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Exploring Haptic Stimulation Patterns to Enhance Breathing Exercises

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Abstract

This Creative Technology thesis investigates the application of haptics in teaching breathing techniques, leveraging the unique capability of haptics to provide a tangible and personal learning experience. Unlike visual and auditory feedback, haptic feedback allows users to physically feel the guidance and feedback on their own actions, enhancing the learning process. The primary aim was to identify beneficial characteristics of haptic stimulation patterns and those that are less effective.

To achieve this, a Wearable Haptic Breathing Assistant prototype was developed, consisting of an ESP32 microcontroller, a breathing sensor, and eight vibrotactile motors arranged in a sleeve around the abdomen—with four motors on the abdomen and four on the lower back. Two rounds of user testing were conducted with six participants each. The tests were evaluated using a questionnaire focusing on six different aspects contributing to the 'overall comfort' of a haptic stimulation pattern, complemented by an open interview for additional feedback by the participants. In the first round, four patterns were evaluated, and feedback from these tests were used for improvements of the prototype. The revised prototype and a new set of patterns were then tested in the second round. The patterns tested in this thesis covered time cues without feedback, guiding feedback, direct feedback, and terminal feedback.

The results revealed that users prefer guided feedback and reassurance that they are performing the exercises correctly. Without clear guidance, users experienced increased cognitive load, which took away from the relaxation intended by slow breathing exercises. One pattern with particularly active vibrations was found to be very stressful for the participants. Developing and testing the prototype highlighted critical aspects for a proper haptic-guided breathing system, such as responsiveness, accuracy, and consistency in tracking breathing behavior, as well as the need for powerful, durable, and high-fidelity motors for providing clear and effective haptic feedback.

The thesis addressed three knowledge questions and three design questions, answered through a combination of a background research, consisting of a literature review, an analysis of state-of-the-art research papers and commercially available products, and, secondly, the test results of the two user tests performed in this thesis project. A comprehensive set of recommendations is provided to guide future research in the development of haptic breathing assistants.

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1 Introduction

This Creative Technology BSc thesis is about designing and improving upon a prototype of a Wearable Haptic Breathing Assistant (WHBA) that uses biofeedback. It will be designed according to the Creative Technology Design Method, which uses an iterative and explorative approach. The device will guide individuals in learning the basis of abdominal breathing and will act as a breathing pacer. Biofeedback of breathing behavior is implemented using vibrotactile motors on the upper body of the wearer. In multiple studies, this application has been demonstrated before. However, rather than focusing resources on the effectiveness of slow breathing or biofeedback, this thesis aims to explore the characteristics and possibilities of haptic patterns themselves, since this has not been widely researched and documented yet.

Breathing is a vital aspect of the human experience. Not only does it supply the body with oxygen to keep our cells alive, but it also plays a significant role in the physical and mental wellbeing of an individual. Oftentimes, when engaging in everyday activities, breathing may be at a relatively high pace. This is undesirable for people who are already stressed or anxious. By consciously lowering the breathing rate, several beneficial psychophysiological effects can be observed. These are, amongst others, lower heartrate and blood pressure, and feelings of being less stressed or anxious. Breathwork is seen as a potent tool to use in the busy nature of the world we live in.

In the Western society, many people are inexperienced with deliberate breathwork. They may benefit from regular breathing exercises that can increase their well-being and health. The WHBA prototype is designed to help inexperienced people to be more in-tune with their own breathing and reach the beneficial slow breathing rate. The WHBA will measure the expansion of the abdomen of the wearer and give haptic cues to their abdomen and lower back accordingly. To evaluate characteristics of haptic stimulation patterns, two user tests are used. In these tests, no medical biomarkers (such as heart rate, blood pressure or blood oxygen) are collected, since that is outside of the scope of this explorative thesis. The patterns are evaluated on six aspects that resemble the overall comfort of that pattern. The second user test will use an improved WHBA prototype, using the feedback of the first user test. After the user tests, the results are discussed, and the research questions will be answered.

1.1 Research Questions

This thesis aims to answer the following Research Question and sub questions:

How can haptic stimulation and/or feedback assist people in learning and adopting breathing techniques?

To answer this from a Creative Technology Design perspective, a background analysis should be performed prior to the design process. The following Knowledge Questions (KQs) should provide an adequate understanding of the topic of breathing, breathwork, and haptic feedback:

KQ1: What breathing techniques may be effective to teach with haptic stimulation patterns?

KQ2: Where on the human body would haptic stimulation be comfortable and effective to teach breathing techniques?

KQ3: How to evaluate the effectiveness of haptic stimulation in teaching breathing techniques?

These Knowledge Questions will be answered in section 2.4 using the findings of the background research. Having these KQs answered, the Creative Technology Design process can be initialized with Design Questions (DQs). This will function as a starting point in the first phase 'Iteration' of the prototype, as well as exploring the natural mapping properties of haptic feedback patterns. The DQs are as follows:

DQ1: How can the system synchronize with the personal breathing preferences of the wearer, such that the wearer does not feel as if they have to rush their breathing to keep the pace of the system?

DQ2: What haptic stimulation patterns are effective in teaching individuals certain breathing techniques?

DQ3: What characteristics of haptic stimulation patterns make some patterns more preferable to other patterns?

The Design Questions will be answered in Chapter 6 in section 6.3.1.

2 Background Research

Before the proposed haptic system can be built, some of the research questions should be answered first. The Knowledge Questions can be answered with the help of this chapter's background research. For a comprehensive overview of breathing and haptic feedback, a literature review will be performed. After the literature has been examined in section 2.1, an overview of the state of the art will be provided in section 2.2. Here, studies and products that tried the similar concept of using haptic stimulation for guided breathing will be discussed. The key takeaways of the literature review and the state of the art are presented in section 2.3. And finally, this chapter concludes with answering the Knowledge Questions in section 2.4.

2.1 Literature Review

This literature review is divided into the following sections: breathing, autonomic nervous system, cardiovascular effects, stress, breathing techniques, and haptic stimulation and feedback. The articles were searched for using Research Gate, Scopus, Google Scholar, and Bing AI. In some cases, relevant references in found papers were also examined and referenced on their own. The articles are from scientific journals that are peer-reviewed.

2.1.1 Breathing

Breathing is the essential act of pulmonary gas exchange. It allows oxygen being taken up into the bloodstream, and carbon dioxide to be expelled from the blood. As we breathe in, the lungs are pulled downwards by the diaphragm muscle. When this large, dome-shaped muscle contracts, the lungs are stretched and expanded. The space created by this action creates a negative air-pressure, or vacuum, which is naturally replaced with outside air: the inhalation. When the diaphragm relaxes, the air is naturally pushed out by a positive pressure in the lungs due to a reduction in the volume of the chest: the exhale.

The upcoming sections will explain how a slow breathing rate of 3 to 7 cycles per minute can result in the profound psychophysiological changes, including being more social and having a higher resilience to stress factors. The interplay between the respiratory system, the autonomic nervous system, and the cardiovascular system will be discussed. This will not be in-depth, as the intricate details of the respiratory system, cardiovascular system, and neuroscience are outside the scope of this thesis. However, it is important to understand to some degree how breathing achieves its psychophysiological effects and, therefore, the nervous system will be explained in the next section.

2.1.2 Autonomic Nervous System

Breathing, an involuntary yet vital bodily function, is regulated by the autonomic nervous system (ANS). The ANS is a complex network that is split into two primary subsystems: the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). The SNS, often referred to as the fight-flight-or-freeze mode, prepares the body for situations that require immediate attention or pose a potential threat. On the other hand, the PNS, also known as the rest-digest-repair mode, works to conserve energy and maintain bodily functions in a state of rest.

The SNS originates anatomically from the brain stem, extending downwards through the upper body, following the path alongside the spinal cord. From here, it connects to various internal organs through nerve centers or ganglia. This connectivity allows the SNS to rapidly respond to stressors, preparing the body for potential threats by mobilizing energy resources, increasing heart rate, and heightening alertness. In contrast to the SNS, the PNS follows a less orderly route, primarily through the vagus nerve, one of the longest nerves in the body. The PNS works in opposition to the SNS, promoting relaxation, digestion, and energy conservation. When the body is in a resting state, the PNS takes the lead, slowing the heart rate, regulating digestion, and generally maintaining bodily functions in a state of equilibrium. As Gregor Hasler [1, Ch. 2] has noted, the interaction between the SNS and the PNS is intricate, with an almost poetic dynamic between them. There is a finite amount of energy available in our bodies, and using these two ANS modalities, our bodies optimize its energy balance with each system taking the lead as circumstances require.

The PNS, when activated, has a completely opposite effect on the organs compared to the SNS. While the primary function of the SNS is to mobilize the body's resources in response to threats, the PNS works to conserve energy and maintain bodily functions. In essence, the SNS directs energy outwards, preparing the body for action, while the PNS redirects the energy inwards, focusing on bodily restoration and maintenance. The human body must continuously balance energy allocation for various functions such as digestion, tissue repair, social interactions, cognitive tasks, and physical movement. Therefore, the outwardly directed energy mobilized by the SNS can come at the expense of energy that could have been used internally for bodily maintenance, repair, and digestion.

Stephen Porges' Polyvagal Theory [2] states that an overly active SNS can suppress the social engagement system. This system is managed by a specialized set of myelinated nerves located in the thoracic cavity. These special nerves are a defining aspect of all mammals and are, evolutionary-wise, quite a recent development. The myelinated nerve cells operate at much higher speeds than the unmyelinated nerves in the abdominal cavity and are responsible for social behaviors such as facial expressions, vocalization and listening. Hasler discusses this in [1, p. 37], mentioning that the vagus nerve (through which the parasympathetic mode can act) gets trained at a very young age: “At birth, this nerve is developed enough to let the child communicate by using simple facial expressions: to accept or decline something, to shake the head in excitement, to scream of rage, to watch the mother, to eat, or to puke. Here, Hasler highlights the importance of love and nurture; at a very early age, the vagus nerve needs to be activated together with other nerve centers, to form the social vagus nerve.

When the SNS is dominant due to perceived threats or stress, the PNS and the social engagement system can be inhibited, leading to a perception of the environment as hostile or unsafe. This, in turn can stimulate the SNS again, resulting in a positive feedback loop that leads to more stress or fear. The effectiveness of breathwork lies in its ability to stimulate the PNS, breaking that self-perpetuating cycle, promoting relaxation, and re-engagement of the social engagement system. Through breathwork, the activation of the PNS can be achieved by leveraging the effects of two important mechanisms of the respiratory-cardiovascular interplay: the heart rate sinus arrhythmia and the baroreflex mechanism. These will be described in the next section.

2.1.3 Breathing and the Cardiovascular System

The vagus nerve, part of the PNS, is the key component in the calming effects of deliberate slow breathing. Two main mechanisms activate the PNS to slow down the heart rate: the baroreflex and heart rate sinus arrhythmia (HRSA). The baroreflex is a more direct mechanism where the baroreceptors in the aortic arch and the carotid sinuses sense differences in blood pressure. This difference in blood pressure occurs when the intrathoracic pressure increases and decreases with each breath cycle. To compensate for these fluctuations in blood pressure, the PNS is either activated to decrease, or suppressed to increase, the heart rate, respectively.

