their features, complexity, and other attributes are relevant information to understand how the breath is influenced by such characteristics. The brief description following each one of the tracks on the list of audio stimulus above, was collected from a detailed description found on the research article "Headphones or Speakers? An Exploratory Study of Their Effects on Spontaneous Body Movement to Rhythmic Music" [88].

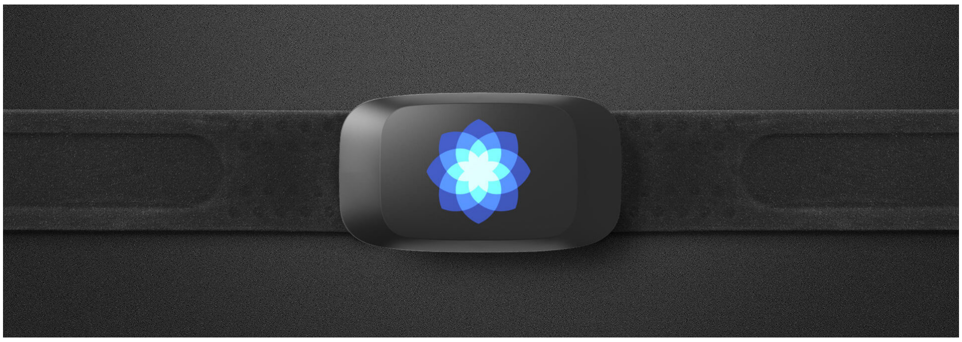

Figure 3.10: Flow Sensor
Source: https://erikjohannes.no/RespiratoryPatterns/

3.4.1 Sensor

To understand precisely the data obtained, it is necessary to know technical details about the sensor that collected the data. The breathing sensor used to collect the breath data [67] for the previous mentioned experiment [37] was the *Flow* (figure 3.10), a strain gauge sensor developed by a Norwegian startup called *Sweetzpot*. The article "Evaluating a Low-Cost Strain Gauge Breathing Sensor for Sleep Apnea Detection at Home" [41] published on the conference *2021 IEEE International Conference on Communications Workshops (ICC Workshops)*, evaluates the Flow sensor, and it provides technical information about the data output from it. The report observes that the Flow sensor can distinguish between normal breathing and a disrupted breathing pattern precisely. The report also found issues regarding the sensor's build quality, data acquisition, and sampling rate stability, but these are irrelevant for this prototype.

According to the article "Quantifying the Signal Quality of Low-cost Respiratory Effort Sensors for Sleep Apnea Monitoring", the Flow sensor has a nominal sampling rate of 10Hz, with a sensitivity of 98,91%, and a positive predictive value of 98,81% [49]. The sample rate is an important specification to be considered when scaling and processing the data sets to make sense in a linear manner, when comparing the two types of data (breath and music).

Since Flow gauges the respiratory effort by strapping a belt (figure 3.11) around the user's thorax, bigger stretches output bigger numbers, indicating deeper breaths. This is because this type of sensor can detect the respiratory quality and behavior by measuring the thoracic expansion resulted from the respiration. Understanding how the sensor works is crucial to understand what the numbers are informing in the data acquired.

3.4.2 Data Analysis

Once I understood the basics of the data acquired, the first step taken with the information available was to open the breathing data of one of the subjects (subject 10) in a spreadsheet and compare to their audio listening sample order trying to find patterns that indicate the correlation

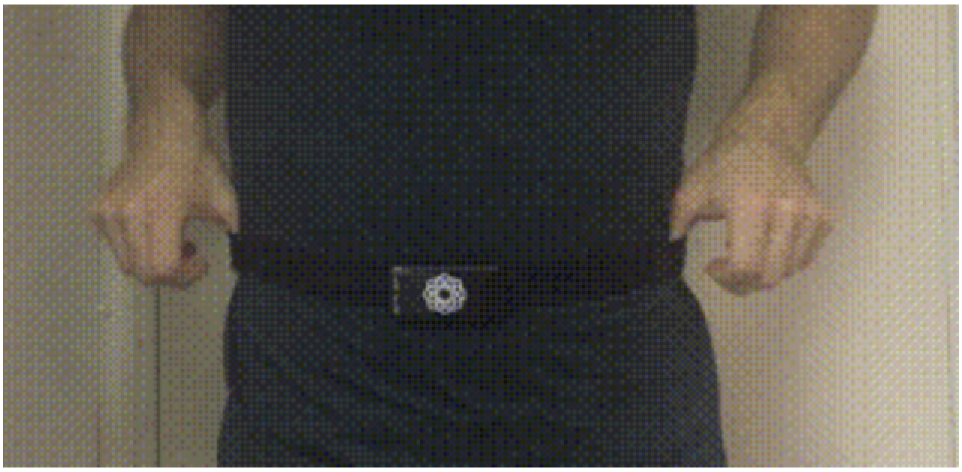

Figure 3.11: Flow belt usage
Source: https://erikjohannes.no/RespiratoryPatterns/

between the different data sets. Since the breathing data is displayed in sample units and not seconds, to make any comparisons to the audio samples comprehensible I took in consideration the sensor's sample rate (10Hz) and marked every 10 row in the table to facilitate the visualization of what represents 1 second in the data table that I got from the "Headphones/speakers Experiment, 2018" experiment.

From that point I generated a chart (figure 3.12) to visualize the data oscillation in time, hence observing the breathing behavior at determined time sections of the subject's listening session - in this case, 313 samples from the start to sample 313, meaning 30 seconds of the beginning of the session. The y-axis displays the level of contraction or expansion of the sensor's belt, indicating thorax expansions while inhaling or contraction during exhalation. A relatively flat line on the peak amplitude of the wave means an interval with the thorax filled with air before exhalation, while flat lines on the negative peaks indicate intervals with an empty chest before the next inhalation. The x-axis represents the time in samples (10Hz).

As mentioned, every listening session starts with 30 seconds of silence before the first audio stimulus, meaning that this is the breathing behavior of the subject 10 (S10) while in the first 30 seconds in silence.

Moreover, I decided to compare the next 45 seconds (figure 3.13) of the listening session, meaning that this time the subject 10 was listening to the stimulus marked as number 1 in the Stimulus table provided, which is the sample named as "Andre", which is an EDM track with a low level of complexity.

Analyzing the comparative chart, we can observe the difference between the two breathing patterns. The blue line displays the breathing pattern of the subject 10 starting at the very beginning of the session while listening to 30 seconds of silence. The three first waves show a higher amplitude, which can be interpreted as the participant starting the session

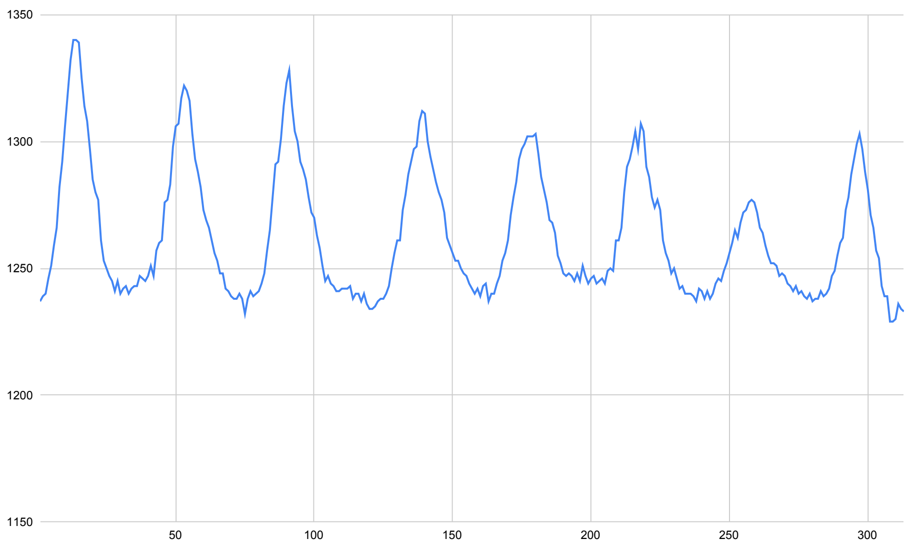

Figure 3.12: Chart generated from 313 samples (or the 30 first seconds) of the "Headphones/speakers Experiment, 2018" experiment data

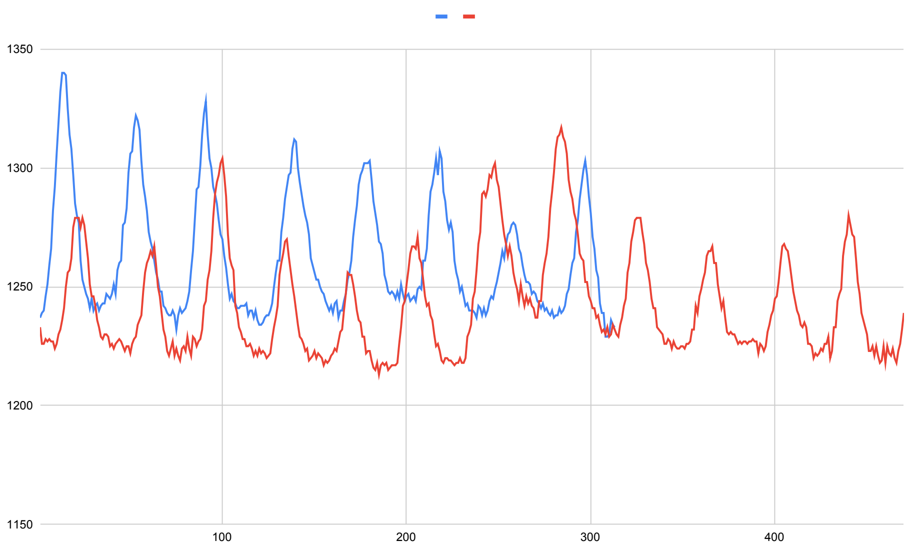

Figure 3.13: Chart generated from the comparison between the breath patterns during 30 seconds (313 samples) of silence (blue) in contrast to 45 seconds (470 samples) while listening to the track "Andre" (red).

with deeper breaths with slightly shorter intervals between inhalations. Sequentially, the waves show decreased peaks (the level of the stretch of the sensor) in time, indicating shallower breaths with longer intervals with an empty chest after exhalation. On the other hand, the red line shows the breathing behavioral changes in the next 45 seconds of the song stimulus, when the participant listened to the track "Andre". The red line shows more variance between the amplitudes and the values along the waves, with much less smooth curves. It also indicates shallower breathing with a smaller amplitude and deeper levels of thoracic contraction. Another behavioral difference is displayed by the slightly increased number of cycles in the middle of this session, indicating a faster respiration pace at this point, although it returns to the previous pace quickly.

These differences in the pattern can indicate that the sound stimulus impinges an influence on the breathing behavior of the listener. From this point, more questions are raised regarding the correlations between the sound stimulus and respiration. What does the sound stimulus "look" like compared to the breathing patterns at the same moment of the session? Which features of the sound can be related to such changes in breathing behavior?

This prototype aims to simplify the visualization of these correlations and broaden the accessibility to this information, facilitating the understanding of these questions. At this point in the prototyping process, I started researching the different types of data visualization and possible techniques to overlay different types of data.

3.5 Data visualization

Once the data set was acquired and a research on the several applicable types of visualization was performed, I had a better perspective of what types of mappings could be utilized for this project. Initially I selected one subject as a study case to experiment with different approaches for the sound data visualization. Then I prepared a file setting together all the audio stimulus samples in order according to the selected subject's (S10) listening journey. This audio file also included the silent sections of the experience, which provided a better understanding of how the dynamic between the absence and the presence of sound information would affect the way in which the sound data information could be translated into graphic elements.

3.5.1 Audio data visualization

After organizing the data received, I started working on solutions for the audio data visualization. The first step taken in the process of transforming sound data into visual information, was to obtain musical information from the audio file that I prepared. Music information retrieval (MIR) is a research field dedicated to explore computational processes in order to extract data from music. The process starts when the audio signal (analog

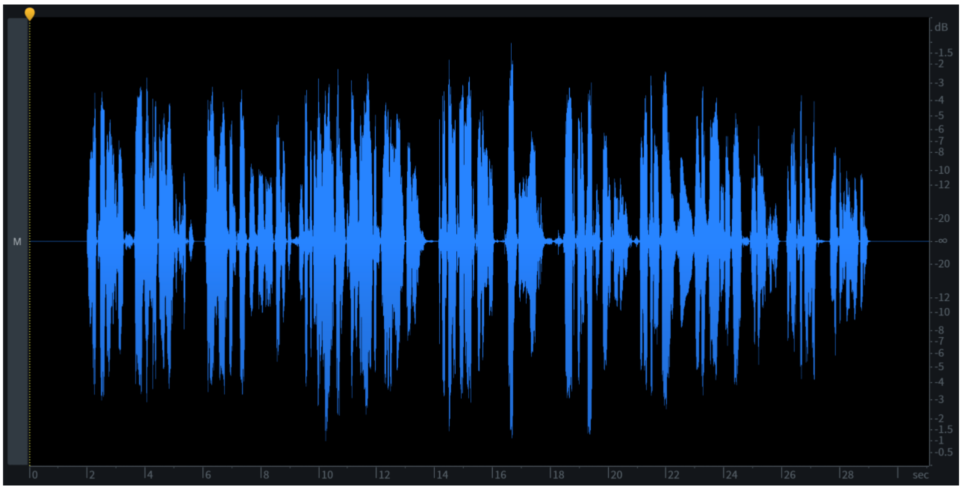

Figure 3.14: Traditional waveform
Source:
https://www.izotope.com/en/learn/understanding-spectrograms.html

or digital) input is analysed in its digital form as a sequence of samples in time. There are several types of music information that can be used for creative solutions such as innovative music searching, classification, recommendation, transcription, beat and melody tracking, sound and lyrics analyses, and consequently music visualization is one of them too.

The most common type of audio signal visualization which most people recognize is the *waveform*. A waveform graphic (figure 3.14) displays the audio signal's amplitude changing in time [13]. This information allows a person to understand the level of the energy content of audio through its duration, and also spot peaks, compression, and clipping signals for example. That alone can be a good indicator of the influences of the audio content on the subject's breathing patterns, but other types of audio data can be valuable information for a deeper understating of these correlations.

Adding another dimension of information along with the audio amplitude, *spectrograms* are a more complex and detailed tool for audio data analyses. Spectrograms provide a visualization of the frequency content intensity and amplitude varying with time [51]. Commonly, spectrograms are displayed as heatmaps (figure 3.15). Whereas the frequency content is typically represented by the colour location on the y-axis, the amplitude is classically displayed as the brightness of the colour, and the x-axis is the time dimension.

As a first approach to this project, I opted for the spectrogram to represent the audio stimulus data visually. I took this choice considering that the spectrogram provides information regarding the frequency content and amplitude of the audio, allowing interesting correlations between the audio stimulus and the breathing data responses over time. In this case, however, I opted for developing a circular spectrogram for artistic purposes. A circular representation denotes the impression of a cyclic narrative to the visualization, which relates to the cyclic character of the

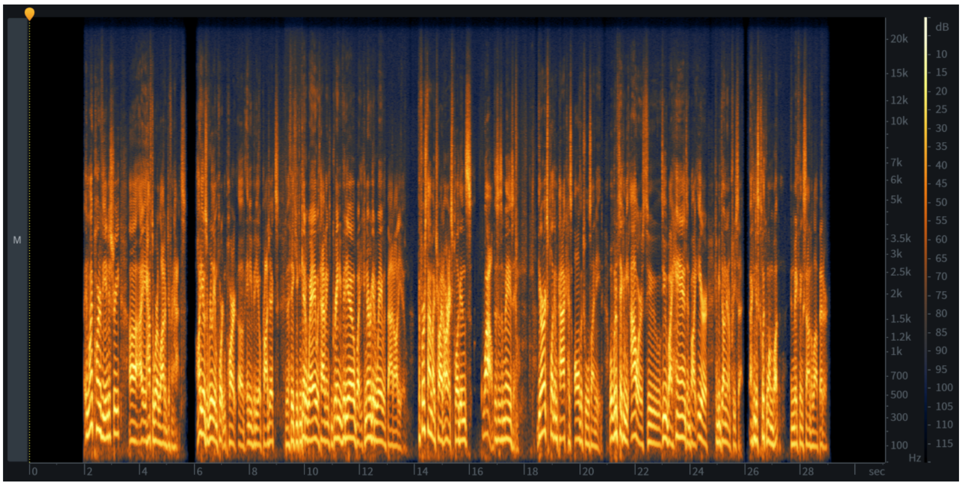

Figure 3.15: Spectrogram heatmap display
Source:
https://www.izotope.com/en/learn/understanding-spectrograms.html

breath, and also to the way music has been reproduced on analog media like a vinyl record for instance. Moreover, a circular visualization looks artistically appealing to the general user, dissociating it from the classic chart style and other classical technical representations for audio data.

To generate a spectrogram on p5.js, you can use the audio analyses algorithm *FFT (Fast Fourier Transform)*, which distinguishes the sound signal frequencies, isolating them within the signal's waveform. The p5.FFT object computes the audio signal's amplitude along with the time domain, in which the values returned represent the amplitude of the waveform at the respective sample in time, and also the amplitude along with the frequency domain, returning an array in which the frequencies are represented by the indices, and the values are the amplitude for each frequency (reference information found at https://p5js.org/reference/#/p5.FFT).

On the first trial (figure 3.16) I used a random audio sample that I had available from an online tutorial provided by "The Code Train" as a study case, and coded the circular spectrogram on *JavaScript p5.js* which provided the visual result showed by the figure 3.16.

With this visualization, it is possible to see the audio data behavior in time, possible silent gaps, parts where the audio is mostly in the low-frequency range, and some emphasized frequencies. Although it is an interesting figure by itself, it still can be improved in terms of clarity and aesthetics, and more importantly, it needs yet to interact with the breathing data.

The first perceived improvement for this art was to increase, thicken up, and spread the lines a bit more to make the information clearer. That also makes room for the breathing data to be placed on the top of the spectrogram, or dynamically interact with it. Also, the use of colours can make the spectrogram details clearer to be spotted.

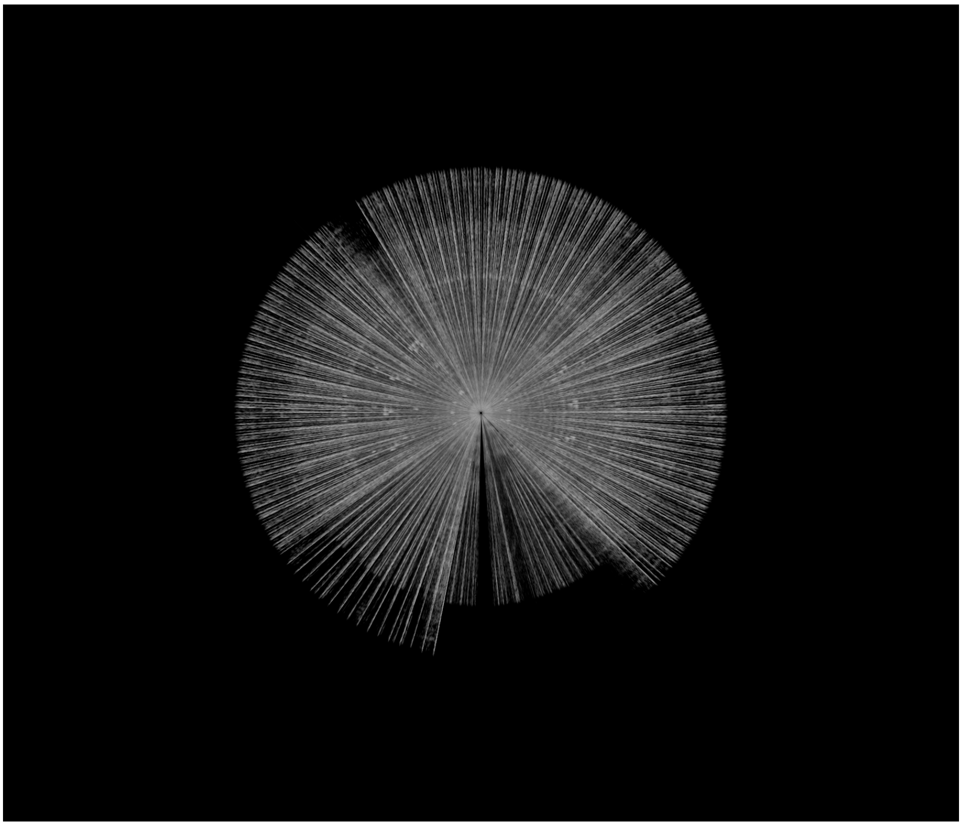

Figure 3.16: Circular Spectrogram made with p5.js (JavaScript)

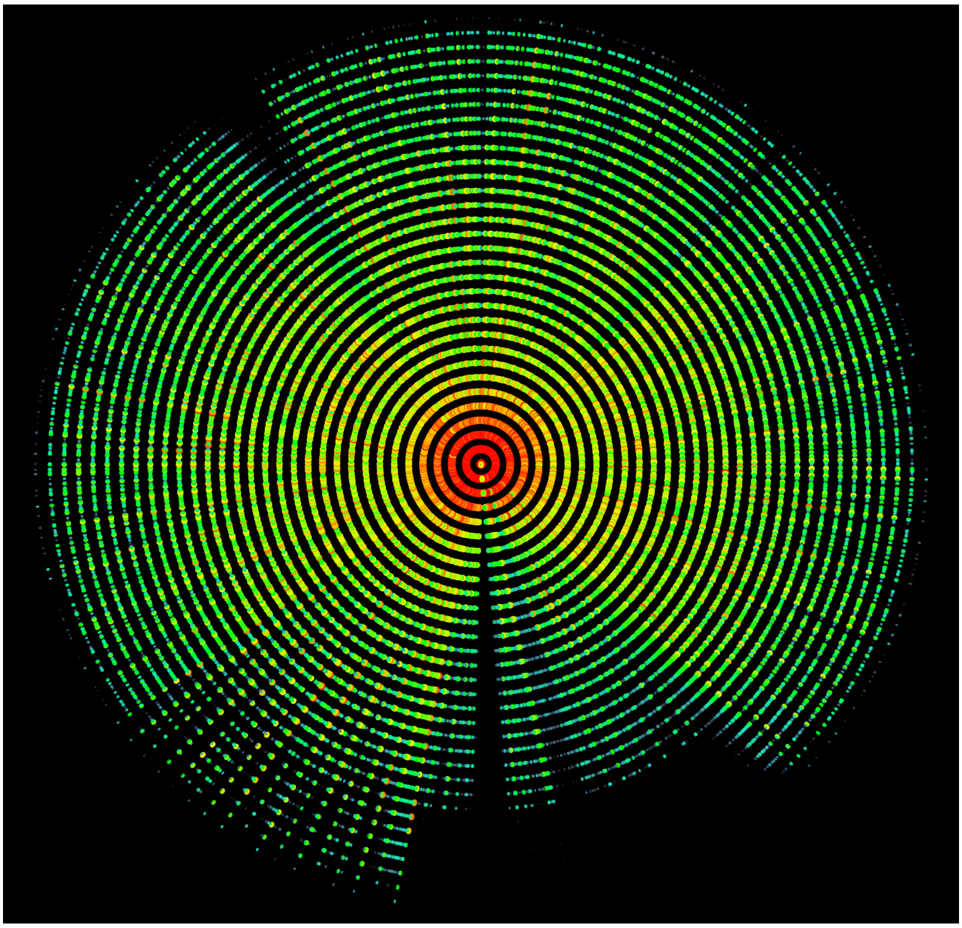

Figure 3.17: Colorized circular Spectrogram (p5.js)

After implementing an HSB (hue, saturation, and brightness) based color mode, I made the spectrogram data react according to the colors attributes, such as hue (or the color gradient) representing the energy levels of the frequency content, from blue or total faded, as the weakest frequencies, to red, representing the strongest frequencies. The color implementation with adjustments on the line stroke weight, and reducing the *FFT's* bin array length, provided the aesthetic displayed in the figure 3.17.

The colours applied to the spectrogram provide a better understanding of the energy level variation within the frequency content over time. One can observe for example, that the bass frequencies (displayed on the innermost rings) have a constant high level of energy compared to the highest frequencies, which vary more with the song's dynamics.

Aesthetically analyzing it, it is possible to interpret that the black and white image displays characteristics of spatial object photography, whereas the colorized image can transmit the idea of a tree trunk sliced, showing the growth layers of the sliced "tree". That is a good start, the colours are beautifully displayed and the circular shape makes it expand, and gives it movement. Moreover, the "tree" analogy is very convenient considering that the final art will display breathing data information.

As the circular spectrogram provided a satisfactory visual result, I went for the next step which is working with the breathing data to create interaction between both types of data.

3.5.2 Breath data visualization

After defining a satisfactory method to visualize the data from the audio, I started working on the breath data visualization. The first procedure at this point was to parse the breath data to p5js in the correct format. The breath data came as a csv file, so my initial thought was that I would just have to make sure that the csv file was formatted with comma-separated values. Then on p5js, I loaded the table and stored the data rows values in an array called *data* using a *for loop*. The process seemed to be working as it should when logging the table on the console. However, when I tried to use the array for calculations like the *mean*, *average*, and other procedures, the program was outputting errors. Then I realized that the csv file was displaying numbers as *string*, which had to be converted to numbers. It is worth mentioning this troubleshooting part of the process since something so simple can take a lot of creative time for people that are new to programming.

Once the program was reading the breath data table correctly, the creative process started again. The breath data can be visualized in many different ways, yet in the present application, the goal is to make it interact with the sound data in a meaningful and clear way. At this point, I started researching the many types of geometrical representation that I could apply to the breath data. Dot plots, line graphs, flow fields, Spirograph, and shapes like dynamic arcs seemed to be a good fit to interact with the spectrogram, in my perception.

There were taken into consideration other solutions other than layering different composed shapes representing the breath and sound data individually. Another way to create this interaction is to make one data input modulate the other data visual output. For instance, it is possible to make the breath data modulate the spectrogram, either changing the colors and shape of the final visual structure of the spectrogram or modulating how the input is received by the function responsible to draw it. For example, the breath data could modulate the size of the lines, or their stroke weight, by considering the value of the numbers coming from the breath data.

Choosing a visual structure to represent the breath data was an iterative process. After several tests, I found a structure that represents breath from a conceptual perspective but also that carries aesthetic consistency regarding a symbolic representation of breathing. The most important in this case was that the chosen shape has a friendly code structure that allows the mappings to provide meaningful progressive changes on the shape, that can be understood in terms of data behavior.

Following the sequence of pictures below it is possible to see the iterative progression, starting with the breath data represented by dots in a circular structure, followed by some of the tests done during the iterative

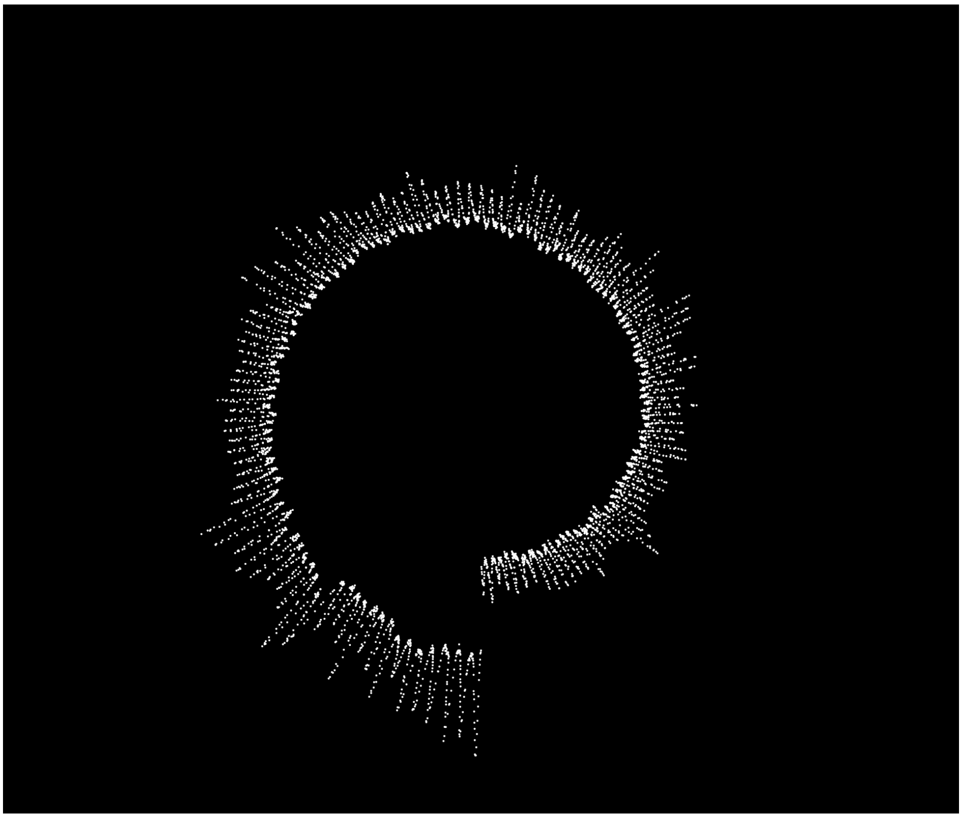

Figure 3.18: Breath data of the full session 1 (S1) represented in dots in a circular plane

process.