The second mechanism, HRSA, is a more complex and involving mechanism that links breathing to the heart rate. Intrathoracic pressure is also taken into the equation, alongside diaphragmatic movement, heart volume and blood flow rates, and compensatory shifts in vagal activation [3]. When breathing in, the vagal activity is suppressed, causing the heart rate to increase. When breathing out, the vagal activity is increased, causing the heart rate to slow down. This is beneficial for the body, since increasing the heart rate increases the uptake of oxygen, while decreasing allows for greater expulsion of CO_2 while breathing out.

The cardiovascular response to breathing can be leveraged by voluntarily regulated breathing practices, or in other words, breathing techniques or ‘breathwork’ [4, 5]. Breathwork will be explored in section 2.1.5. First, the topic of stress is further explored in the next section. This exploration is essential to the thesis’s motivation: using haptics to guide breathing, which in turn improves the quality of life and wellbeing by reducing physical and mental stress.

2.1.4 Stress

As Fink [6] describes: “the term ‘stress’ has different meanings for different people under different conditions.”. This thesis follows the definition ‘a form of psychological and physiological tension in response to external or internal stimuli’. Stress reduction is important, because stress is linked to a shorter lifespan and overall poorer physical and mental health. In a large study by McManus et al. [7] involving the biomedical data of 500,000 ‘generally healthy’ UK citizens, it was shown that there are clear links between stress and changes in brain microstructure, impairment in cognitive abilities, and more negative mental health outcomes. Both stress exposure during childhood and adulthood were correlated with decreased cognitive working memory, executive function, and a higher number of diagnosed mental health problems. This shows that stress has a significant impact on mental health. Not only has stress an impact on mental health, but also on the physical health.

Stress is known to have a physiological impact where the sympathetic mode of the autonomic nervous system is predominantly active—alongside other stress response neurobiological pathways that are outside the scope of this thesis—resulting in an increase in heart rate and blood pressure, and a decrease in heart rate variability [6, 8]. Gordon and Mendes [8] found that real-life stressors, such as financial or family issues, have different effects on our physiology compared to artificial stressors in lab environments. Their study revealed that momentary stress increases blood pressure and heart rate reactivity, with high-arousal negative emotions (e.g., anger) amplifying this response, while low-arousal positive emotions (e.g., calmness) dampen the reactivity. As stress is a prominent factor in this connected society, this thesis hopes to help individuals lower their stress levels by guiding them in breathing techniques with the use of haptic stimulation. Breathing techniques are the tools for the act of breathwork. In the next section, breathwork will be examined, to gain a better understanding of its origins, alongside studies on its effectiveness in improving wellbeing.

2.1.5 Breathwork

Breathwork, the voluntary act of changing the rate, pattern, and depth of respiration, has garnered attention for its potential effects on the mind and body, including the aforementioned cardiac system [9, 10]. While it has ancient roots in Eastern traditions, such as pranayama, modern studies have demonstrated its ability to reduce anxiety, stress, and heart rate in anxiety and panic disorders [3, 9, 10]. As a safe, scalable, and cost-effective method, breathwork can be practiced without an instructor or measurement equipment. The beneficial effects may already be experienced by breathing 5 or 6 times per minute [10]. This is known as 'coherent' or 'resonant' breathing [5]. When this type of breathing is performed at 3 to 8 times per minute, the parasympathetic mode of the ANS gets predominantly active. More on this breathing technique will be examined in section 2.1.6.1.

Extensive literature reviews reveal no adverse effects directly caused by breathwork, with positive results for non-clinical applications but mixed findings for clinical studies [9, 10]. Breathwork applied in a therapeutic environment is, however, not yet a substitute for cognitive behavioral therapy (CBT) in anxiety management, but it can be seen as a promising additional technique for persons with anxiety and panic disorders. More research is needed to explore its potential and place in the therapeutic environment; particularly study designs with a low probability of bias and a focus on participant wellbeing [10]. It can be concluded that breathwork holds the potential of reducing psychophysiological problems such as stress and anxiety, resulting in a calmer and more balanced body and mind [5].

2.1.6 Breathing Techniques

The previous two sections demonstrate the consequences of stress and the ability of breathing exercises to reduce stress. This section will now explain various breathing exercises. To approach these breathing techniques systematically, each will be presented with a brief description and step-by-step instructions. After these breathing techniques are presented, a section about safety considerations will conclude this section on breathing techniques (2.1.6.7).

2.1.6.1 Diaphragmatic Breathing (Resonant/Coherence Breathing)

Also known as 'abdominal breathing' or 'belly breathing', diaphragmatic breathing makes use of the diaphragm. This is a muscle that divides the upper body in two cavities: the thoracic and the abdominal cavities [5]. As already discussed in section 2.1.1, when the diaphragm contracts, the lungs are stretched downwards and get filled with air due to pressure differences. Using the abdominal cavity to create the pressure difference is more efficient than chest breathing, or sometimes called 'inverse breathing'; this is when the chest is expanded while the abdomen stays relatively still. Chest breathing is shallower than abdominal breathing, as the volume of inhaled air per chest-initialized breath is lower than using the abdomen. Therefore, to get the same amount of oxygen, there is an automatic increase in breathing rate. This may even lead to dyspnea (i.e., breathlessness or the inability to get an adequate breath [11]), resulting in a heightened activation of sympathetic nervous activity, and, in turn, more stress and lower heart rate variability.

Gerbarg et al. [5] mention that, in general, a breathing rate of 4.5 to 6.0 breathing cycles per minute (cpm) is most effective for individuals with a height of less than 183cm (6 feet), and a rate of 3.0 to 4.5 cpm for individuals longer than 183cm. It is found that the parasympathetic mode is already predominantly active at a rate of eight cpm [13]. To provide more context: at a breathing rate of five cpm, it means that the total breath cycle takes around 12 seconds (approximately 4-5 seconds for inspiration, a 1-second rest, and 6-7 seconds for expiration).

There exists no standardized method for diaphragmatic breathing. Oftentimes, it is performed along the ways of what is described in 2.1.6.1.1. In therapy, the technique is performed by a patient with the aid of a therapist. Usually, in these settings, a hand or an object is used to let the patient experience the feeling of ‘pushing something away’ by breathing with their belly, instead of their chest. The object that is pushed away by the expanded belly can, for example, be a ball or a hand (either someone’s own hand or that of the therapist). In Chapter 4, the concept of breathing something away will be discussed in the context of recreating that experience using haptics. This technique can be used in various therapeutic contexts, including yoga, meditation, physical therapy, and treatments for conditions like chronic obstructive pulmonary disease (COPD), anxiety, and stress.

2.1.6.1.1 Instructions

1. **Positioning:** Sit comfortably or lie flat on your back. Ensure your body is relaxed, and your surroundings are calm and quiet.
2. **Hand Placement:** Place one hand on your chest and the other on your belly. The latter is optional, but it allows the person to better visualize and understand how the upper body is moving.
3. **Inhale:** Breathe in slowly through your nose, allowing your stomach to push against your hand. The hand on your chest should remain as still as possible during especially the first part of the inhale (when almost fully inhaled, it is natural that the chest moves up a bit as well).
4. **Hold:** Pause briefly after the inhale.

5. **Exhale:** Slowly breathe out via the nose or mouth, optionally with pursed lips. The exhale should take longer than the inhale.
6. **Wait:** Wait briefly and repeat steps 3 through 6 for several cycles. There is no need to force the breathing or go to the absolutes of fully filled or -emptied lungs. The breathing should be comfortable, controlled, and relaxed.

2.1.6.2 Box Breathing

Box Breathing, also known as ‘Square Breathing’, is a technique that is often used to manage stress, improve focus, and promote relaxation. It involves a series of controlled, equal-duration inhalations, holds, exhalations [3]. Box breathing is often employed by individuals under high-stress situations, including athletes and military personnel—which is why this technique is also dubbed as the ‘Navy SEAL breathing technique’ due to its effectiveness in generating a calm and focused state of being. Mark Divine, a former Navy SEAL, has popularized box breathing through his fitness program and books [14]. The focus aspect is produced by the conscious focus on the breath, coupled with a visualization of the square and the progress of the breathing cycle.

The technique is named after the square shape that represents its pattern, with each side of the square corresponding to a different phase of the breathing cycle. Each side is typically four to six seconds long. According to Divine, the standard is four seconds. He states that, unless you are trying to increase your breath-holding capacity, using a time interval of more than six seconds has no benefits and is better to be avoided. By breathing and holding for a set amount of time, this technique can shift the autonomic nervous system towards parasympathetic dominance, which provides the benefits of increased relaxation, social state, and recovery. Using four seconds would result in a breathing cycle of 16 seconds, meaning 3.75 cpm. This is a great target according to [5], referencing a study that found that a breathing rate of three cpm was suboptimal in terms of heart rate variability, compared to four cpm. This seems to be in line with the statement of Divine to not use more than 6 seconds per phase of the box breathing square [14]. Now, an overview of the instructions is presented.

2.1.6.2.1 Instructions

1. **Position:** Sit comfortably or lie flat on your back. Relax your body and ensure your surroundings are calm and quiet.
2. **Inhale:** Breathe in slowly through your nose for a count of four.
3. **Hold:** Keep the breath held in for a count of four.
4. **Exhale:** Slowly breathe out through your nose for a count of four.

5. **Hold:** Wait for another count of four before beginning the next breath cycle.
6. **Repeat:** Continue this cycle for several minutes.

2.1.6.3 4-7-8 Breathing

The 4-7-8 breathing technique is a simple yet powerful breathing method that promotes calmness and tranquility. It is based on pranayama, an ancient Indian practice that means 'regulation of breath' [15]. Just like the previously discussed box breathing, the power of 4-7-8 breathing lies in its cyclic nature. A big advocate of this method is Dr. Andrew Weil, a renowned physician in integrative medicine that popularized this breathing style in 2015, because of its effectiveness in reducing anxiety, helping insomnia, and managing cravings [15].

The name 4-7-8 denotes the count duration for each step in the breathing cycle: inhale for 4 seconds, hold the breath for 7 seconds, and exhale for 8 seconds. This technique aims to decrease the speed of breathing and increase the amount of oxygen in the bloodstream. The extended exhalation is especially significant, as it triggers the body's parasympathetic system, encouraging a state of relaxation. The instructions are now presented.

2.1.6.3.1 Instructions

1. **Positioning:** Sit or lie down in a comfortable position. Try to relax your body and find a quiet environment.
2. **Inhale:** Slowly breathe in through your nose for a count of four. This should be relatively silent.
3. **Hold:** Retain your breath for a count of seven.
4. **Exhale:** Gradually release the breath through your mouth, making a soft whoosh sound, for a count of eight.
5. **Repeat:** Continue this cycle three more times, for a total of four breath cycles. With practice, you can extend this to eight cycles per session.

2.1.6.4 Alternate Nostril Breathing

Alternate nostril breathing, known in Sanskrit as Nadi Shodhana, is a fundamental technique within pranayama, the ancient Indian practice of breath control. This breathing method is believed to balance the body's energy systems, improve focus, and induce a state of relaxation.

The technique involves breathing through one nostril at a time. Typically, the thumb of the right hand is used to close the right nostril, and the ring finger is used to close the left nostril. The process starts with an exhale, followed by inhale through one nostril, switching, and then exhale and inhale through the other nostril. This would harmonize the left and right hemispheres of the brain, balancing the physical and emotional states [16]. The technique is performed according to the following instructions.

2.1.6.4.1 Instructions

1. **Positioning:** Sit comfortably, with your spine erect and shoulders relaxed. Make sure your environment is calm and quiet.
2. **Preparation:** Using the right thumb, gently close the right nostril.
3. **Inhale:** Breathe in slowly through the left nostril.
4. **Switch:** Close the left nostril with your ring finger and release the thumb off the right nostril.
5. **Exhale:** Exhale through the right nostril.
6. **Inhale:** Keep the left nostril closed and inhale through the right nostril.
7. **Switch:** Close the right nostril and open the left nostril.
8. **Exhale:** Exhale through the left nostril. This completes one cycle.
9. **Repeat:** Continue these alternated nostril inhale-exhale steps for as many cycles as comfortable. The breathing should be comfortable, controlled, and relaxed.

2.1.6.5 Controlled Hyperventilation (Wim Hof Method)

Controlled hyperventilation refers to intentionally increasing the breathing rate. People might know it as being part of the ‘Wim Hof Breathing Method’. Controlled hyperventilation differs significantly from the other presented breathing techniques; where the previously mentioned techniques were focusing on the activation of the parasympathetic nervous system, controlled hyperventilation aims at creating a temporary deficit of carbon dioxide ($CO2$) in the body, also known as hypocapnia. This deficit has various effects on the body, such as an elevated blood pH-level, vasoconstriction, and feelings of light-headedness. If done for too long, it might lead to numbness in hands, feet, or lips, and other potentially harmful effects such as heart palpitations, fainting and even seizures. Namely, the contraction of the blood vessels (vasoconstriction) happens throughout the body, including in the brain. This attributes to the sensation of light-headedness. If an individual is not familiar with this technique, it is advised to only practice this technique in presence of a qualified instructor. Individuals with cardiovascular problems should first consult their general practitioner.

The technique is popularized by Wim Hof and is known worldwide. The Wim Hof Method includes cold exposure, meditation, and the Wim Hof Breathing Method, which comprises of three to four cycles of controlled cyclic hyperventilation and breath holds [17].

According to Hof, his method leads to increased mental and physical resilience against stressors, increased energy levels, increased mindfulness, and improved immune function.

The improved immune function has been significantly demonstrated by a relatively small-scale, but an elaborate study by Radboud University in 2014 [18]. Further examination of more scientific results is outside the scope of this thesis. One way of performing cyclic hyperventilation, followed by breath holding is to the following instructions.

2.1.6.5.1 Instructions

1. **Positioning:** Sit or lie down in a comfortable position in a safe environment. Avoid standing due to the risk of fainting.
2. **Inhale:** Take a deep breath in, fully filling the lungs.
3. **Exhale:** Exhale quickly in 1 to 2 seconds, but not fully – leave some air in the lungs.
4. **Inhale:** Inhale quickly in 1 to 2 seconds.
5. **Repeat:** Continue this rapid inhale-exhale cycle for approximately 15-30 breaths (or until you feel a tingling sensation in your body).
6. **Hold:** When you stop the quick breathing cycle, exhale fully and hold your breath for as long as you comfortably can.
7. **Recovery Breath:** Inhale fully and deeply and hold it for about 15 seconds.
8. **Normal Breathing:** Resume normal breathing and take a moment to observe any changes in your physical or mental state.

2.1.6.6 Physiological Sigh (Huberman Method)

The Physiological Sigh, partly popularized by neuroscientist Andrew Huberman in 2023 [23], is a naturally occurring breathing pattern observed in humans and other mammals, notably during sleep, moments of relaxation, or in response to stress and anxiety. This technique is also mentioned in papers under the name Dragon's Breath [19]. The technique involves a double inhalation, followed by a prolonged sigh on the exhalation, which serves as a reflex that aids in emotional regulation, stress relief, and maintaining lung function [3, 20, 21].

From a neuroscientific perspective, this reflex is modulated by a network of neurons in the pre-Bötzinger complex in the brain, which responds to heightened levels of carbon dioxide in the body. It effectively acts as a resetting mechanism for our respiratory system, promoting the reopening of collapsed alveoli in the lungs, thereby increasing the efficiency of the gas exchange in the lungs [22].

While physiological sighs often occur unconsciously, they can also be performed voluntarily as a stress-relief technique. They can be used in the context of breathwork exercises, especially useful in reducing the symptoms of anxiety, panic attacks, insomnia, asthma, and inflammation. It also may enhance cognitive performance, memory, and creativity [23].

2.1.6.6.1 Instructions

1. **Positioning:** Ensure you are in a comfortable position, sitting, or lying flat. Ensure your body is relaxed, and your surroundings are calm.
2. **Initial Inhale:** Take a deep breath in through your nose, using your diaphragm so your belly expands fully.
3. **Second Inhale:** Without exhaling, take another breath in through your nose, filling the lungs to their maximum capacity.
4. **Pause:** Hold your breath for a brief moment.
5. **Exhale:** Release all the air through your mouth in a relaxed, sighing manner. The exhale should be longer than the combined inhalations.
6. **Repeat:** This can be done a few times in a row, but it is not meant to be a continuous pattern of breathing. Use it as a tool to reset your state of mind or body.

2.1.6.7 General Considerations for Safety

In general, breathing techniques are considered safe and beneficial for most individuals. However, there are certain considerations to keep in mind when practicing these exercises. For instance, people with specific medical conditions, such as asthma, COPD, cardiovascular issues, or other medical considerations, should consult with their healthcare provider before starting any breathing exercises to ensure their safety and appropriateness. Fincham et al. [10] stress the importance of exercising precaution at all times. They state that clinicians should consider on an individual basis whether breathwork may exacerbate the symptoms of certain mental and/or physical health conditions. Some techniques involve rapid or forceful breaths, which may lead to hyperventilation in certain individuals, causing dizziness, light-headedness, or even fainting. In individuals that endured some form of traumatic experience, breathing techniques (both quick and slow) may lead to fear, stress, reliving the traumatic experience, or even panic attacks or hyperventilation. Trauma psychotherapist Amanda Gregory [24] reminds us it is not useful to ‘just take a deep breath’ when a traumatized person is close to hyperventilation or a panic attack, since during hyperventilation, there is a lack of carbon dioxide in the blood. She references Dr. Julia Englund Strait: “Taking a deep breath, especially a quick one, is essentially extending and exacerbating the hyperventilation cycle. If you are having a panic attack, or feel close to it, taking a big gulp of even more O2 is the very last thing you should do, because it will tip the scales again in favor of less CO2. With that big gulp of air, you are pumping even more oxygen." [24].

However, an insightful research paper by Gerbarg et al. [5] found that slow breathing practices may help to activate certain physiological states that allow for a heightened capacity of empathy, compassion, and understanding in individuals, raising many examples where breathing techniques caused positive outcomes for people with certain illnesses. So, even though breathing techniques pose some risks to a certain demographic, used in the right way by professionals, the breathing techniques can be beneficial too for this same demographic.

Another consideration for ensuring the techniques' effectiveness is that individuals may over-fixate on perfecting a particular breathing technique. This can sometimes result in added stress or anxiety, counteracting the intended relaxation benefits. It is essential to approach these techniques with a relaxed and open mindset, allowing for individual variation and comfort. The WHBA prototype of this thesis should be able to synchronize with the wearer's breathing pattern, as it is one of the design requirements of this project. The next section will provide information on haptic stimulation, which will be useful in the design process of the haptic wearable device.

2.1.7 Haptic Stimulation and Feedback

The concept of breathwork and its effectiveness have been discussed in the previous sections. Now, the attention will be shifted to haptic stimulation and feedback. The core aim of this thesis is to develop a system that utilizes haptic cues to guide the system's user through breathwork. Haptic feedback is considered to be an effective alternative to visual and auditory cues for several reasons. This section aims to provide an overview of haptic stimulation, its applications, its role in motor learning, its limitations, and its potential for future use.

2.1.7.1 Haptics

The terms 'haptic stimulation' and 'haptic feedback' are often used interchangeably, but it is crucial to distinguish between the two. Haptic stimulation involves the use of actuators to generate tactile sensations such as pressure, vibration, stroke, and touch [25]. Haptic feedback is used to refer to both tactile and kinesthetic perception in the context of motor learning [26]. Tactile perception is usually conveyed through the skin, such as by vibrations or pressure. Kinesthetic perception works via receptors in the muscles and tendons that allow us to feel the position of our limbs and body parts. Haptic feedback, however, is using haptic stimulation in a way that responds to the actions of the user.

According to Sigrist et al. [26], haptic feedback extends the haptic guidance. Haptic guidance refers to physically guiding the subject through the ideal motion using a haptic interface. This could, for example, be a robot arm that guides the body part of an athlete through the perfect motion. Haptic augmented feedback, however, aims to teach the movement without necessarily guiding the body part; it uses any kind of haptic perception that teaches the necessary features that guide the subject toward, and not necessarily through, the desired motion. This definition also distinguishes haptic augmented feedback from haptic rendering, which refers to feeling virtual objects haptically, of which more is described in 2.1.7.4.

Different types of haptic feedback, such as vibration, force feedback, and tactile feedback, have been utilized in a variety of applications. For instance, vibration feedback is commonly used in mobile devices to provide alerts, while force feedback has been used in gaming to enhance immersion [26]. A field that can benefit from implementing haptic force feedback is the Robot-assisted minimally invasive surgery (RMIS) [27]. This technology allows doctors to perform internal surgeries through tiny incisions. However, due to the lack of proper haptic feedback, its current success is limited. Using their natural hands, surgeons can feel every little detail in what they are doing, such as the texture, thickness, elasticity, resistance, and other aspects of tissues. Not feeling this information makes using RMIS a challenging task [28]. Currently, there are a few RAS (Robot Assisted Surgery) machines that have implemented a form of haptic feedback in the joysticks, but more refinement and innovation is needed. A possible solution to this is haptic gloves, which allows the operator of various robots to not only control them, but also ‘feel’ what the robot feels [29].

Another implementation of haptics is in the field of social touch. Huisman [30] has written a comprehensive overview of the field of social touch and touch itself. For infants and children, touch is an important aspect of their upbringing, as it supports bonding, and conveys feelings of safety, comfort, and love. This is why the proper early development of the vagus nerve in children is essential, as Hasler describes in [1, p. 37]. In grown-ups, touch remains an important aspect of social interactions. Besides visual and auditory information, touch is also an important way of communication in people, especially in friends, family, and romantic interactions. With the right intentions of the giver, touch can invoke positive emotions, and reduce pain and stress signals.

Combining the power of touch with technology, leads to the use of haptic solutions. There are several types of haptic applications, such as temperature, vibration, and force. These use different receptors in and under the skin. An implementation of this is ‘mediated touch’, which detects touch with, for example, sensors, after which the signal is transmitted via a medium—such as through the internet—so it can be rendered at the recipient using actuators. An extensive list of prototypes using this mechanism is provided in the paper by Huisman [30].