First, I plotted the breath data of the entire session (S1) on p5js in a circular structure (figure 3.18) mainly to match the time/sample position of the audio data, but also for the same aesthetic reasons considered when designing the circular spectrogram. In such manner I could have a comparative perspective and see if there is any correlations between the musical stimuli and the breath responses.

The first thing I notice after observing the circular graph is how the breath patterns clearly change throughout the session (S1). It starts with deep inhalations (bigger values indicating greater chest expansion) and exhalations (greater difference between maximum and minimum values) in the first 3 sections (silence - music - silence) of the session. Although, the minimum values are not as small as the ones observed at the end of the session, indicating that the subject S10 did not perform full, deep exhalations at this point of the session. On the other hand, the graph indicates that the exhalations are deeper (with the smaller values of the troughs suggesting a deeper contraction of the subject's chest) by the end of the session.

I decided to plot a classic line chart from the breath data on Google Sheets to check if the graph drawn on p5 was correct and if my interpretation of the data patterns makes sense, which got confirmed by

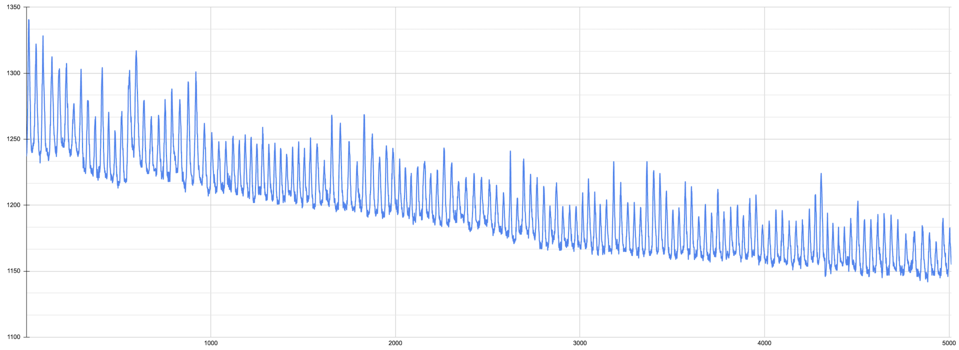

Figure 3.19: Line chart of the entire breath session plotted on Google Sheets

the chart (figure 3.19).

Then I drew the audio data of the full session including the silence gaps in between the songs (figures 3.20 and 3.21), overlaying the breathing data, to have an overview of how the visuals can interact and how the data sets behave together in the same canvas.

After plotting the overview graph including the song and silence sections I could observe that the intervals between each wave get gradually shorter as the session develops towards the end, suggesting that the breath rate becomes higher in the second half of the session. It also shows that the inhalations become shallower contrasting to the deeper contraction of the chest indicating deeper exhalations by the end of the session. Another observation is that it is not clear if the silence sections are influenced by the preview music stimuli or if it is directly showing the result of the silent moment on the breathing patterns. That interpretation can be more accurate if one knows how fast the breath patterns are responding to the immediate stimuli, be it silence or music.

The overview plot provided interesting visuals, but they were still far from the aesthetic desired. The first obvious improvement is to translate the breathing data into shapes that modulate with the changes in the data input. This part of the process started by exploring potential modular structures and testing out how these shapes behave with different slices of the data (the different silent and music sections of the listening session). The first structure tested was a Spirograph type of shape (figures 3.22, 3.23, and 3.24).

This first trial generated an appealing shape, which can be related to a "breathing structure" that contracts and expands its "line mesh" according to the airflow. That could generate a semiotic analysis correlating representations of breathing activity to the details of this structure. However, when I tested the same code with different sections of the data, it did not provide the expected modulations, so I decided to try a different structure that would give me more agency on the mappings and control of the results.

The initial approach taken was ta map the mean, standard deviation, and variance of the sections of the data in order to understand more about

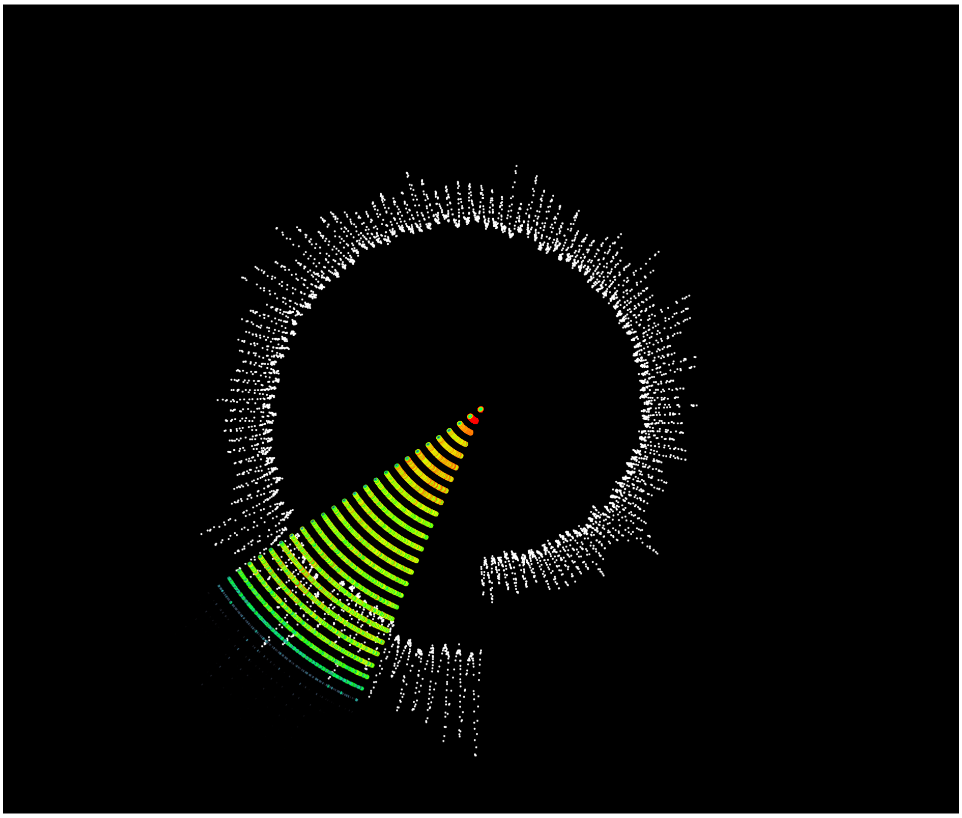

Figure 3.20: Breath data (S1) in dots + Spectrogram of the first sample "Andre.wav" after the first segment (30 seconds) of silence

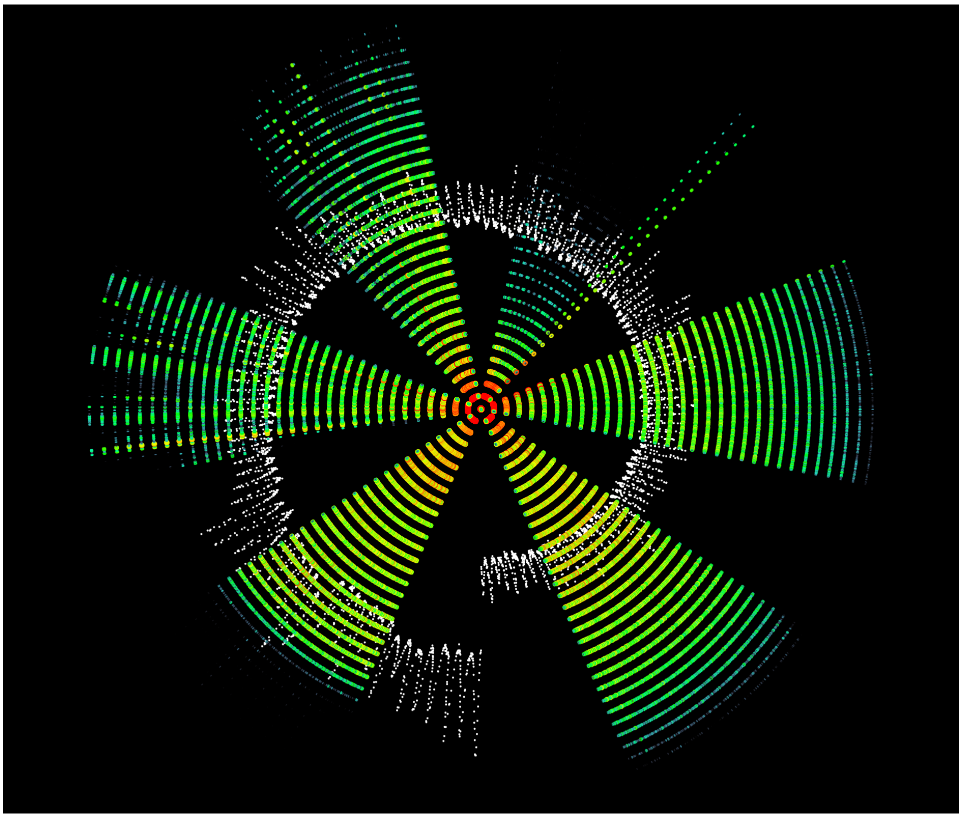

Figure 3.21: Breath data in dots + Spectrogram of all songs (S1) + silence segments

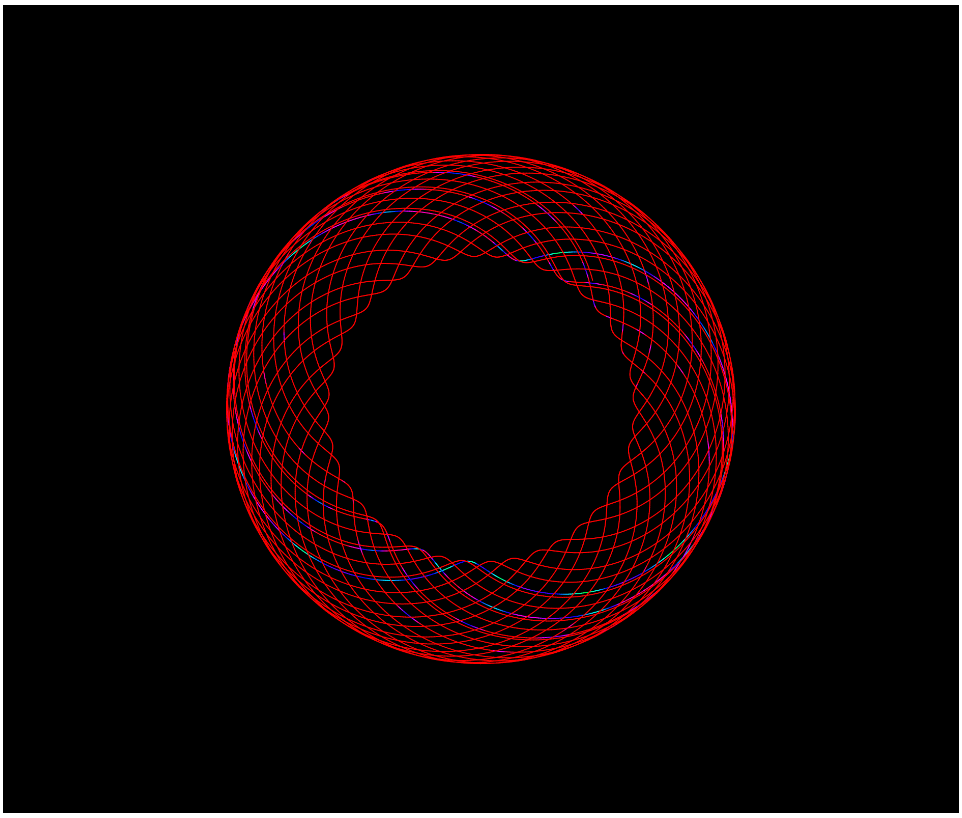

Figure 3.22: Spirograph test-shape from the first silence segment (S10 listening session)

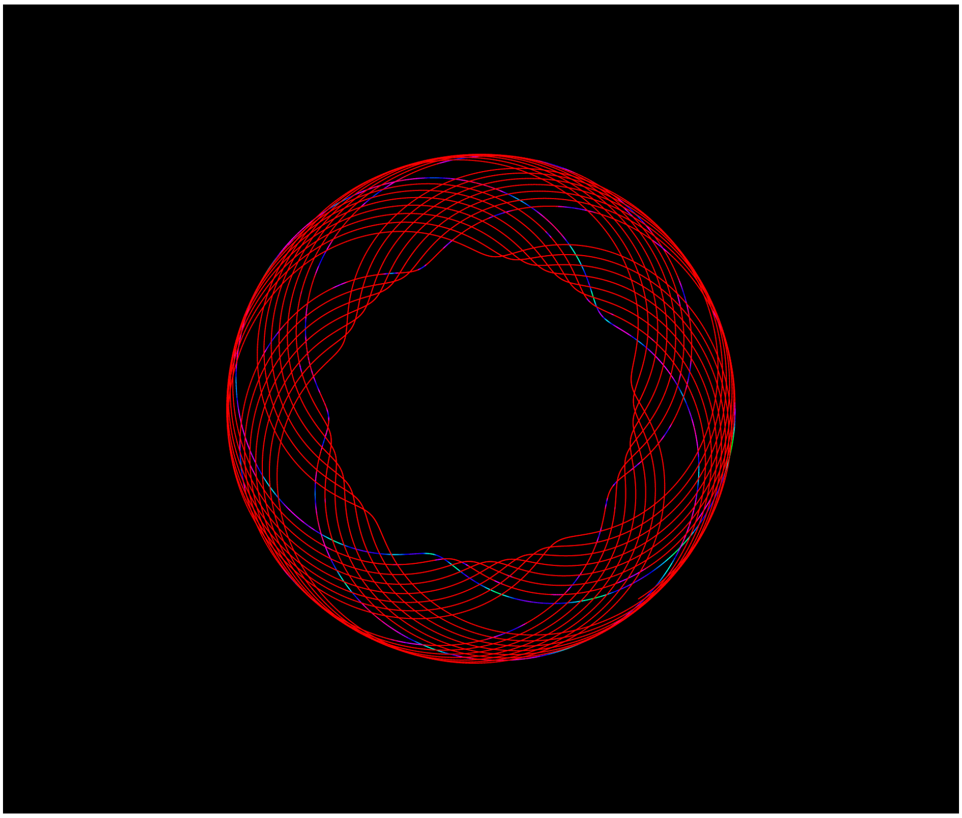

Figure 3.23: Spirograph test-shape from the first song segment (S10 listening session)