Important for realistically conveying mediated touch, is that the receiver must believe the sensations are coming from the sender. Visual and auditory information help to convey this [30]. Mediated touch can be combined with Lederman and Jones' 'haptic stroke illusion' [25]. This method, using precise motor placements and timing, gives the illusion as if somebody strokes the recipient's skin.

2.1.7.2 Haptics in Wearables

Haptics has proven to be a highly effective feedback system for a multitude of wearable devices, including fitness trackers and smartwatches. These devices use haptic feedback as an interface to communicate information to the user, without requiring them to interrupt their activities to look at a display or listen to audio instructions. Although haptic feedback in wearables may not provide detailed or precise data (such as the exact timing of each step during a run), it excels in providing binary information (like whether the user has maintained their running pace over the last kilometer, or whether their heart rate has remained within the desired range).

2.1.7.3 Haptics in Motor Learning

Haptic feedback plays a significant role in physical therapy, sports, and rehabilitation, helping patients improve their movements and exercises [26]. Concurrent feedback, which is provided during the execution of a movement, can be beneficial for learning new physical actions. However, at some point, terminal feedback (which is feedback that is provided after the completion of a movement) is necessary to ensure that the individual has genuinely learned the movement and is not overly dependent on the system using concurrent feedback.

2.1.7.4 Limitations and Future Prospects of Haptics

Despite its many benefits, haptic feedback also has certain limitations. These include the accuracy of the feedback, the cost of the technology, and potential discomfort for the user [25]. For instance, while haptic devices can provide a sense of touch, replicating the full range of human touch sensations accurately can be challenging. Moreover, high-quality haptic devices can be expensive, potentially limiting their widespread use.

The future of haptic technology is looking promising, especially with the integration of haptic rendering in virtual reality (VR). VR platforms are increasingly adopting haptic feedback to create more immersive experiences, thereby bridging the gap between the virtual and real worlds. Already in 2006, Kuchenbecker et al. devised a way to use haptic feedback on the hand to make impacts with virtual objects feel real [31]. For example, when touching a block of Styrofoam, it could feel as if the user is touching a real wooden block.

Additionally, advancements in sensor technology are allowing for more precise and nuanced haptic feedback. Improvements in technology can provide detailed information about the user's interaction with their environment, which can be used to create highly accurate haptic feedback [32]. Simple vibration motors lack the quick response times that is needed for realistic virtual texture rendering. However, a voice coil or variable-friction surface displays do have the capacity to render the high bandwidth, high-frequency vibrations, which is a promising technology for future VR implementations of haptic feedback.

2.1.7.5 Conclusion on Haptics

The sections above have highlighted the potential of haptic stimulation and feedback as a tool for conveying information in a unique manner, distinct from visual and auditory feedback. The possibility of integrating haptic feedback with other modalities for a multimodal approach is highly promising. However, the use of haptics as a standalone modality requires further research. Haptic feedback can be sensed without visual or auditory cues, making it a valuable implementation for delivering cues during cognitive tasks. Haptic feedback is often experienced more personally compared to the apparent external visual- and auditory cues. In the context of motor learning and rehabilitation, haptic feedback can provide efficient, personalized information to users in ways that other forms of feedback cannot [26].

Breathing can be categorized as a form of motor learning. Research on this topic has been advancing in the last years. In the next section, an overview is presented of the current state of the art.

2.2 State of the Art

Before the design process can start, it is essential to look at existing work and relevant research papers in the field. Several research projects were identified that used haptic stimulation or feedback to guide the breathing of the participants. Additionally, some research papers were included that used haptics to inform about moving through the environment, since these also provide insights in using haptics and thinking about pattern design. An overview of the gathered research papers can be found in Table 1. This is not a complete list of all studies involving haptics and breathing, but rather aims at providing a representative perspective on the field of haptics in breathing guidance, and to a lesser extent, other forms of haptics or guided breathing applications. After that, Section 2.2.2 will shift the focus from academic accomplishments to commercially available solutions for guided breathing.

2.2.1 Similar Academic Research Papers

This section will describe relevant, similar research papers. In Table 1, an overview of the sources and their properties can be found. Every entry in the table is described in the upcoming sections. For each source, helpful takeaways are highlighted. The takeaways will be summed up in section 2.3 and will contribute to the answers to the Knowledge Questions in section 2.4.

Table 1 - Overview of Relevant Research Papers

Authors	Setting	Application	Biofeedback	Form factor	Target
Balters et al., 2018 [33]	Driving Course	VT	No	Car seat mat	Slow breathing
Balters et al., 2020 [34]	Driving Sim	VT	No	Car seat mat	Fast breathing
Barontini et al., 2020 [35]	Hallway	VT	Yes	Upper arm wearable	Navigation
Bouny et al., 2023 [36]	Lab	VT, V	Yes	Device in hand palm	Slow breathing
Bumatay & Seo, 2017 [37]	Lab	VT, A	Yes	Mobile phone in pillow on abdomen	Slow breathing
Chen et al., 2015 [38]	Outdoors	V, A	No	Mobile phone application	Rhythmic breathing while walking
Choi et al., 2022 [46]	Lab	P	Yes	Clip-on wearable	Slow breathing
Dijk & Weffers, 2011 [39]	Lab	VT, V, A	Yes	Couch with haptic blankets	Slow breathing

Ghandeharioun & Picard, 2017 [40]	Lab	V, A, T	Yes	Computer program and wristband	Slow breathing
Miri et al., 2020 [41]	Lab	VT	Yes	Actuator pads on body	Slow breathing
Mitchell et al., 2010 [42]	Lab	V	Yes	Digital avatar	"Active Cycle"-breathing for cystic fibrosis
Paredes et al., 2017 [19]	Driving Sim	VT	No	Car seat mat	Posture and breathing exercises
Papadopoulou et al., 2019 [43]	Lab	T, TT	Yes	Sleeve for underarm	Emotional regulation
Valsted et al., 2017 [44]	Athletics Track	VT	Yes	Wristband	Rhythmic breathing while running
Yu et al., 2015 [45]	Lab	P	No	Pneumatic pouch in hand	Slow breathing
Zepf et al., 2021 [47]	Driving Course	VT, A	Yes	Car seat (built-in subwoofers)	Slow breathing

Table 1 shows relevant papers that are discussed in this State of the Art-overview section. Alphabetically listed per authors of the corresponding research papers, the table mentions the research environment, application type (with the following abbreviations: VT – Vibrotactile; V – Visual; A – Auditory; T – Temperature; P – Pneumatic-tactile; TT – Tension-tactile), the presence of biofeedback, form factor of intervention and the targeted result.

2.2.1.1 Stanford's Car Seat

Stanford University has several research papers on haptics and guided breathing, of which three are discussed here. In these research papers Balters et al. [33, 34] and Paredes et al. [19], used a car seat with forty-one vibrotactile motors. When a person is sitting in the seat, these forty-one motors would cover the whole back of the person. This number of motors allow for precise patterns of haptic stimulation. Paredes et al. [19] researched the car seat in conjunction with a driving simulator, to see how drivers' fatigue can be reduced by letting the driver follow instructions to move their body. These instructions were given by several different patterns. For example, a stroke on the right would mean 'lean to the right'. Or a tap on the shoulder meant 'move head to the right'. Issues about driving safety were raised, as moving your head sidewards resulted in less visibility on the road. Next to these instructions, the car seat also had integrated breathing guidance, which is more relevant to the topic of this thesis. Their implementation of box breathing was for example an upwards stroke to breathe in for four seconds, then another to hold the breath, and conversely, one downward stroke to breathe out, and another to hold.

Results show that the deep breathing mode was preferred out of all movements (including the instructions for the body exercises). The researchers noted that patterns should not be dubious. An interesting example of their qualitative evaluation is the question "Would you agree that this stimulus wants to communicate X?". This question will be seen as inspiration for formulating this thesis' evaluation questions for in the questionnaire.

A year later, Balters et al. [33] expanded on Paredes et al.'s setup [19]. In this research paper, the driving seat and driving sim was evaluated in the context of a fast-paced breathing intervention to boost the driver's arousal state. Tiredness, fatigue, boredom, and drowsiness have been identified as some of the main causes of traffic incidents. The 41-motor car seat provided a simple up-and-down haptic pattern. Qualitative feedback reported, amongst other things, the desire for both fast and slow breathing speeds. Most participants (6/8) were positive towards the intervention and its possibilities. The researchers aimed at a 30% increase in breathing rate but warn for the possibility of hyperventilation or lightheadedness. This is one of the unique instances of targeting a heightened breathing rate, instead of trying to slow one's breathing rate. One of the eight participants reported that they encountered psychological issues by breathing too quickly, as they linked that with anxiety.

In 2020, Balters et al. [34] took the car seat intervention on the road. Dubbed as 'Calm Commute', they had installed the 41-motor grid into an actual car. The programmed pattern was an up-and-down pattern, just like the pattern that was used in [33]. The test participants were instructed to drive around the parking garage. There was a statistically significant decrease in breathing rate and a prolonged reduction in arousal state. One of the main design recommendations is to offer more diverse kinds of haptic patterns, which aligns with the goal of this thesis (except this thesis is not focused on driving). Other two main points of improvements were to offer time for the user to familiarize themselves with the system, and to let the user adjust the strength of the haptic stimulation. The latter is a recommendation given in more research papers that are discussed in this State of the Art-section.

Concludingly, the 41-motor grid of Stanford University has been used in various research papers, focusing on fast breathing, slow breathing and other awareness-improving exercises while driving. The takeaways from these papers for this thesis are the aspect of letting the user control the strength of the patterns and the value of formulating adequate evaluative questions to gain qualitative feedback.

2.2.1.2 Haptic Navigation for the Visually Impaired

In this research paper, Barontini et al. [35] created a wearable haptic system that helps in guiding visually impaired or blind people in navigating indoor spaces. Using an RGB-D camera, the system could detect obstacles on the path. Important in their Human-Centered Design approach was ensuring that the haptic instructions were clear and unequivocal, such that the user does not become confused about what instruction the system is giving. To deliver the haptic cues, a device with two motors and a band is used. This device goes around the upper arm and, with the help of the two motors, the band can tighten, loosen, and rotate clockwise or counterclockwise. With this, the instructions ‘stop’, ‘go’, ‘left’, and ‘right’ could be signaled respectively, simulating how an accompanying person would signal with their hand on the arm of the blind person. Both blindfolded and visually impaired participants found it easy and comfortable to use.

Takeaways of this study are allowing users to customize their experience, and benefits of a discreet and portable design. Also, this paper included the aspect of natural mapping, which involves translating natural occurring body movement into analogous informative haptic signals.

2.2.1.3 Breathing Assistant to Hold in Hands

The goal of this paper by Bouny et al. [36] was to reach resonant breathing with the use of visual and haptic feedback. A device that fitted in the hand palm could display a bar that moved up and down and produce vibrotactile cues. The target rate for coherent breathing in this study was a breathing cycle of ten seconds, meaning a breathing rate of six cycles per minute. With a group of thirty-two participants, either visual, haptic, or both modalities were tested. The researchers made a noteworthy remark about the haptic-only modality: individuals may not perceive the haptic stimuli with the same acuity. According to referenced literature in [36] by Feygin et al. [48] and Reuter et al. [49], haptic sensing depends on the motivation, focused attention, and cognitive and emotional statuses of individuals. The visual-haptic modality was the most effective in achieving coherent breathing.

The takeaway of this research paper is the insight that haptic sensing is dependent on multiple factors and differs between people. Following this observation, this thesis' WHBA prototype might benefit from a user-controlled intensity option.

2.2.1.4 Breathing Assistant in Pillow

Bumatay and Seo [37] have researched the role of biofeedback and haptic stimulation in mobile paced breathing tools. The goal of the study was to explore haptic cues and biofeedback modalities. The three modalities were haptic, auditory, and both haptic and auditory simultaneously. Next to that, the cues were either manually controlled via an unmarked slider or automatically adjusted based on biofeedback from the breathing rate. The haptics and sound were delivered by phone (with attached headphones) that was put inside a pillow. The user could sit in a quiet environment holding the pillow to their abdomen.

Similarly to other sources in this State of the Art-section, the researchers noted that personal preferences are a key factor while using haptics. In their study, the manual and biofeedback mode were rated quite equally (48% manual, 43% biofeedback, 9% no preference with N=21). Some participants wanted to control the technology themselves, whereas others appreciated just breathing along the cues. However, both interaction types were desirable. The modality of only haptic stimulation was the most effective and most liked, with some users comparing it to a cat's purring.

A key takeaway for this thesis' project is to be wary of the personal preferences of what the lowest breathing rate is that users feel comfortable with. Some users in this study reported that the biofeedback system required them to breathe uncomfortably slow. In the design process of this thesis' WHBA, this may be accounted for using an adjustable slow-breathing target rate.

2.2.1.5 Meditative Rhythmic Walking

This short conference paper by Chen et al. [38] described a mobile phone app that provides biofeedback during walking. The goal of this system was to achieve a meditative walking state, citing the beneficial implications of mindful walking by Thich Nhat Hanh [50]. The application provides a visual and acoustic representation of when the breathing rate is in tune with the walking pace. The steps were measured using the phone's on-board accelerometer and the breathing rate was calculated using the microphone of the earphones.

The project by Chen et al. [38] does not involve haptics or advanced sensors, nor does it include much information on the steps taken. Despite its limitations, the paper is relevant to this State of the Art-overview, as it expands the scope of using breathing and biofeedback techniques to achieve a calm state of being.

2.2.1.6 Pneumatic Modules

Choi et al. [46] created a clippable pneumatic haptic feedback device consisting of three pneumatic modules. These modules could inflate and deflate, resulting in a perceivable pressure sensation on the upper body of the wearer. The research paper was focused on the design of a wearable haptic breathing assistant. Therefore, this extensive research paper goes in-depth on various design aspects, such as the aspect of keeping the technology hidden from view, or users being able to control the intensity of the cues. Two main haptic patterns were evaluated. One sequential pattern, where the modules activate after each other (with a slight overlap), and a synchronized pattern where all the three modules activate at the same time. The sequential pattern was rated higher in pleasantness and comfort and resulted in lower stress compared to the synchronized pattern. However, the researchers observed that test participants preferred different patterns for different reasons. The stress factor, for example, was not a predictor on a preference for a pattern. Some participants reported that they would prefer either pattern based on the environment.

The researchers recommend the intervention to be worn for extended periods of time, like more than two hours per day, because testing for five minutes per session did not show significant reduction in breathing rate. Also, the goal breathing rate in relation to the environment and context should be considered, as slow breathing during exercise or active tasks is not suitable. Like other research papers discussed in this State of the Art-section, the researchers recommend the personalization of the cues by the user, such that the user has control over the intensity and tactile patterns.

2.2.1.7 Breathe With the Ocean

Dijk and Weffers [39] presented a concept called ‘Breathe with the Ocean’. The researchers drew an analogy from the ocean; the system used visual, auditory, and haptic cues to simulate the waves of an ocean. Its design required the user to lie on a bed or a couch, between a haptic blanket with 176 small motors that surround both the front and back of the user. The haptic pattern started at the feet, continued all the way to the head, and ‘retreated’ again, simulating the waves washing up the beach. Simultaneously, the sound of those waves is played in sync. The user would follow the flow of the waves with their breath.

The researchers evaluated both a one-size-fits-all modality (no biofeedback) as well as two biofeedback modes that use several bio-signals, including breathing rate, to adjust the rate of the cues. One version was where the system *follows* the breathing rate of the user, and one where the system *leads* the user. The former was meant to make the user more aware of their own breathing rate using multimodal feedback, whereas the latter is meant to guide the user in slow breathing to reach their optimal rate where the HRV is the highest.

This study offers some valuable insights, like the fact that persons may perform an occasional sigh during the use of the system; the algorithm should take this into account. The user should not have to rush or slow down their breath, but the system should adapt to the user. This leads to the recommendation that the experience should be optimized, since even minor negative experiences can undermine the system's calming effects.

2.2.1.8 BrightBeat

Ghandeharioun and Picard [40] have made a system called BrightBeat. This system is aimed at maintaining an optimal breathing rate during cognitive tasks on a computer. The feedback modes consisted of auditory, visual, and thermal cues. While other papers discussed in this State of the Art-section mostly use soft, but apparent cues, BrightBeat uses "barely perceptible" cues; the researchers claim that only individuals who are distracted from their task will notice the stimuli. During cognitive tasks, the breathing rate is naturally slightly higher than at a relaxed state. When the breathing rate of a test participant exceeded a predetermined breathing rate, BrightBeat would activate to slow the breathing rate back down. The results were statistically significant (N=32), and the intervention group reported higher calmness compared to the control group, indicating the effectiveness of the intervention.

The method of determining the relaxed breathing rate of a user, and applying cues at a slightly lower rate, will be considered in the design of this thesis' WHBA.

2.2.1.9 Designing and Evaluating a PIV

Miri et al. [41] have conducted a comprehensive research paper about designing a Personalizable and Inconspicuous Vibrotactile breathing pacer (PIV), which is related to this thesis' WHBA. The researchers aimed to explore two questions: what the best placement for the PIV on the body is, and what characteristics of haptic patterns are effective. The test participants had no distinct preference of body sites, but the researchers found the abdomen to be the best, because it caused the least fluctuations in breath-depth. Very deep breathing is not advised, as it results in a less-smooth breathing experience.

The patterns were applied by only two vibrotactile motors on either the chest, abdomen, or lower back. The patterns were sinusoidal with different changes in either amplitude, frequency, or both. The researchers found that changes in frequency were easier to detect than changes in amplitude. Moreover, a recommendation is given that the change of either frequency or amplitude should be at least 20% to 30% to be perceivable with vibrotactile motors.

A follow-up study of Miri et al. [51] showed that the PIV was effective in reducing anxiety in the presence of a cognitive stressor. It was found that the factor Openness was a promising predictor in the effectiveness of the PIV, meaning that the intervention was more effective on individuals with low openness characteristics. This may be due to the probability that low-openness individuals are less inclined to use other, less-private means of affect regulating technology. Which highlighted the design goal of the PIV needing to be hidden from sight.

Takeaways include that the abdomen and lower back are suitable for vibrotactile stimulation for breathing purposes, as well as the insight of how much either the frequency or amplitude has to change before being perceivable, and the finding of frequency-based changes being better distinguishable than amplitude-based changes. Lastly, Miri et al. highlight the importance of personalization. To help other researchers with this step, the researchers included an extensive documentation of their personalization routine that proved to be successful in their study.

2.2.1.10 Buddy for Active Cycle-breathing

In the research paper by Mitchell et al. [42] it is reported that in Ireland one in nineteen citizens are carriers of the cystic fibrosis gene. This disease leads to breathing complications from phlegm formation in the lungs. There is a breathing technique, called ‘Active Cycle’, that alleviates the symptoms by taking four to five deep breaths, and then holding the breath. To assist individuals in this breathing exercise, the researchers developed a system that gives visual biofeedback. The breathing sensor was embedded in a textile garment. The expansion of the chest and abdomen was visualized in a computer program. The user of the system had to follow the mouth movement of a digital avatar that gave the cues to various breathing exercises, as shown in Figure 1.

The paper also outlines their performance evaluation method. The researchers used a coefficient R, calculated through an equation, to correlate the user's actual behavior against the biofeedback instructions. This coefficient, which ranges between -1 and 1, helps quantify the effectiveness of the biofeedback system. This could be interesting to implement in the WHBA prototype.

Figure 1 - Digital Avatar Giving Instructions [42]

2.2.1.11 Haptic Sleeve for Emotional Regulation

According to Papadopoulou et al. [43], emotional awareness in humans can be aided by using rhythmic stimuli, such as light, vibration and sounds. Interoceptive awareness is highly related to emotional awareness. Interoception is the experience of the internal state of the body. Too high levels of interoception have been linked to anxiety [24, 43]. Using external stimuli, the body can follow the provided rhythm. This is a similar implementation of the barely noticeable cues in BrightBeat (2.2.1.8).

Papadopoulou et al.'s approach of implementing such rhythmic stimuli was to create a sleeve that fits on one of the underarms. This sleeve could provide both warmth and tactile haptic stimulation, simulating the aspects of human touch. The goal was to simulate therapeutic human touch. The sleeve was made of several cuffs in a row. Each of these cuffs had internal nitinol wires that, based on temperature, could 'reset' to their predetermined shape. In this case, when heated to above 45°C, the metal would try to flatten itself, since a linear and flat line was the 'set' shape. Below these temperatures, the metal was being forced back into an arc shape, because of the strength of the fabric. Depending on the current flowing through the wires, the temperature can be adjusted. This is an interesting way of applying both tactile and warmth feedback with just one wire.

The test participants were not fully informed about the true goal of the research. Namely, they thought that they would do a quiz and that the sleeve's impact on cognitive performance was the subject of the research. Measuring electrodermal activity (EDA), the researchers could measure the participants' sympathetic arousal state. There was one control group with an inactive sleeve. The slow-rhythm group had the rhythm matched to their relaxed breathing rate, and the fast-rhythm group had the sleeve's rhythm set to 25% of their relaxed breathing rate.

In terms of the EDA, the results were not statistically significant. The only statistically significant result was that the fast group breathed indeed faster than the control group. The researchers believe that the not-significant results may be attributed to the small sample size of N=18. The evaluation involved a questionnaire and interview. Here, all the slow group-participants indicated that they felt positive towards the intervention. The researchers found a positive correlation between slow speed and calmness, and a negative correlation between fast speed and calmness.

What can be taken away from this paper for this thesis is their method of qualitative evaluation, which involves both a questionnaire and an interview. This way, there is ample opportunity to gain qualitative feedback.

2.2.1.12 Strive

Strive is the name of a tool that aims to help runners with achieving rhythmic breathing. The study by Valsted et al. [44] explored the use of a wristband and a breathing sensor to inform runners when to breathe. The breathing sensor was made from a rubber strap, connected to a sensor that measured the variable resistance inside the band. When the chest expands, the resistance increases. This method was very effective at counting the breaths and steps while running, with an accuracy of 98%. The research paper includes two studies. In the first study, the researchers wanted to find out what haptic pattern works best in conveying the breathing cues. The two tested haptic feedback patterns were: receiving haptic feedback only when breathing in, or only when breathing out.