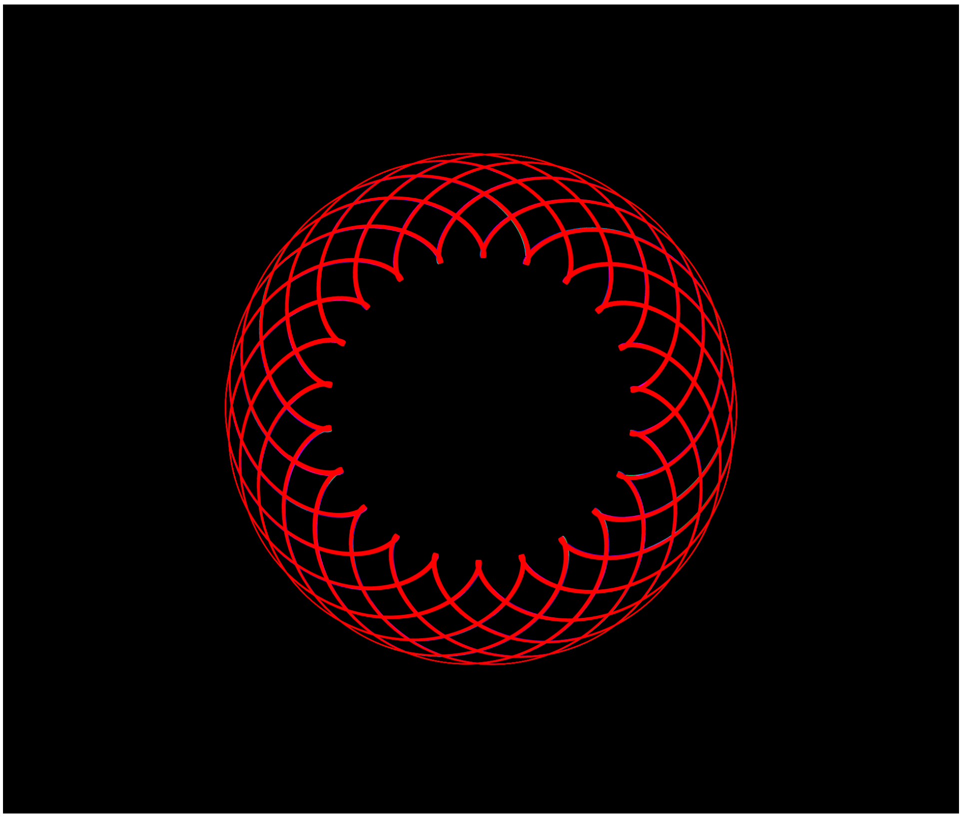

Figure 3.24: Spirograph test-shape from the following silence segment (S10 listening session)

the breath characteristics of the selected section, and to synthesize this information into a shape that can convey such information. Using the figure 3.23 as example, I intended to correlate deep inhalations to the size of the inner circle, the complexity and number of lines to the standard deviation, and the colour to the mean of the section. However, following the tests, the figure 3.24 shows a totally different behaviour, which did not correlate to the progression of the values from the last section to the actual section that generated this shape.

These tests allowed me to see how different measurements of the data (minimum, maximum, mean, standard deviation, and variance) would affect the shape's structure. At this point, I started to study how these measurements could be interpreted to create interesting mappings for them. The Spirograph provided beautiful visuals, but with my understanding of the geometry behind this type of shape I could not create a progressive correlation between the different visual results, which did not inform me what was happening with the input data clearly, therefore it did not provide meaningful interpretations of the breath data.

Finally, I found a structure (figure 3.25) that provided me control of the results, hence I moved forward focusing the work on the mappings and aesthetic choices.

The chosen structure (figure 3.25) has a regular circle as its basis.

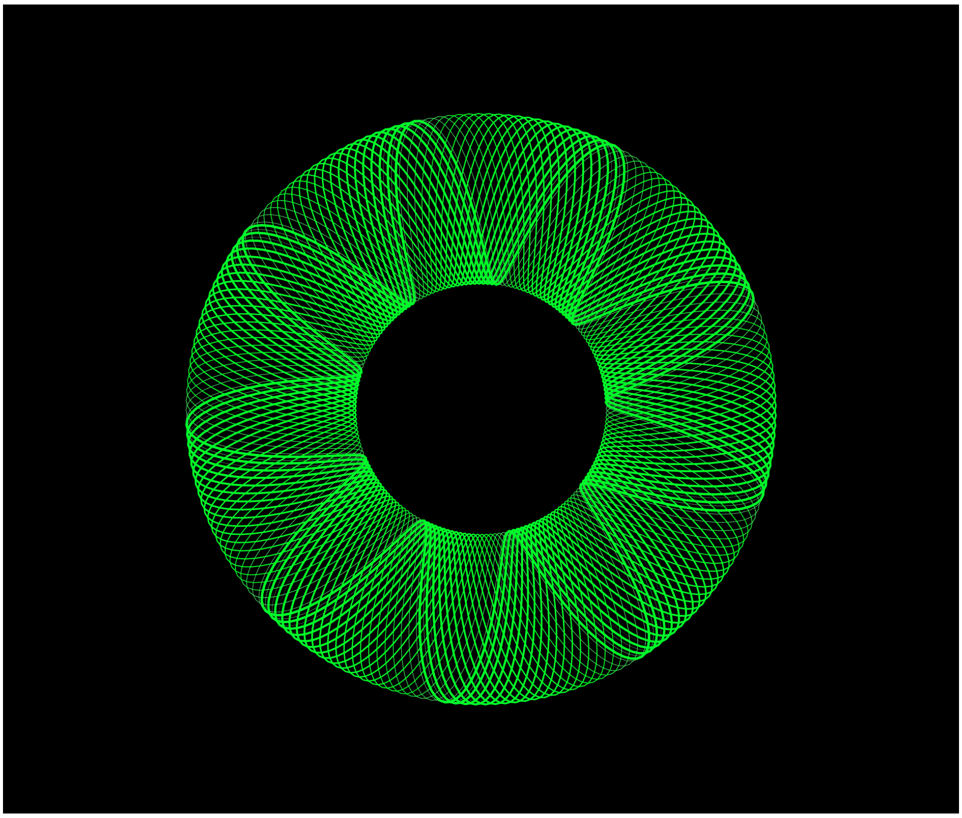

Figure 3.25: Chosen shape representing the first silence segment (S10 listening session)

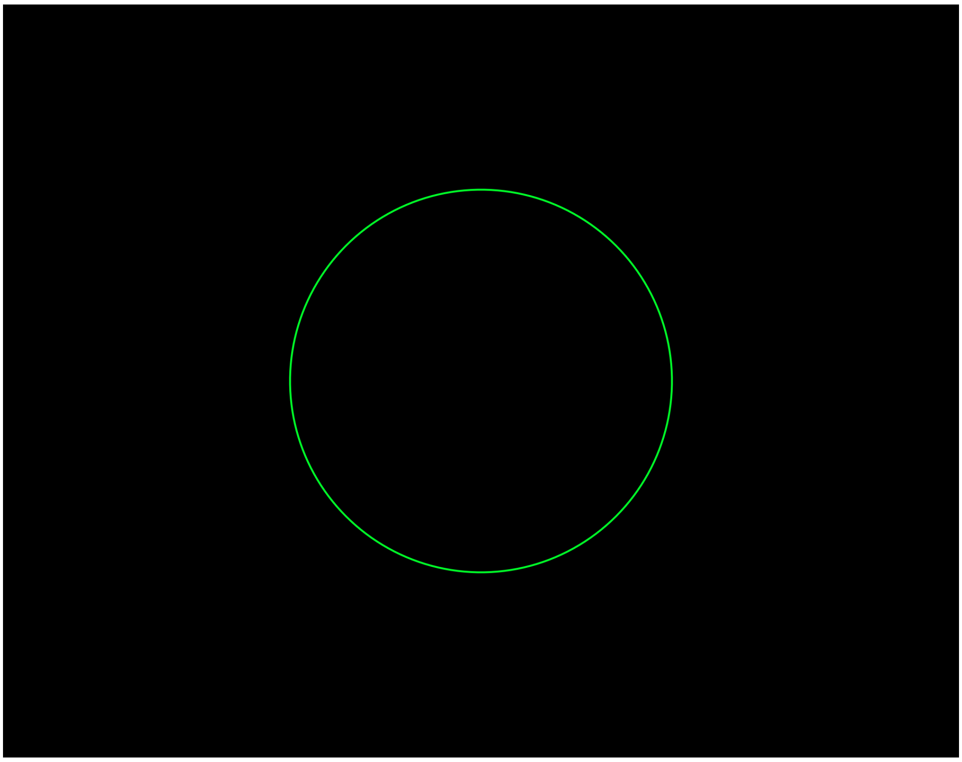

Figure 3.26: Breath shape circle basis

It develops in complexity with a *for loop* that draws petal curves and multiplies the lines according to the number of times that the function runs the loop (i < loop length), these multiplied lines get rotated ending the shape. The composition of this structure is based on these three variables that are modulated by the breath data measurements. Below you can see how this shape develops within the iterative testing process (figures 3.26, 3.27, 3.28, 3.29, 3.30, and 3.31) according to the value of these three variables.

3.5.3 Mappings

Once I understood the structure building the shape, I started testing how different measurements of the data would behave as input of the main variables in the structure. The measurements are listed below:

- Mean
- Standard Deviation
- Variance
- Maximum value
- Minimum value

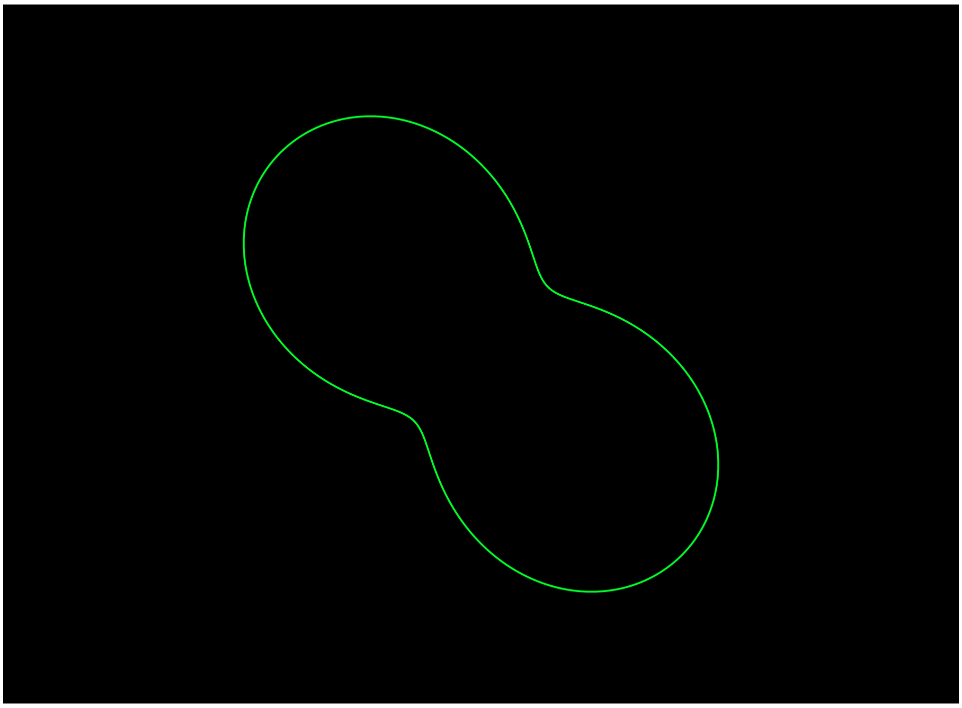

Figure 3.27: Breath shape - circle basis - number of petals = 2 (sin(2))

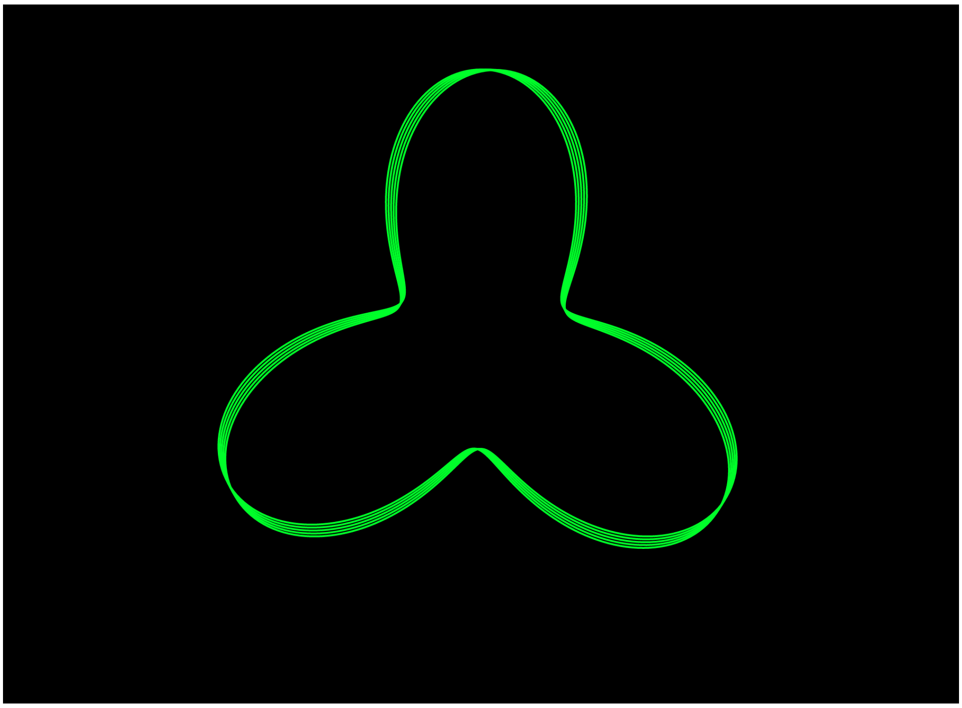

Figure 3.28: Breath shape - 3 petals / number of lines (for loop length) = 5

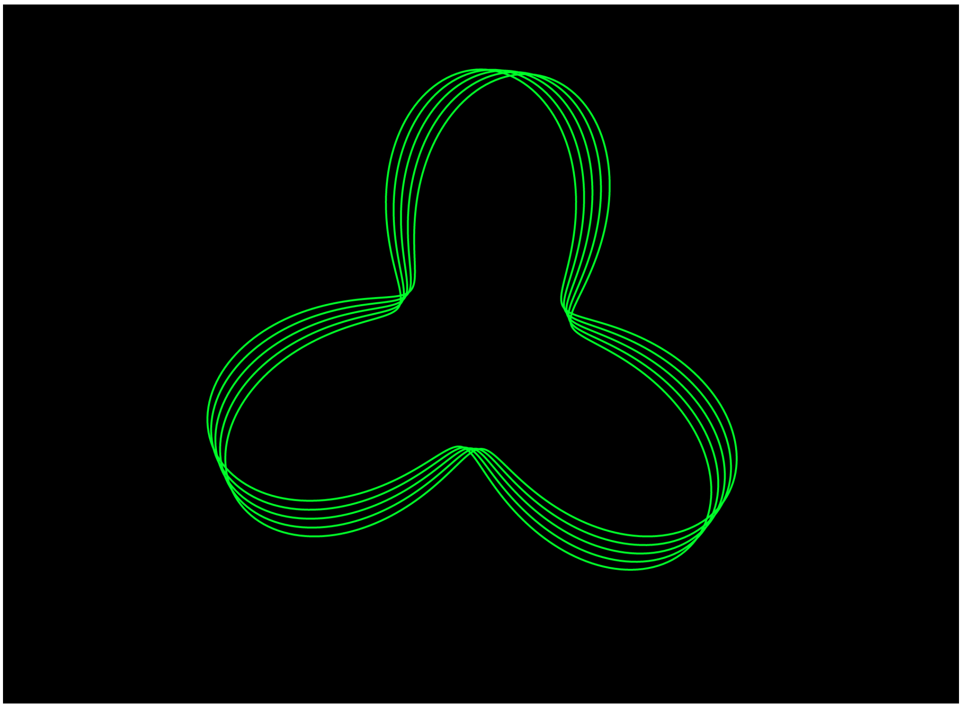

Figure 3.29: Breath shape - 3 petals / number of lines (for loop length) = 5 / rotation angle = 5