The breathing technique that was used in this paper was the rhythmic breathing technique, introduced by Coates and Kowalchik's book 'Running on Air' [52]. This method dictates to breathe in for three steps and breathe out for two steps. (This technique is specific to an exercise environment and that is why it is not described in Section 2.1.6 – Breathing Techniques). The researchers noted that more complex haptic patterns were indistinguishable by the test participants. Haptic cues while breathing out were preferred over cues to breathe in. Namely, inhale-based cues lead to unnatural-feeling breathing behavior in some participants.

The second part of the study focused on temporal aspects of the cues while running on a track. Three modes were evaluated: continuous-, periodic- and manual feedback. Qualitative feedback indicated that the manual feedback was most preferred. The other two modes were considered more intrusive and harder to uphold the rhythm. However, qualitative data showed that the continuous mode offered the best performances. The researchers recommend the continuous mode for training with shorter periods or interval training. The other two modes are more suitable for long runs.

One of the takeaways of this paper are the recommendation to keep the patterns simple. The test participants were confused when there were vibrations for both breathing in and out. Even though these results came from an exercise environment, it is worth to consider this finding in this thesis' WHBA. Another takeaway is that the continuous feedback offered the best results, even though it was experienced as intrusive or frustrating for longer exposures. The informative nature of continuous feedback will be considered in designing the WHBA. The accuracy of 98% of the breathing sensor and band are promising results, given they evaluated the accuracy for 1.5 hours while running on a treadmill. The WHBA will also use a similar strap- and sensor system.

2.2.1.13 Pneumatic Pouch

Yu et al. [45] researched a tactile interface for guided breathing. Their idea was a pouch, the size of a computer mouse, which inflates and deflates itself. The user of the system can lay their hand around the pouch at feel the expansion increasing and decreasing, symbolizing the actual lungs filling up with air and exhaling. This study was a two-part study. The first study focused on the stress level reduction before and after the use of the device. The second part focused on the design and interface itself, which is more on-topic for this thesis. Seventy percent of the participant indicated that the haptic interface was their favorite out of testing haptic, auditory, and visual cues for guided breathing separately.

The researchers emphasized that the breathing training is a learning experience, which is good to consider for this thesis' WHBA. The user is expected to engage and learn with the technology, rather than solely being exposed to it. The inflatable pouch was a great implementation of a 'natural mapping' technique, which means that the interface felt intuitive to follow. This is another aspect that should be considered in the design process of the WHBA.

2.2.1.14 Breathing Guidance while Driving

Zepf et al. [47] researched the use of auditory and haptic feedback for guided breathing while driving in a car. The BioZephyr sensor measured the heart rate, heart rate variability and the breathing rate. When the breathing rate of a test participant exceeded a predetermined threshold, the cues would be activated at a rate of two breath cycles per minute slower than the actual breathing rate of that participant. Both acoustic and acoustic + haptic feedback showed significant results for breathing rate reduction. Haptics alone did not show any significant results.

For the WHBA prototype of this thesis, the aspect of delivering the cues at a rate that is slower than the actual breathing rate will be considered in the design process. This approach can be seen as a seductive approach of behavior change according to the design model by Tromp, Hekkert & Verbeek [53], since it uses low salience and uses weak force, which aligns with the intended design principle of this project.

2.2.2 Commercial Solutions

Using haptics to aid in wellbeing is not exclusive to academic papers. There are also commercially available products that have their own approach of using haptics to increase the quality of life of the user. Some of these are highlighted in the following sections.

2.2.2.1 Elitac Wearables

The Dutch company Elitac Wearables B.V. creates health-focused haptic wearables. Elitac specializes in integrating electronics with textiles and aims to incorporate haptic feedback to better the quality of life. Examples of their products are FysioPal [54], a device that reminds the user of their posture; NavigationBelt [55], a military-grade belt that allows operators to feel the direction of mission objectives by following the vibrations; and BalanceBelt [56], a medically certified belt that informs the user about their body position. All of these examples include haptic feedback in unique ways. The NavigationBelt and the FysioPal are depicted in Figure 2.

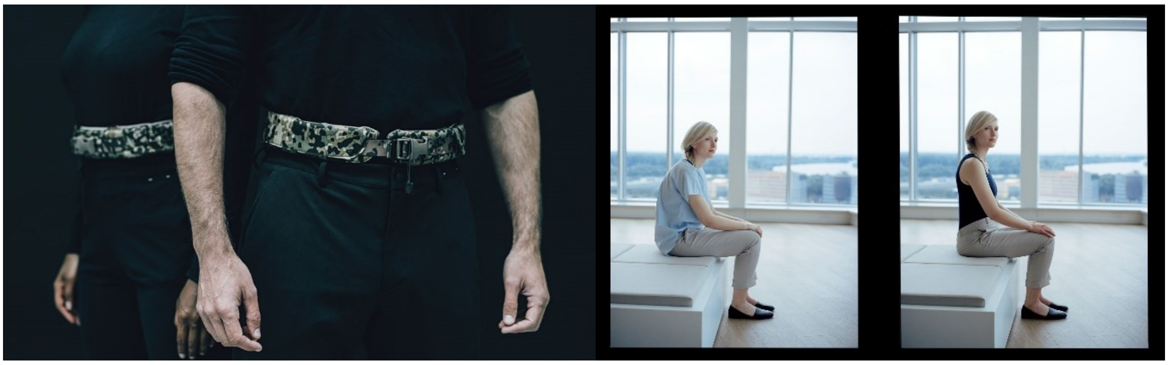

Figure 2 - Elitac NavigationBelt [55] (left) and Elitac FysioPal [54] (right)

2.2.2.2 Spire Stone

The Spire Stone [57] is mainly a pedometer that clips on a waist belt. The built-in accelerometer, however, is also used to track the breathing of the wearer. Connected to a mobile app, the app can estimate the wearer’s mood and stress level. The original Spire Stone is not available anymore, but Spire Health have focused on a business-to-business service for remote patient monitoring. Their newest tracker [58] can stick semi-permanently to clothing, lasting up to a year without recharge, and it can even remain on the clothing during laundry. The device tracks breathing, heart rate, and activity, and sends an automatic alert when the medical condition of a patient changes. Then, the care team can check the dashboard for the readings and respond swiftly with their care and support. An example of the dashboard and the new Spire tracker can be found in Figure 3.

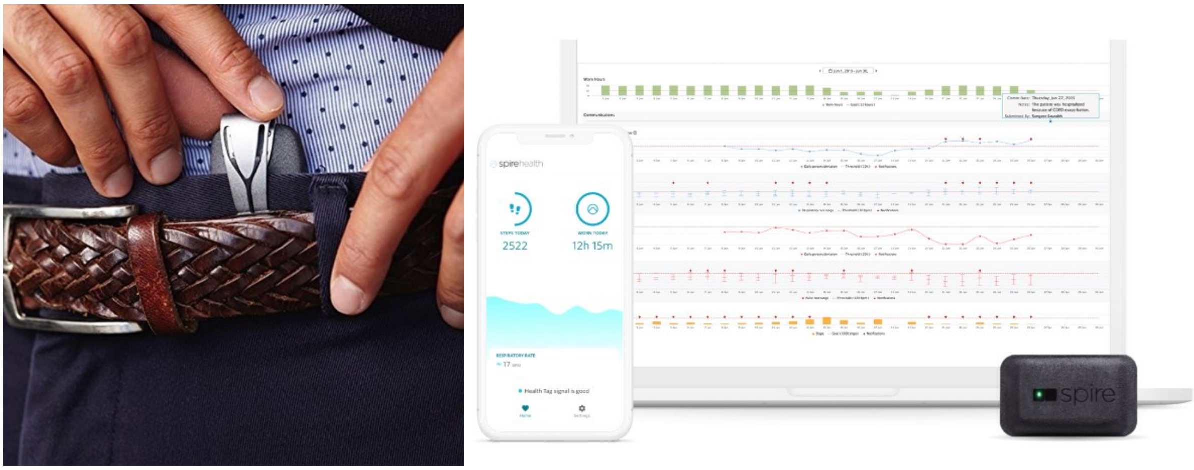

Figure 3 - Spire Stone [57] (left) and new Spire Health Medical Tracker [58] Dashboard (right)

2.2.2.3 Lief HRV

Lief [59], depicted in Figure 4, is a wearable EGC that measures heart rate and heart rate variability (HRV) throughout the day. Once the device registers a too low HRV, it starts a breathing exercise. The user can follow the vibrotactile cues with their breathing, while the Lief is simultaneously monitoring the rise in HRV. Once the HRV is restored, the breathing exercise turns off.

Figure 4 - Lief: A Wearable ECG Patch [59]

2.2.2.4 Smartwatch Apps

Modern watches like the Fitbit and Apple Watch [60] offer a feature that allows the wearer to perform a breathing exercise. Generally, these take a few minutes to complete. The watch uses its haptic motor to give haptic cues that the user can follow. During the exercise, the watch keeps note of the heart rate. If the app notices that the wearer is breathing out of sync, it will notify the user and tries to pick up the coherency again. Both the Fitbit and the Apple Watch also rely on visual cues. An animation is played that the user can follow by breathing in and out as the animation expands and shrinks. Apple Watch users have the option to get reminders throughout the day to start a short breathing exercise. An example of such a reminder can be found in Figure 5, which shows the reminder on an Apple Watch.

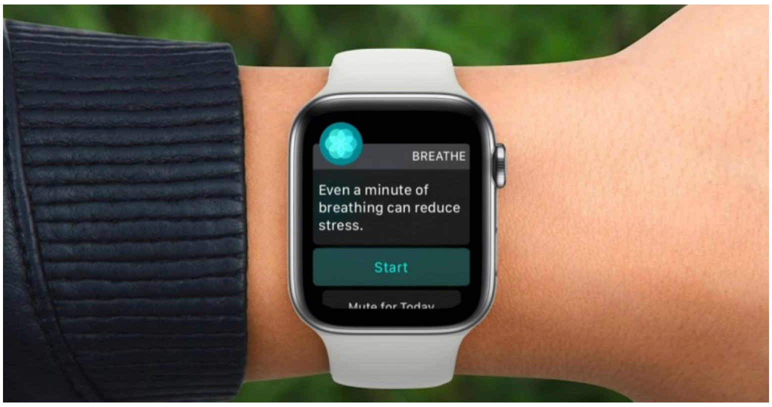

Figure 5 - Reminder to the Apple Watch Wearer to Breathe [61]

2.3 Takeaways of Background Analysis

After reviewing both literature and state-of-the-art research, several key takeaways emerge that are important and relevant to the development of the WHBA. Firstly, the literature shows that breathing has a significant impact on both physical and mental wellbeing. The beneficial psychophysiological effects can be achieved through various breathing techniques that involve slow breathing, such as diaphragmatic breathing, box breathing or 4-7-8 breathing. By slowing down the breathing rate, the parasympathetic nervous system becomes active and helps lower the heart rate, while simultaneously lowering stress and increasing social openness.