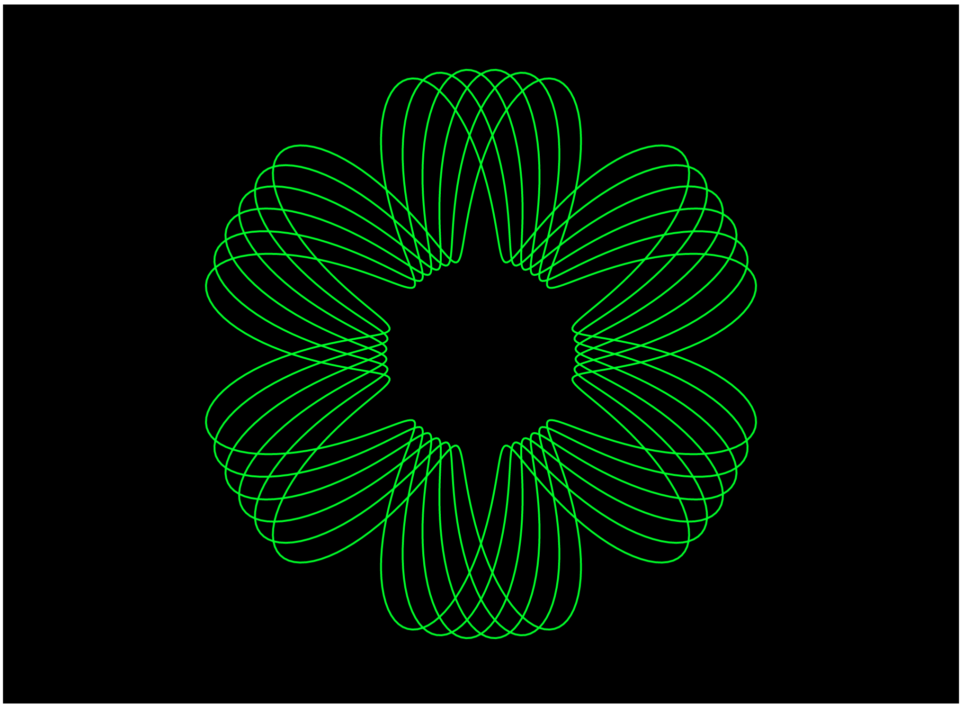

Figure 3.30: Breath shape - 6 petals / number of lines = 6 / rotation = 6

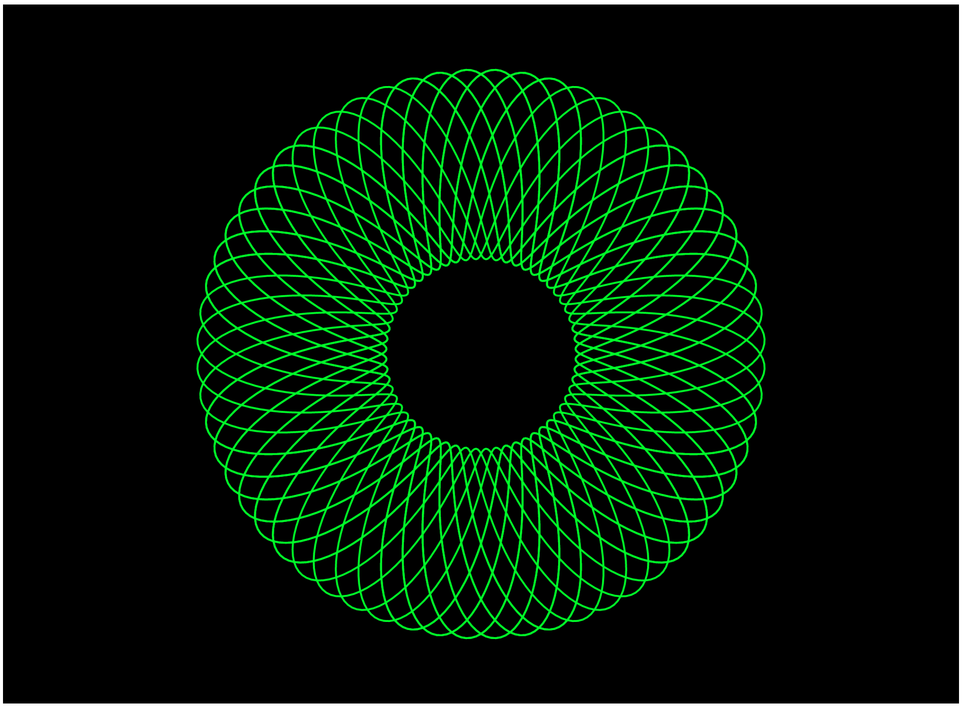

Figure 3.31: Breath shape - 12 petals / number of lines = 12 / rotation = 12

These measurements were used to create the following mappings, which are a result of a testing process with several iterations. Some of the values were mapped to fit the variable value range, e.g.: the color Hue that goes from 0 to 360.

- Number of lines = Standard Deviation
  loop(i = 0; i < Deviation; i++)
- Number of petals = Standard Deviation
  map(Std. Deviation, 0, (dataMax-dataMin)/4, 2, 15)
- Inner circle circumference = Minimum session's value (exhalation)
  dataMin/10
- Outer circle circumference = Maximum session's value (inhalation)
  map(dataMax, dataMin, dataMax, 200, 290);
- Stroke Hue = Variance (this mapping was inverted for conceptual sense)
  map(Variance, 0, 1000, 350, 0)
- Stroke Saturation = Mean
  map(Mean, dataMin, dataMax, 1, 20) * i (the saturation value is a mapped Mean value to a range, between 1-20 that when multiplied for the i of the for loop, generates a movement effect)
- Rotation angle = Mean
  map(Mean, dataMin, dataMax, 1.5, 3)

These correlations allow the user to understand the behaviour of the breath by observing the characteristics of the shape generated from the breathing session. Therefore, one can read the different arts produced from different "music-breath" sessions and compare them, also understanding how the music 'looks like' during each session, by analysing the spectrogram of the sound listened during the session.

To simplify the understanding of the mappings above, I decided to create a legend that can serve as a guide for the user to read the art generated by their "breath-painting" sessions.

- The greater the **number of lines** (and complexity) on the shape, the bigger the **deviation**, which suggests that the breath session was unstable, varying in quality (deep or shallow breathing).
- The same applies for the **number of petals**, more petals meaning **more variation** on the breath pattern.
- The smaller the **inner circle circumference** is, the **deeper exhalation** performed during the session.
- The bigger the **outer circle circumference** is, the **deeper inhalation** performed during the session.
- For the **color Hue value**, the warmer the color (from purple-blue-cyan-green-yellow-orange to red), the greater the **variance** of the session was, which indicates that the user performed an **inconsistent breath** pattern. The closer it gets to the red color, suggests a tendency to aroused states, while the more consistent the breath is, suggests calmer states represented by colder tones closer to the blue color. (figure: 3.32)
- The **stroke saturation** also indicates the level of **variance**. If the saturation is low, it means that the variance of the session was low, suggesting stable breathing patterns. The opposite applies: if the saturation is high, it indicates an unstable breathing pattern.
- The **rotation angle** affects the shape **creating unique results** for each session. The interpretation of this variable is not as clear and informative as the other mentioned above in this list. It is based on the *Mean* of the breathing session, and it was mapped for **aesthetic purposes**.

In addition, to provide a more technical understanding of the interaction between both data sets, I implemented a "breath dots" button, which draws the breath data in dots as a regular graph, but in a circular shape. That allows the user to compare breath and sound on a linear progression, and see changes in pattern taking into consideration the time domain. In many cases, the dotted breath data can be an additional element to the composition of the art, contributing aesthetically as well.

In the next section, I will explore the results of the data visualization generated on several different segments of the session S1. At this point, it is

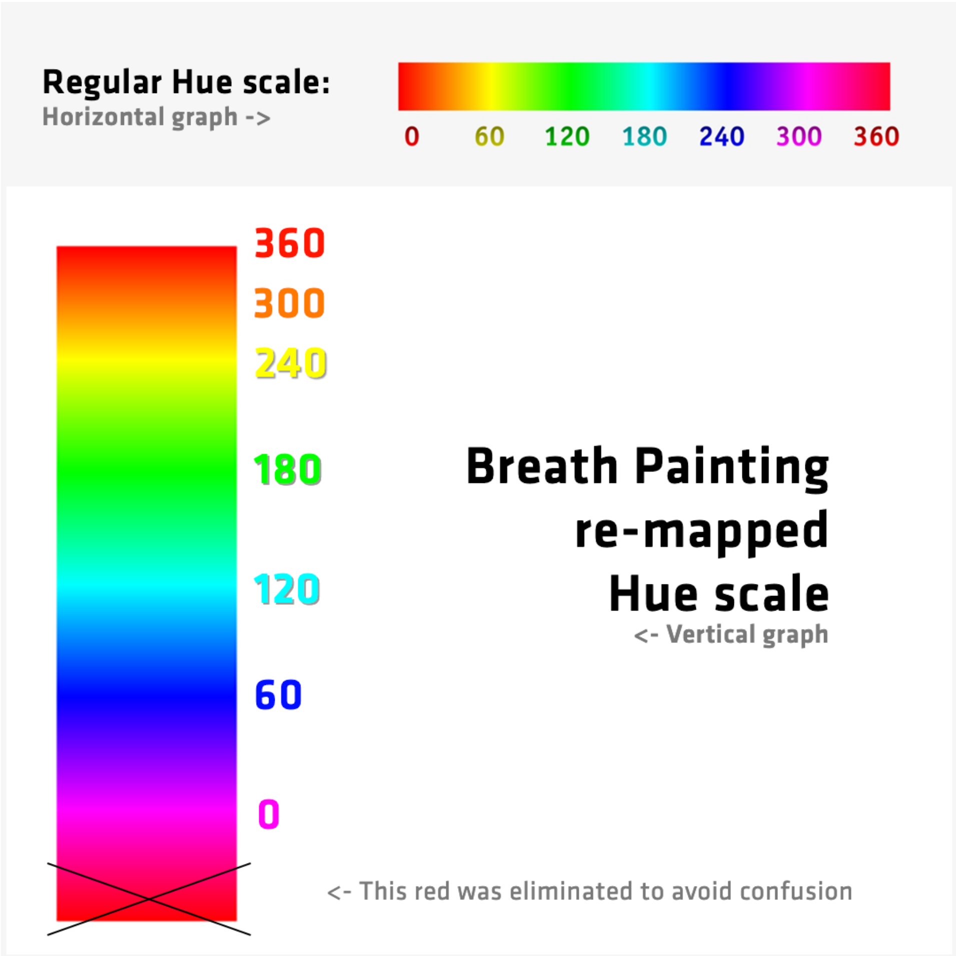

Figure 3.32: Hue scale re-mapped for the conceptual purposes of the project

possible to see the progression of the breath data through the art generated. By analysing the characteristics of each art generated and comparing them among several segments, as well as comparing to the line chart of the entire breath data session, the reliability of the shapes generated and the accuracy of the information conveyed was confirmed.

3.5.4 Art

After confirming the reliability of the breath data visualizations, the last step taken was to fine-tune the *Breath Painting* art, working on the interaction between the two different draws produced by the breath data and the audio data. The aim here was to develop a consistent graphical language that expresses adequately the type of information and emotional content desired for this project. To make viable the correlation between the musical stimuli and the respiration behavior, both types of data are drawn on the same canvas and can be displayed simultaneously with a harmonized aesthetic. By displaying the draws simultaneously, the interface allows the user to compare and visualize the development of the breath session in parallel to the music stimuli within the time domain.

At this point, the choices were made regarding aesthetic qualities. To assure consistency, I plotted the *Breath Painting* of several segments of the session in different combinations and implemented a few changes in scale to some of the variables on the mappings. To facilitate this process, I created a legend (figure 3.33) listing the audio stimuli respecting the order in which it was reproduced during the experiment session S1 for the subject S10. The legend contains also the sample interval for each segment of the session, where every silence segment has 313 samples of duration, while every song segment has 470 samples of duration. This process provided me with a variety of visual results that facilitated the comparisons, leading to a final decision. After plotting several different segments, I realized that the breath shapes can benefit from two types of visualization. The *type 1* respects the initial mappings created for the inner circle and outer circle circumferences, which provides clearer information regarding the minimum (exhalation) and maximum (inhalation) values for the session. Due to the smaller inner circumference, the *type 1* generates shapes that are easier to differentiate from each other, as this way the user can see the details of the inner and outer "petals" of the shape. That creates more uniqueness, and some shapes are easily relatable to flower-like structures. On the other hand, the *type 2* was implemented to facilitate the visualization of details of the spectrogram when plotted in combination with the breath shape. Scaling the inner circle circumference 3x also generated interesting results. Due to the distortion caused by scaling the inner circle to fit the spectrogram, it generates more abstract shapes, that are not related to flower-like structures. That can be interesting not only to visualize the spectrogram clearer but also to get away from associations with the meanings conveyed by correlating the art with flowers, focusing the interpretation on the technical perspective of the data. The circumferences sizes on the *type 2* are still relevant and can be used for analyzing the maximum and minimum, but they are less evidently differentiated. In this case, the user is induced to focus on the details of the ring generated by the breath shape, which can be beneficial if the focus is to have a better understanding of the data presented. Thus, I implemented two buttons (TYPE 1/TYPE 2) to allow the user to choose the type of breath shape visualization.