While performing breathing exercises, safety and wellbeing are paramount. For example, people with traumatic experiences related to breathing, or who have underlying medical conditions such as asthma or COPD, breathing exercises should be performed cautiously, as negative experiences can negate the positive effects and may lead to increased stress and anxiety. However, generally, the literature applauds the relative ease-of-use, accessibility, safeness, and effectiveness of breathing exercises.

Haptics are a unique way of assisting in motor learning, compared to visual and auditory cues. Haptics provide a more personal experience and can deliver information with less cognitive processing than sound and visuals require. Namely, haptics can be felt, rather than interpreted. A system as the WHBA can be used both as a learning tool and a breathing pacer. In case of a learning tool, biofeedback can be used to guide the user in the motor movement. As a breathing pacer, the system can be activated when the user is breathing ‘too fast’. Then, the haptic cues can be provided at a slightly lower-than-actual rate to guide the user back to the calm breathing rate.

From the State of the Art-section, it is evident that using haptics for personal breathing assistants is an interesting field, with many different approaches. These studies have led to unique takeaways for the design project of the WHBA. A pattern emerges in the findings of the papers: The perception of haptics is a personal experience: the device must support some level of personalization of, for example, vibrotactile strength or manual control of the tempo of the haptic cues; Haptic feedback should be located near the natural breathing areas, such as the abdomen and lower back, to avoid the asymmetry and unnatural posture associated with wrist-based solutions; Haptic patterns should be easy, comfortable, and intuitive to understand: the user should not feel lost or pressured to ‘catch up’. Using biofeedback, the system should adjust to the user; Haptics can be used to either learn or guide individuals in breathing techniques. One way of incorporating guiding is by presenting a cue rhythm that is slightly lower than the actual breathing rate; And lastly, the evaluation of haptic prototype systems is of qualitative nature. Using short questionnaires and interviews leads to valuable insights by test participants.

There exist some commercially available haptic breathing appliances, but it is a relatively small field. It is promising to see the state-of-the-art research endeavors to this subject, as some research papers demonstrate creative and cost-effective ways of implementing haptics and biofeedback. This paves the way for new products and projects that may distribute the beneficial effects of haptics and breath regulation to the world.

2.4 Answering the Knowledge Questions

The literature review and state of the art allow for the Knowledge Questions to be answered. For each of the three Knowledge Questions, the question itself is phrased, after which an answer is provided. The answers to these questions help the initial phase of the design process that starts in Chapter 4.

2.4.1 Knowledge Question 1

“What breathing techniques may be effective to teach with haptic stimulation patterns?”

Both in the literature research papers and the State of the Art-overview papers, slow breathing is the most researched and tested breathing technique. There are also quick-breathing approaches, such as in [33], but slow breathing seems to be the most widely used breathing technique. The psychophysiological benefits are well-documented. There are several breathing techniques to facilitate slow breathing: diaphragmatic and coherent breathing, box breathing, and 4-7-8 breathing.

Important with these techniques is that the breaths are performed by diaphragmatic breathing instead of the ‘higher-up’ breathing with the chest. Haptics are considered the most effective tool to assist individuals in this motor learning task. The haptics can be programmed in such a way that the user feels the system responds to their abdominal breathing more than their chest breathing, persuading the user to use their abdomen. This then, formulates a design goal of that the WHBA should function as a motor learning tool to train the wearer in breathing with the abdomen instead of the chest.

2.4.2 Knowledge Question 2

“Where on the human body would haptic stimulation be comfortable and effective to teach breathing techniques?”

In the State of the Art-overview papers, it becomes clear that the torso is the mostly used area for haptic stimulation for guided breathing. The torso is proximally close to the breathing function and is therefore more appropriate than the peripherals such as the wrist. Moreover, the torso leaves enough space to apply symmetrical haptic cues. Some research papers and commercial products use a wrist-worn device, but that would lead to an unnatural and unsymmetrical body position according to [41]. Other papers, such as [19] used the whole back to apply haptic cues, but these cues were quite complex, requiring cognitive deciphering, leaving some participants confused.

The abdomen and lower back are suitable places for haptic stimulation. These locations are not intrusive, and limit potential complexity of the haptic patterns. The abdomen can be used to simulate a therapeutic technique where the patient is required to ‘breathe away’ an object on their abdomen, such as a book or the therapist’s hand. The lower back is also part of the breathing movement since it expands too when breathing in [41]. Therefore, using both the abdomen and the lower back seems like the most appropriate choice for this thesis’ WHBA prototype.

2.4.3 Knowledge Question 3

Since the experience of haptic stimulation is very personal, evaluating haptic patterns requires qualitative feedback. The State of the Art-papers showed multiple ways to evaluate the effectiveness of their interventions. There were cases of testing their project on an intervention group and comparing it to a control group, or those that analyzed biological readings on the same person, comparing the results before and after the intervention. However, this thesis is small-scale and aims to not validate the biological efficacy of the WHBA, but rather explore the characteristics and possibilities of the haptic patterns. For this type of research, qualitative feedback is required.

Two main methods of qualitative feedback were used in the State of the Art-overview papers: short questionnaires about the experience and feelings of a participant, and an interview format where the participant was invited to share their experience in their own words. Using the feedback, the patterns can be improved upon and evaluated again to gain even more feedback. The feedback will help understand what characteristics are valued in haptic stimulation patterns, as well as improve the prototype and, finally, generate a list of recommendations for future research in this field.

3 Method

Before the design process of the haptic feedback patterns starts, the prototype itself is needed. This chapter will inform about the components and wiring schematic used to have a functional prototype that can measure abdominal expansion and generate vibrational patterns on the abdomen and lower back based on the sensor's data. Information about the evaluation method and ethical aspects are presented towards the end in this chapter.

3.1 Design Method

There exist numerous design approaches to develop a product or project. In case of a creative engineering project, an unfit approach would be something known as the 'waterfall' approach. This is where the design and development are performed in a linear fashion, with little to no feedback from the client until the final product is delivered. Using such a design method for the whole design process is not efficient: it costs a lot of resources to finish the whole design sequence and this system is not optimized for user-client centered design. The study program Creative Technology follows a novel design process that was proposed by Angelika Mader and Wouter Eggink [64]. Their model is a hybrid between Industrial Design's user centered design, and 'classic', more linear, engineering design principles.

The model consists of four phases: Ideation, Specification, Realization and Evaluation. All three design phases use the divergent and convergent approach. This allows for a structured, yet flexible framework. Using this approach, the pitfall of tunnel vision is avoided: each phase, the divergence allows for exploring possible options that may be even outside the direct desired scope. When these ideas are generated, the ideas can be converged by checking if the solutions still cover all design goals. Using convergence, the designer can use their knowledge and their understanding of the project's requirement to narrow the possible solutions down to an idea that can be specified in the next phase. In all of these phases, the designer reflects and evaluates the solution with regards to the requirements and user experience.

3.2 Sensors

The breathing sensor used in the WHBA prototype is called 'BreathPal' [62]. It is produced on a small scale by Ben Bulsink in Enschede. The sensor can report the expansion of both the abdomen and chest separately, using two stretchable bands. The expansion is measured by interpreting electrical measurements of the internal copper wire. The stretch of the copper wire creates a measurable and predictable response. The precise working of this sensor is outside the scope of this thesis project.

Using the sensor is straightforward. One strap goes around the abdomen and, optionally, the other strap goes around the chest. The main control unit has a positive, negative, and serial wire. In the WHBA, it is powered by its own USB connection on 5V. Once the power is applied, the sensor turns on. The BreathPal will output a string of information via its serial output pin. The first two values of this string are important for this thesis, which are the values of the abdominal and chest expansion, respectively. The reported value is in arbitrary units, but the change between the readings is accurate and useful. The specific sensor used in this project gives out a new reading every 100ms. Since the breathing cycles are quite long (multiple seconds long), this will be a short enough update interval to provide real-time feedback of the breathing behavior. However, the difference between the sensor values is sometimes negligible, making it hard to analyze in the software on the microcontroller. The readings are captured on an ESP32 microcontroller at a Baud rate of 38400. The ESP32 is a good choice for this project, as illustrated in section 3.4.

3.3 Actuators

To provide the haptic stimulation, eight vibrational motors will be used. The motors used in this project are not of a particular brand and they are provided by the supervisor of this project. They are dc motors that function up to 5V. Because of their very low-profile design, they are small and compact. This makes the motors very suitable to be used in haptic feedback applications. In the WHBA prototype, they will be attached to a soft, elastic, wide velcro sleeve that can wrap around the taille of a person. The motors sit between the clothing of the user and the band. That way, the tension in the band causes the motors to be gently pressed against the body. Naturally, the thicker the clothing, the less detailed the vibrations will have. There is however a shortcoming to these motors.

Their normal use-case is on a solid PCB, for example in a smartphone. Using the motors in a dynamic environment like the WHBA prototype, it becomes apparent that the tiny connector wires are very vulnerable to being moved around, stretched, bent, pressed, and even be vulnerable to the motor’s own vibrations. All these disturbances can easily cause the wires to detach, without the possibility for repair. To solve this physical design challenge, the prototype uses a soft, moldable, silicon-like substance called Sugru. An image of some motors enclosed in their Sugru body can be found in Figure 6. This will stabilize the wires to a certain extent. It is not perfect; during the development of the prototype, some motors stopped functioning even with the molded enclosures. Sugru, a product made by German adhesives company Tesa [63], was easy to use as it can be kneaded freely by hand to mold it in any shape and after 12 to 24 hours, it is cured.

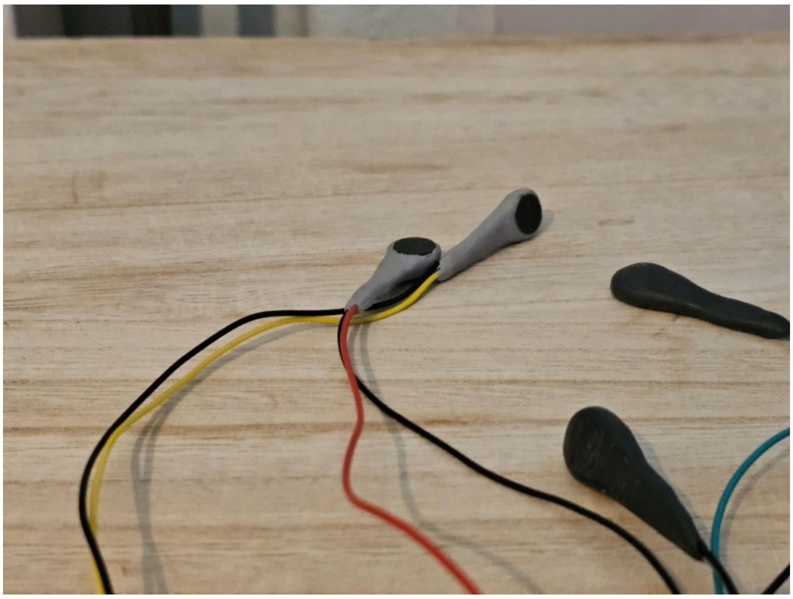

Figure 6 - Small Vibration Motors Enclosed in Soft Sugru Body

3.4 Microcontroller

The sensors and actuators will be used in conjunction with an Adafruit ESP32 Feather microcontroller. Espressif's ESP32 platform is a widely used and well-documented microcontroller platform. It features Wi-Fi and Bluetooth, as well as 'shields' that can be attached to the Adafruit Feather to have expanded functionalities (e.g., an LCD display). Areas of application of this microcontroller are diverse: it excels in Internet-of-Things applications, but it is also a popular choice for DIY or research projects. Example applications are wearables, home automation, robotics, creative art, education, and health monitoring. It is programmable in C++, using, for example, the Arduino IDE with Espressif's library. The Arduino IDE is purposefully built for small-scale, quick-tinkering situations. That is why, during the development of the prototype, Visual Studio Code with the PlatformIO extension was used, because the code of the microcontroller is split up in multiple classes, each with their own header- and implementation files. Working with such a big project in the Arduino IDE is simply not user friendly.