Sample Interval	Audio Stimulus
000-313	SILENCE
313-783	1-Andre
783-1096	SILENCE
1096-1566	4-Neelix 2
1566-1879	SILENCE
1879-2349	3-Neelix 1
2349-2662	SILENCE
2662-3132	2-Metronome
3132-3445	SILENCE
3445-3915	6-Rhythm
3915-4228	SILENCE
4228-4698	5 Pysh
4698-5011	SILENCE

Figure 3.33: Subject 10 - Stimuli order of session S1

Moreover, I exported the arts in different compositions, breath shape (type 1) alone, breath shape (type 1) with spectrogram, breath shape (type 2) alone, breath shape (type 2) with spectrogram, and all of them combined with the dotted breath plot (figure 3.38). I repeated this process for each segment of the entire session to see how the results behave and to detect any tendencies. The figures 3.34, 3.35, 3.36, and 3.37 show the *Breath Painting* arts generated by the listening session of the audio stimulus 1 "Andre". After that, I repeated the process with the third silence segment of the session, from which the figures 3.39, 3.40, and 3.41 show the *Breath Painting* arts generated. To compare different results, the figure 3.42 refers to the art generated by the listening session of the audio stimulus 2 "Metronome". The figure 3.43 shows the art generated by the listening session of the audio stimulus 5 "Pysh, from which the low saturation indicates a low *Variance* value on the breath session. See the captions under the figures for more details regarding the interpretation of these shapes.

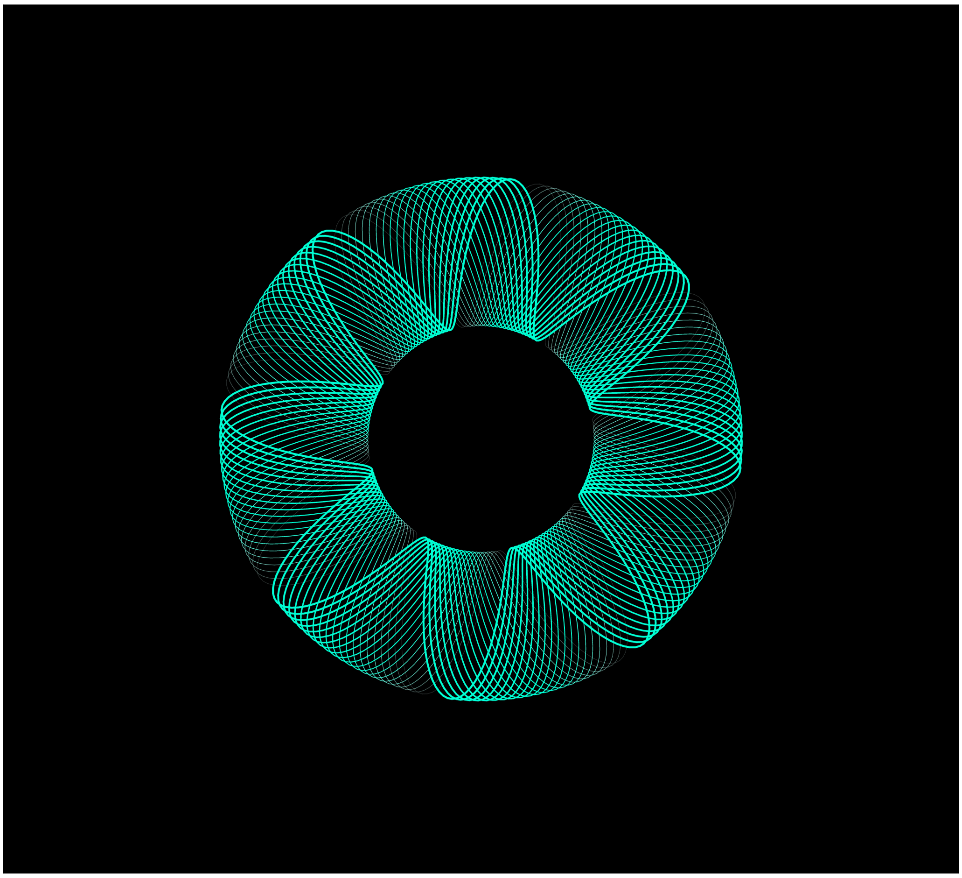

Figure 3.34: Stimulus 1 "Andre" - Breath Shape (type 1) alone. The relatively high number of petals (8), as well as the high number of lines, indicate high deviation and variance levels. The circumference sizes of this shape compared to the other examples in this document, suggest deeper breath patterns during this session. The hue value and saturation of the lines reaffirm the high variance within this session.

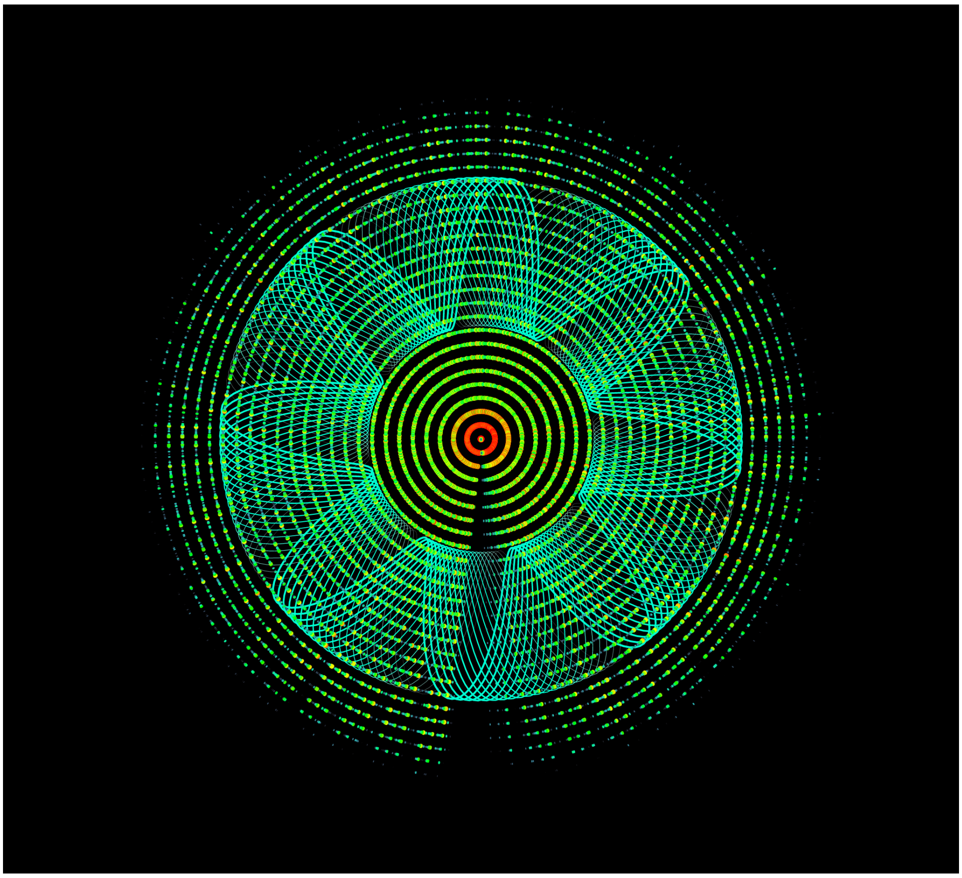

Figure 3.35: Stimulus 1 "Andre" - Breath Shape (type 1) + Spectrogram

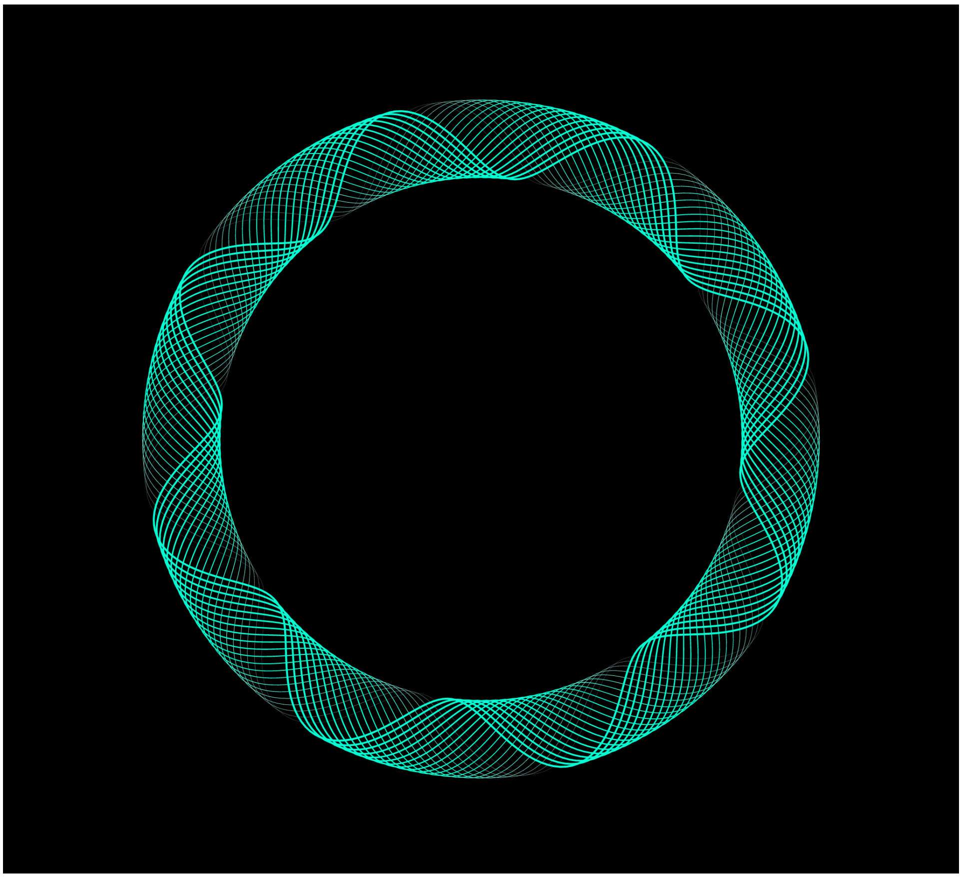

Figure 3.36: Stimulus 1 "Andre" - Breath Shape (type 2) alone

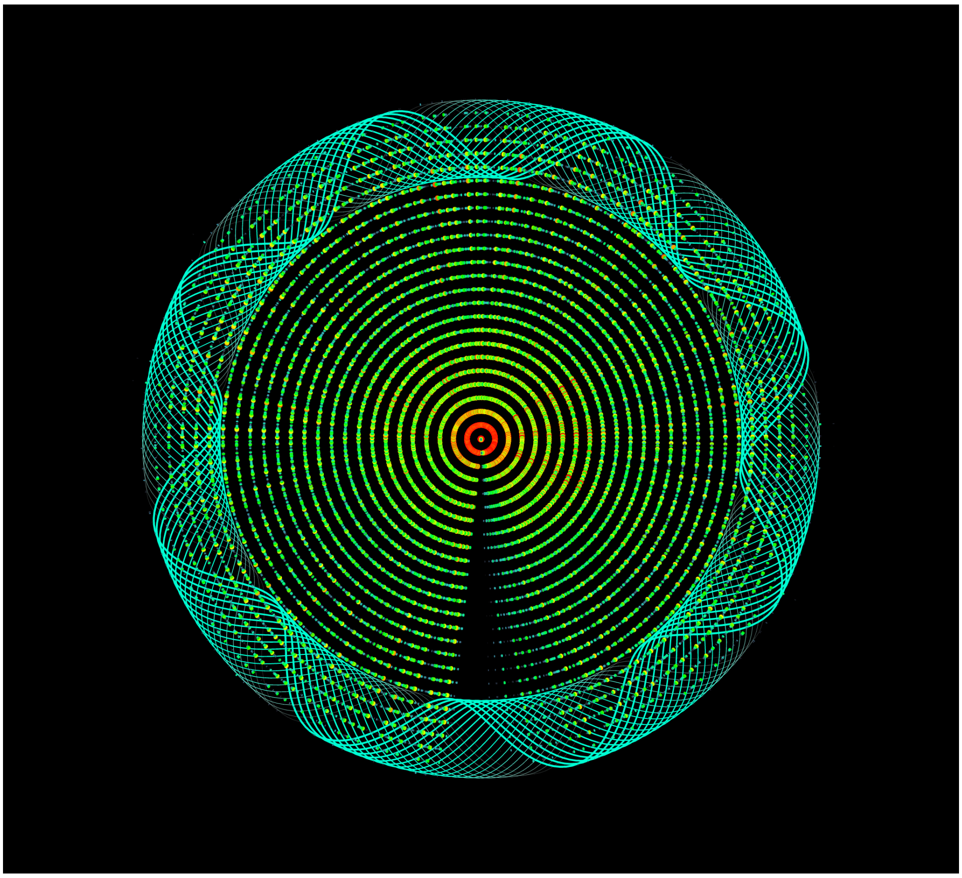

Figure 3.37: Stimulus 1 "Andre" - Breath Shape (type 2) + Spectrogram

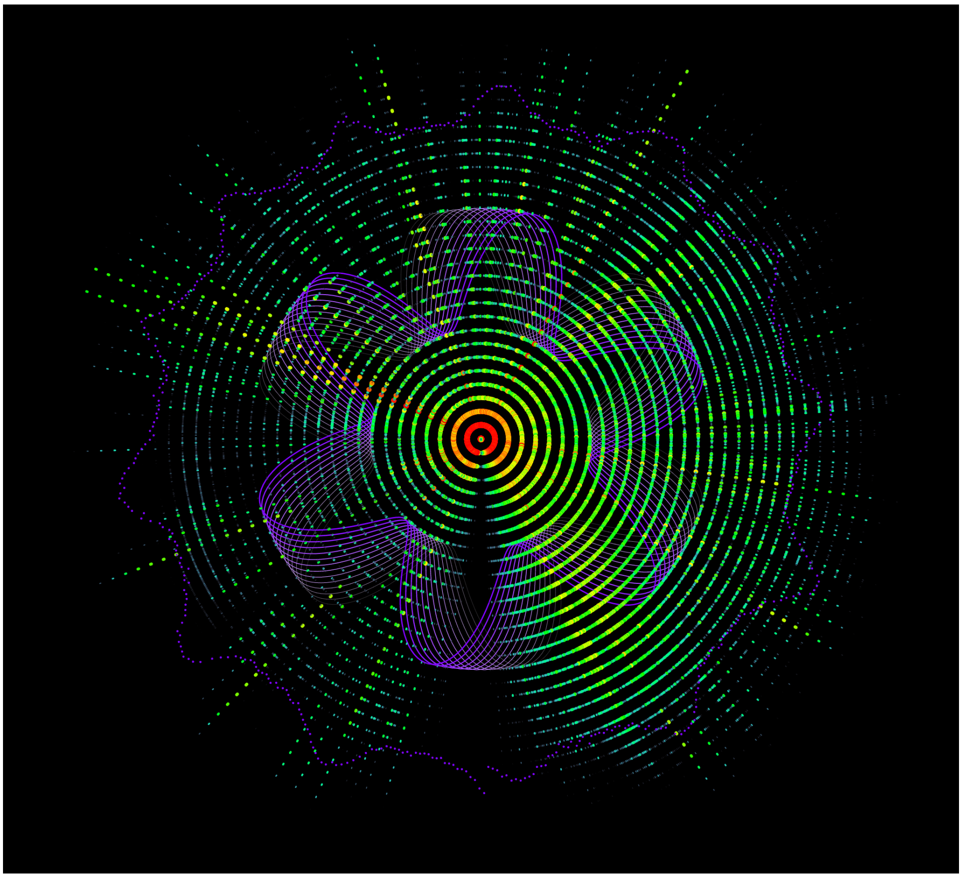

Figure 3.38: Stimulus 3 "Neelix 1" - Breath Shape (type 1) + Spectrogram + dotted breath. This is an example where all the types of visualizations are plotted simultaneously.

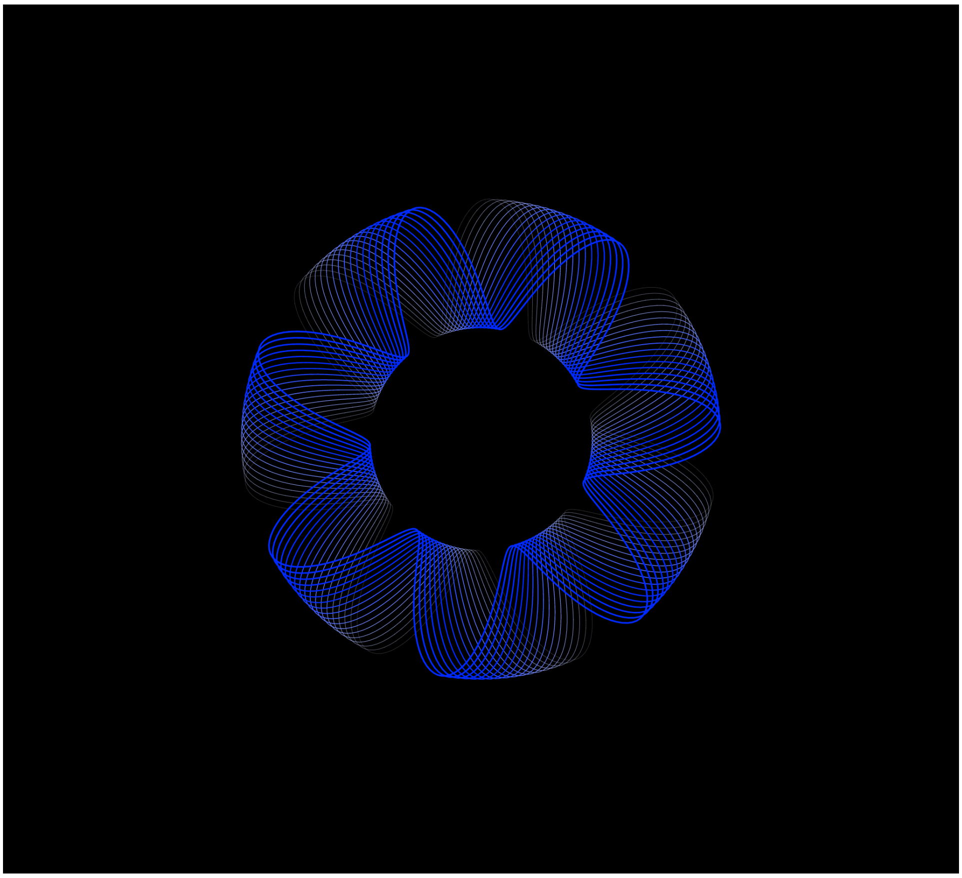

Figure 3.39: Silence 3 - Breath Shape (type 1) alone. With slightly less number of petals (7), as well as less number of lines, this shape indicates smaller deviation and variance levels. The circumference size is also smaller compared to the shape generated from the Stimulus 1 "Andre", suggesting shallower breath patterns. The hue value is low, again indicating lower variance, meaning that the subject S10 performed a more stable breathing pattern during this session.

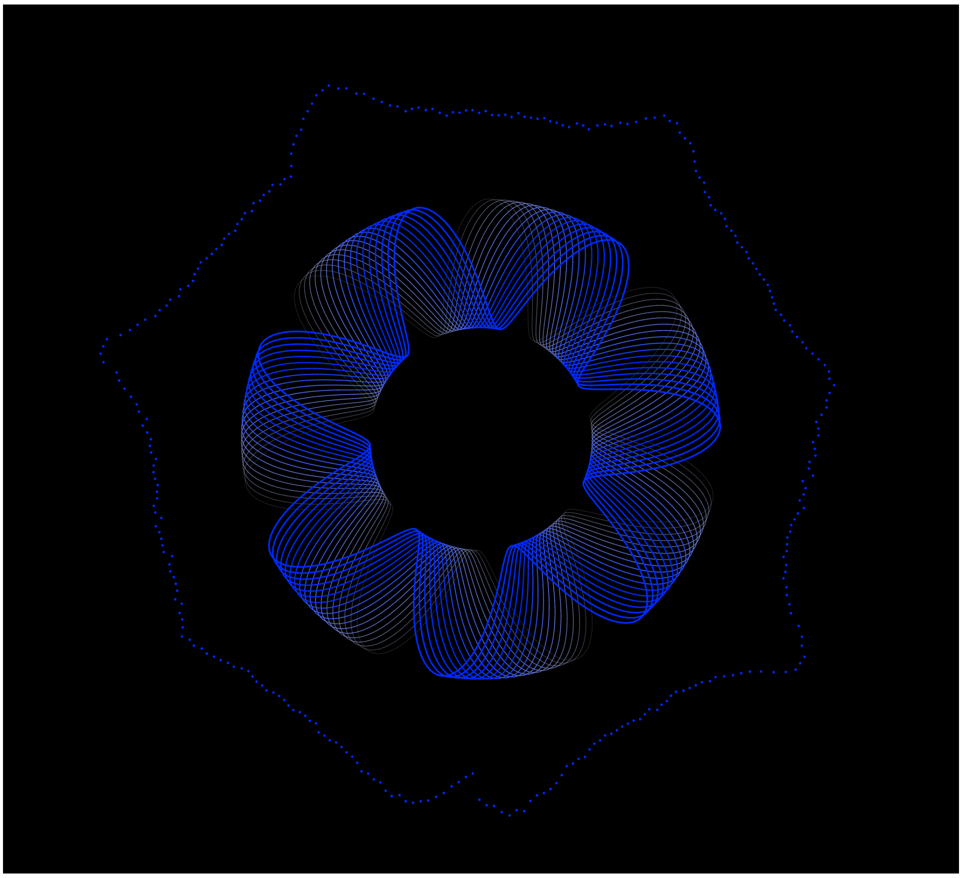

Figure 3.40: Silence 3 - Breath Shape (type 1) + dotted breath. By plotting the dotted breath data together with the breath shape, it is possible to confirm the shallower breath pattern by observing the low crests (peaks) and shallow troughs. The dotted graph also confirms the low deviation and variance levels.

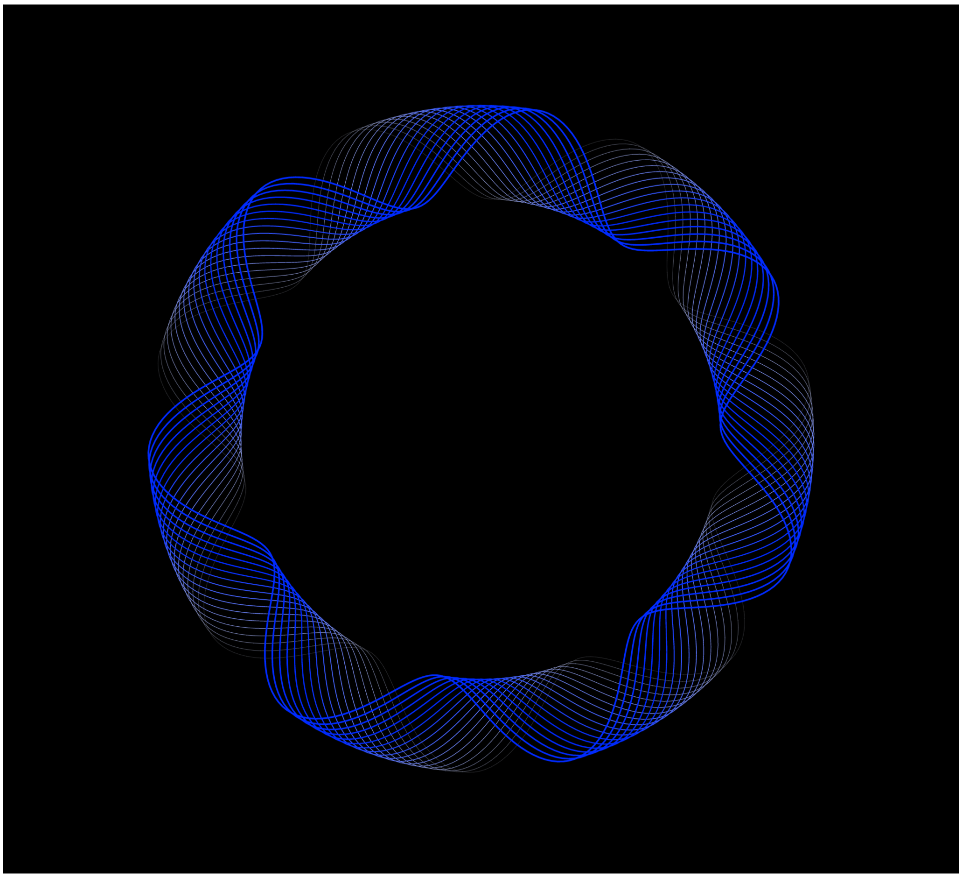

Figure 3.41: Silence 3 - Breath Shape (type 2) alone

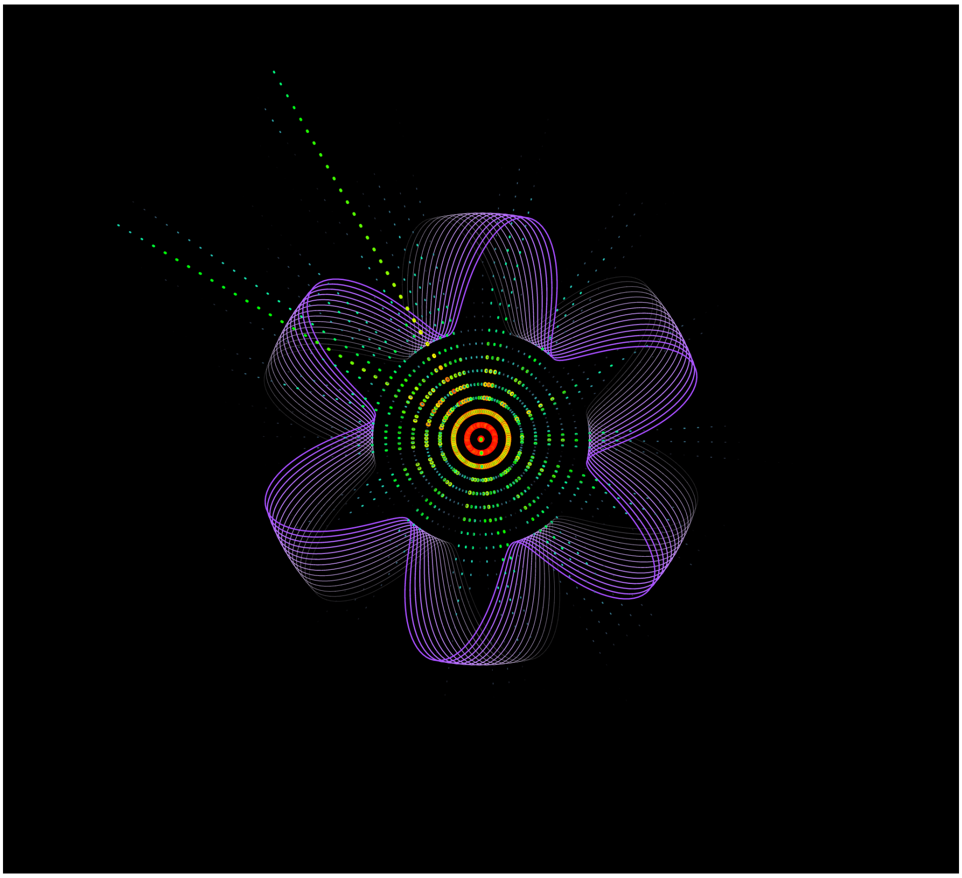

Figure 3.42: Stimulus 2 "Metronome" - Breath Shape (type 1) + Spectrogram. Showing considerably less number of petals (6), as well as less number of lines, this shape indicates even smaller deviation and variance levels. The circumference size is also much smaller compared to the shape generated from the Stimulus 1 "Andre", suggesting shallower breath patterns. The hue value is even lower than the one presented by the "Silence 3" session, indicating small variance. These changes suggest that the subject performed gradually more stable patterns throughout the entire session S1.

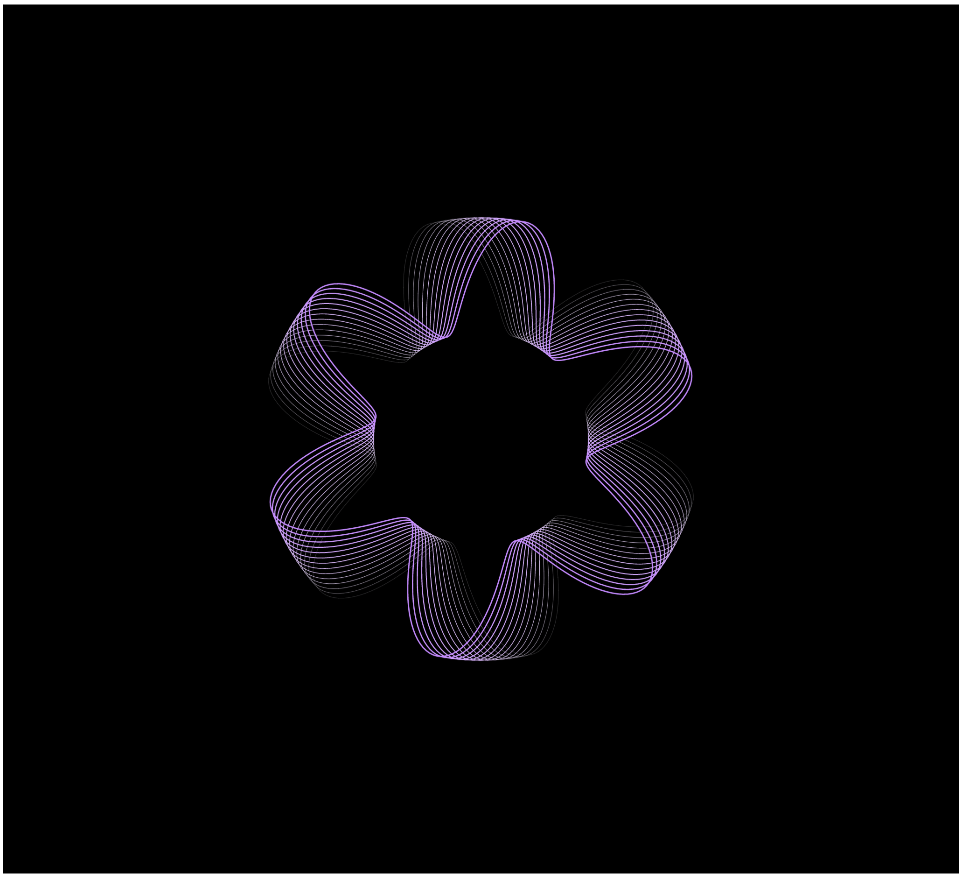

Figure 3.43: Stimulus 5 "Pysh" - Breath Shape (type 1) alone. Again with a smaller number of petals (6), as well as less number of lines, this shape indicates small deviation and variance levels. The circumference size is also much smaller compared to the shape generated at the first segments of the session S1, suggesting gradual decrease of depth on the breath patterns. The hue value is the lowest presented on the examples, indicating the smallest variance, which reaffirms the notion that the subject performed gradually more stable patterns throughout the full session S1.

After analyzing these examples, it is possible to see a tendency for the breath pattern to become more stable and shallower throughout the full session S1. This notion is confirmed when comparing to the chart generated of the full session S1 on *Google Sheets* (figure 3.19). This is a positive indicator for this project. The prototype works as proposed, conveying meaningful information regarding the breath data behavior.

3.5.5 Interface

To help test and export all the arts mentioned previously, it was helpful to develop a basic interface. The interface of the prototype (figure 3.45) is extremely simple but it serves the purpose, as it is not a final product. It is basically eight buttons (figure 3.44) in sequence on the bottom of the screen, that were implemented for testing the arts in different combinations. The

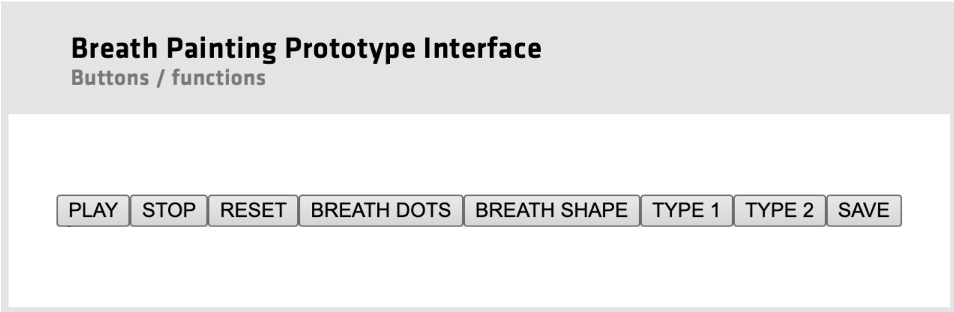

Figure 3.44: Prototype's Interface: Buttons

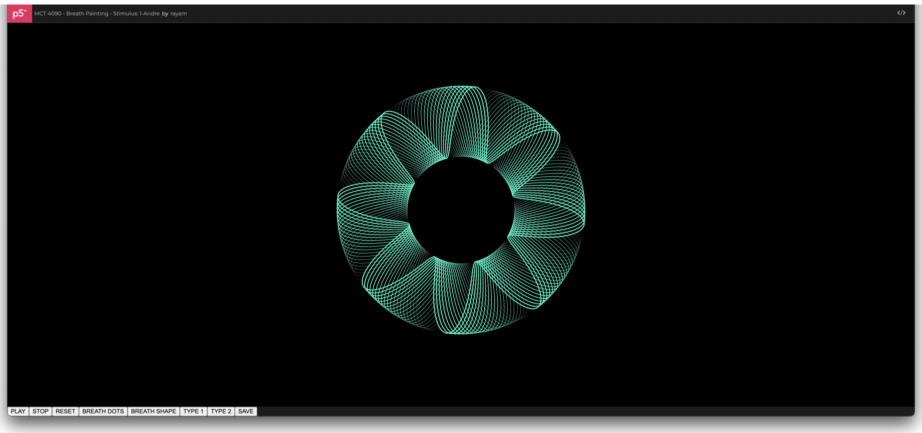

Figure 3.45: Prototype's Interface

first and second buttons are for audio reproduction. The first one is a *PLAY* button that switches to the *PAUSE* function, so the user can reproduce and pause the audio loaded in the code. By default, the audio stimulus pre-loaded is "1-Andre.wav", matching the data segment pre-selected by default as well. It also draws the spectrogram in real-time with the audio reproduction. The second is a *STOP* button, to stop the audio and the spectrogram drawing action. The third button is a *RESET* button, made for resetting not only the audio reproduction, starting again from the beginning, but also to reset the canvas, erasing any art plotted. The fourth button is called *BREATH DOTS*, and as the name indicates, it plots the dotted breath data. The fifth button is called *BREATH SHAPE*, and it plots the breath shape, as the name suggests. This one should be used when the breath shape is not plotted, for instance when the user resets the interface. Then, the sixth and seventh buttons are *TYPE 1* and *TYPE 2*, with the function of switching the breath data types. And finally, the last button is a *SAVE* function, with which the user can export/download the art generated.

Chapter 4

Conclusion

4.1 Summary

In the first chapter, I introduced the topic of this thesis, the goals, motivation, limitations, and the research questions that will be answered in this conclusive chapter. In the second chapter, I went through a literature review, explaining key concepts and definitions of technical terms explored throughout this project. Moreover, in the same chapter, I have done a review of relevant topics investigated by research on music and psychophysiology. Continuing, in the third chapter, I explained the methods I have used to develop the prototype proposed in this project. I began by explaining the aims of the prototype, its relevance as a tool for mental health support, and the iterative process to build it. Furthermore, I did I reviewed relevant work for product research that served as a reference for the prototype. Moving forward, I explored the data used for this project and went through the technical information about the sensor utilized for collecting this data. Moreover, I detailed the iterative process of designing and programming the prototype, finishing with an evaluation of the results. Finally, in the present chapter, I answered the research questions proposed in the introduction, continuing with a discussion about the results and possible improvements for the prototype. In addition, in the *Future Work* section, I described ideas for implementing the prototype for health and educational applications as future work.

4.2 General Discussion

4.2.1 Data Visualization

The prototype presented in the previous chapter is a combination of an abstract data visualization with a customized spectrogram visualization. The spectrogram conveys a more technical and complex type of information if you take into consideration users that are not musically educated and have no technical experience with music information retrieval. However, it is still informative for those who can relate to the dynamics of the sound by observing the gaps and size of the lines, even when they do not understand the frequency content of it. The lines and colors of the spectrogram also play a role contributing on the formation of interesting compositions in combination with the breath shapes. It is important to observe that the focus of this first version of the prototype lies mainly on the breath data visualization, so the complexity of the spectrogram is not an issue, although it can and should be explored further in future work.

The breath shapes, on the other hand, do not display technical data as directly as the spectrogram does, but they convey the interpretation of these technical details with symbolic representations. They might not be as straightforward as a scientific type of data visualization would be, but they are informative, attending to the goal of conveying physiological information to non-technical users. It also works attracting the awareness of the general public to such type of knowledge, by generating appealing visuals. Within their color, complexity, size, and other details, they inform what the breath behavior looks like during a music listening session. The breath shapes can definitely be improved to convey more clear and detailed information, but as a first approach, they achieved a satisfactory result for the goal of this prototype.

Both types of data interact without confusing the information conveyed. Although the time dimension is presented only by the spectrogram, it is possible to analyze and compare the breath data to the audio data timewise, when the breath data is plotted in dots. That is the reason that I implemented the option with a button that can draw the dots with and without the two other shapes, leaving the possibility for a more accurate analysis if desired.

4.2.2 Aesthetics

Once I established the basis of the data visualization, I assessed the aesthetics produced by the breath shapes. The breath shapes provide uniqueness for the *Breath Painting* art. With their abstract aspect, they carry semiotic meaning within the structures that are generated. Despite being digitally drawn, they present what can be considered organic shapes, with circular patterns and smooth curves forming intertwined petal-like elements. At times, the shapes can appear similar to flowers. The line meshes created by the repetition and rotation of these elements suggest expansion and contraction movements, which can be related to the action of the human tissue fibers and organs expanding and contracting to perform breathing activity. After all, the breath shapes present a good balance between technical and artistic approaches. Many types of audio visualization can be implemented, many types of beautiful abstract visuals can be generated with data as well. The challenge lies on how to create interesting abstract visuals that are able to convey meaningful information clearly.

4.3 Revisiting the Research Questions

This thesis achieved its goals by supporting the idea that music can affect an individual's physiological system and, in combination with technology, be used as a tool for mental health support. The answer to the first research question *RQ1: Does music affect an individual's psychophysiological responses?* is positive. Not only physiological responses such as heart rate, respiration rate, and blood pressure are reactive to music stimuli, but emotional responses are also observed in listeners. The emotional content and quality are mostly dependent on the meaning structures carried by the music and the individual's musical preference. The meaning structures are affected by cultural background, previous experience with a determined song, and the message conveyed by the music heard. For instance, established medical treatment protocols take into consideration personal preference when choosing music for pain and anxiety treatments. Happy music trigger facial muscles responsible for the smile, while sad music does the opposite effect, reinforcing the idea that music affects not only physiological responses but also the psychological and emotional content following such responses. Moreover, characteristics of sound attributed to stimulative music like fast beats/tempo, loud passages, and staccato progression, indicated an increase in heart rate, while sedative attributes such as slow tempo, and soft passages with legato progressions, tend to cause a decrease in heart rate. The same type of behavior occurs with blood pressure. Elevated heart rate and blood pressure are common indicatives of an aroused nervous system and anxiety. Therefore, sedative music can be used to down-regulate these physiological responses, hence activating instances of the autonomic nervous system responsible for calm psychological and emotional states.

The respiration is another important "gear" of the physiological system that is highly effective down-regulating the nervous system. The reviewed literature in this thesis have supported answering the question *Q2: Can music change breathing patterns?* The answer is again positive. When it comes to the listener's respiratory phase alignment to music, songs with voice have shown better results. When the music listened contains perceivable respiration sounds, singing voices, and speech, it tends to influence more effectively the listener's respiratory patterns. On the other hand, complex rhythms and groove can negatively impact the respiratory alignment, hence simpler rhythms are more efficient if alignment is the goal. In opposition, the performer's respiration have shown positive influence on the alignment process. Different experiments have indicated considerable entrainment between rhythm and breath period, also pointing the ability of musical rhythms to prompt the circadian rhythms of an individual. Music preference again appears to exert influence on breathing rates, as some studies detected increase in respiration rate regarding personal preference. On the other hand, respiration rate decreases with sedative music. Moreover, lullabies songs have shown positive impact on the oxygen saturation, heart rate, and respiratory rate of infants in Neonatal Intensive Care.

Altogether, the literature review, the investigation and answer to the two previous questions, and the prototype developed in this thesis provided the answer to the question *RQ3: How can music be combined with technology to support mental health?* Once it is confirmed that music can affect the psychophysiological responses of an individual independently of their cultural background and technical understanding of music, it is possible to explore the use of technology to generate creative solutions to support an individual's mental health. Biofeedback tools in combination with music have shown positive results when applied for mental health. Experiments have shown that music in combination with biofeedback or sonification, has had a greater impact on regulating the physiological arousal of participants' heart rate and respiration rate compared to music alone. Gamification and biofeedback have been also showing positive results on well-being. There are many gamification tools currently supporting meditation practices and in use for health care, inducing better heart rate variability, stress reduction, cognitive performance, sports performance, and the list goes on. The present prototype has the same goals, to support mental health and promote well-being. It does it by promoting awareness of the user's breathing patterns and can educate the user on better breathing practices.

4.4 Future Work

A lot of improvement can be done to this project. There is room for exploration of the breath and sound visualizations, and the interaction between them.

The breath shapes, for instance, can be improved in terms of clarity. One way to do that is to increase the differentiation between sessions, making the interpretation faster and clearer. As this type of data is not dramatically changing between sessions (if the user performs natural breathing), the differentiation can be enhanced with mappings that make smaller variations output greater modulations on the structures, broadening the spectrum of changes.

The audio data can also be approached differently. It could become a modulator of the shapes generated by the breath data. With smart mappings, colors and other details of the geometry can convey the audio data keeping the time dimension, frequency, and amplitude information by translating it into different visual attributes of the breath shapes.

Moreover, user experience research can improve significantly the efficiency of this prototype. It would be interesting to test different compositions for the visualizations and ask questions about the understanding of the users regarding the information conveyed. That would also provide input concerning user engagement. An addition that could improve the user's experience and help educate the users about their breathing patterns would be to implement a legend for understanding the quality of their breathing patterns according to the art generated. A legend can help the users to compare their type of art to reference arts that can guide them to evaluate their *Breath Painting*. In addition, useful tips for healthy breathing can be implemented in the user interface of the prototype. These tips can be displayed according to the user's breath session, for instance, if the session shows inconsistent breath patterns, or shallow breathing, the user can get tips on how to improve their breath practices, and can be oriented to follow and align their breath pace with a suggested sedative slow music with visuals that induce a deeper and consistent breath pattern.

This prototype can also be developed to be interactive in real-time with sensors and devices that can open doors for biofeedback systems and gamification. It can be used for educational purposes applied to health by stimulating the user to breathe deep and slow, or leading the user to discover their particular resonant breathing frequency. For example, the visuals can respond to the user's breath in real-time, with visual rewards such as the appearance of beautiful elements, or the unpleasant visual indicators that the user is out of track with their respiration. The interactive system can play with the user's engagement by displaying new appealing elements and sounds that are triggered by the correct bio-data (in this case the breath data) input provided by the user.

Another possible application of this type of system is generating visual elements and composing generative music simultaneously, providing an immersive experience to the user. That can be done by using the biofeedback data output coming from a breath sensor as a trigger, and modulator, for a generational music system that interacts with the visuals that are also modulated in real-time by the breath data of the user. For example, a calming environment like a forest, with nature sounds that blend into the music, together with visuals that are revealed as the user's breath syncs into a desired rate, would be an effective way to educate and induce relaxed states for the users. Kids could also benefit from other environments more appropriate for children. With playful elements, as the kid breaths slower and deeper, the environment displays colorful objects that bounce, for instance. That creates engagement, educating and motivating the child to learn healthier breath practices, consequently providing well-being.

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Appendix

- Supplementary material for this thesis can be found on the link: https://zenodo.org/record/6591937#.YpQeJZNBzh8
- To test the prototype on p5js web based platform, access: https://editor.p5js.org/rayam/full/TPNe9x9ww