The sensor output is connected to a serial pin on the ESP32. The motors, however, are not directly connected to GPIO pins, since the ESP32 is great at controlling things, but not necessarily *driving* things. A small sensor can be powered by its own power, but any electrical component requiring more than 500mA would need its own power supply. The wiring of the prototype is done on a breadboard and is as follows: a 5V power supply is attached to the positive wire of each motor. Simultaneously, this 5V is stabilized using a ceramic and electrolytic capacitor connected to the ground. This prevents inaccurate behavior of the sensor. Without the capacitors, the sensor reading was unreliable while driving all the motors.

The negative of each motor is attached to the collector of a NPN transistor. Since all motors should be controlled individually, each motor has its own transistor. The emitter is connected to ground. Finally, the base of the transistor is attached, via a 10kOhm resistor, to a GPIO pin of the ESP32. Since there are eight motors, eight GPIO pins are used. A strength of the Adafruit Feather is that it supports many PWM (pulse-width modulation) channels. That way, each GPIO gets assigned their own channel. When the GPIO pins are 'off', there is no current in the base of the transistor. The motors will not have an open connection to the ground, so no current is flowing. When the GPIO is supplying a PWM signal, current starts flowing in the transistors, causing the transistor to allow current flowing from the collector to the emitter, which results in a closed loop for the motors. The PWM dictates the voltage of the motor. A cycle of 0 (no current coming from the GPIO pins) results in zero volt-potential across the motors. A cycle of high results in the full 5V across the motors. The next section goes more in-depth about the WHBA prototype.

3.5 The WHBA Prototype

Combining the BreathPal sensor with eight small vibration motors on a breadboard led to the creation of the WHBA prototype. There is a lot happening on the small breadboards. A high-quality picture taken during the building and testing of the prototype is presented in Figure 7. In Figure 8 a Fritzing drawing is shown that depicts the connections on the breadboards.

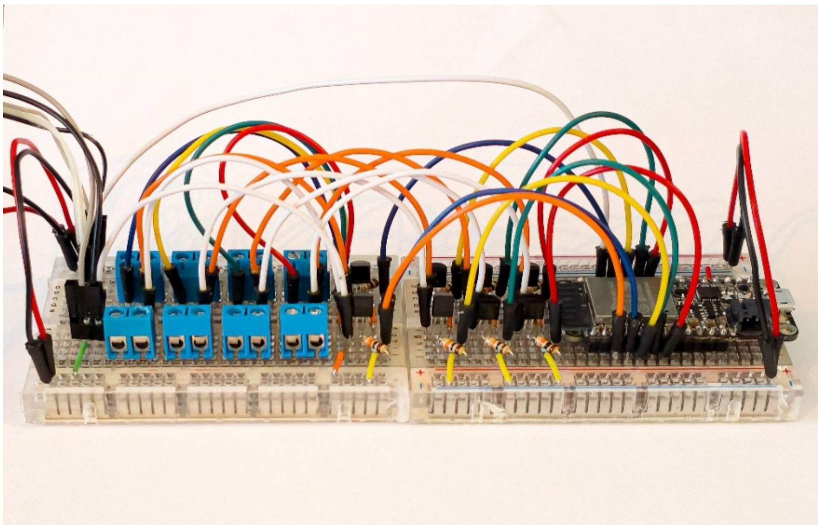

Figure 7 - Picture of the WHBA Prototype (in early development)

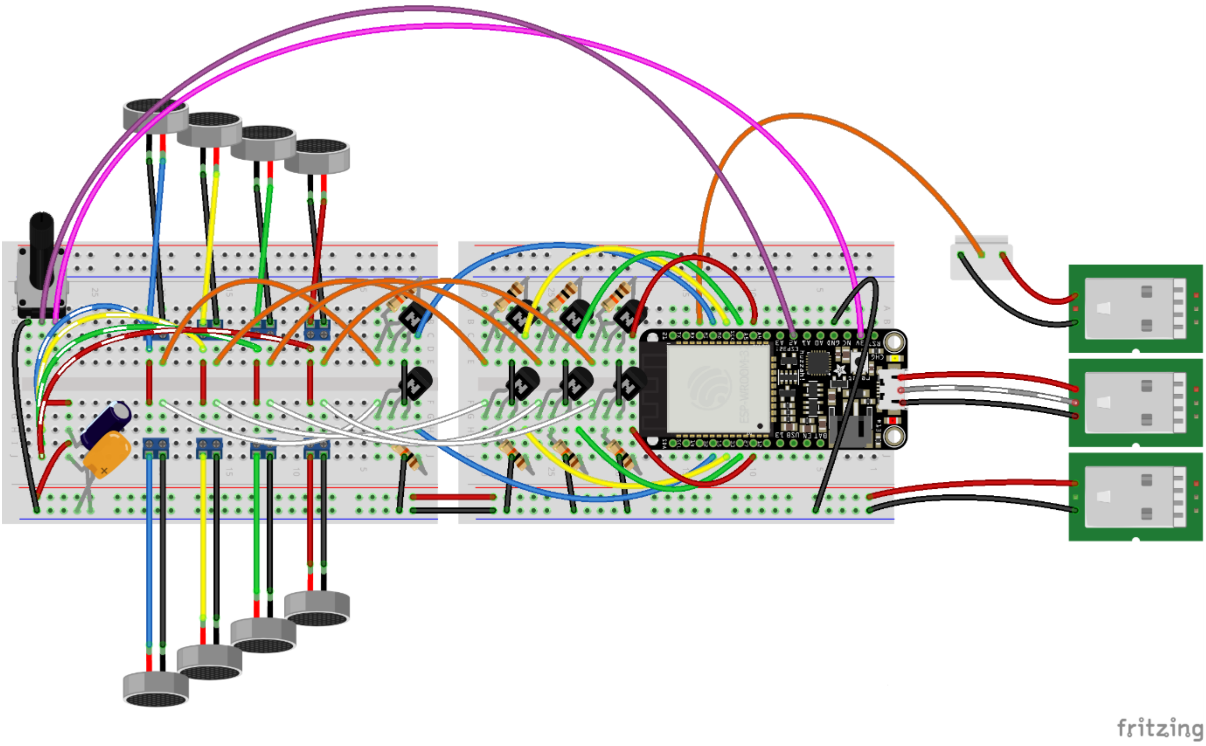

Figure 8 - Illustrative Fritzing Sketch of WHBA Prototype

Figure 8 shows two breadboards, connected on the bottom with a red 5V+ wire and a black ground wire. These bottom rows of the breadboard are then connected to a 5V USB connection. Another USB connection goes directly into the ESP32 micro-USB, to both power the ESP32, as well as to facilitate the serial connection—indicated by the grey-striped wire—between the microcontroller and the PC. The ground of the ESP32 is connected to the ground of the other 5V USB (bottom). The top USB is for powering the BreathPal sensor. The sensor is depicted by the small white rectangle with the black, orange, and red wire. The power of the sensor is in 'separate' from the rest of the circle. The sensor is powered by 5V as well.

During the development of the prototype, the string parsing of the sensor data (serial communication through the orange wire from the sensor to the RX pin of the ESP32) went wrong, due to, likely, high frequency interference. Therefore, two capacitors were used to connect the ground of the big circuit to the 5V of the bottom USB. This eliminated the noise, and the parsing was reliable. This took many weeks of testing different setups, so once this setup worked, it was decided to leave it as it is. That is why the ground of the sensor is not directly connected the power of the sensor to the rest of the circuit. In actuality, a USB divider was used on which all three USBs were attached, so the ground is via that round still equal in that aspect.

A potentiometer can be found in the top left part of the figure. It is attached to the ground with the black wire on the left, and the pink wire is the 3.3V pin from the ESP32. The middle wire (purple) goes to the A2, analog in, pin of the microcontroller. That way, the users could turn the potentiometer to control the maximum intensity of the motors.

Now, the most advanced part of the WHBA is how the motors are driven. The two capacitors are between the 5V on row four and ground. Row four shares its 5V using a small jumper wire to row two. On this row two, four wires (red, green, yellow, blue, all striped in Figure 8) are connected to the four blue screw terminals. They supply the 5V to all eight motors, using four small jumper cables (red) to bridge the middle gap of the breadboard to reach the row of the other four screw terminals.

Each of these terminals has its own unique connection to a set of a NPN transistor and a 10kOhm resistor. The emitter of the transistor is connected to the ground (using small black jumper wires to bridge the gap in the middle of the breadboard, sharing the ground to the other transistor-resistor sets as well. The collector of the transistor is connected to each of the negative rows of the screw terminals. The ESP32 was programmed to have eight individual pulse-width-modulated (PWM) channels on symmetrically selected pins. The bottom four pins lead to the transistor-resistor sets of each motor for the front motors, indicated by the white wires going from the negative motor rows to the collector of the transistor. The same set up is true for the upper part of the breadboard, which control the four motors that go on the lower back of the user: the upper four GPIO pin wires go to each transistor-resistor set of the lower back, after which an orange negative cable goes from the emitter to each motor's negative.

Finally, the motors, which have a continuous 5V on the positive pin, can be controlled by sending a PWM signal from each GPIO pin to its own transistor-resistor set. A high driven PWM signal opens the transistor, given the collector access to the ground. If no current is supplied to the base, the transistor is blocking the flow between the collector and the emitter, thus leaving no potential difference between the motor's pins, leaving the motor completely still.

3.6 Evaluation of Results

The goal of this thesis project is to research the characteristics of vibrational patterns, in the case of real-time haptic feedback during breathing exercises. The thesis hopes to identify aspects of what makes a pattern suitable for use in guided breathing applications, and what aspects are less desirable or effective. For example, how comfortable is a pattern? Is it clear what the pattern wants to communicate with the user? When is a pattern too complex or too simple? What would make a pattern engaging, playful, informative, or enjoyable? How can phase-indicating bumps help convey the beginning or end of a pattern? Would users prefer concurrent feedback, or terminal feedback, or perhaps both? These questions are interesting and relevant. Understanding how vibrations are perceived can lead to the development of wearables that connect to the user in a meaningful and comfortable way. The user should not feel alienated, stressed, annoyed, or upset by technology; the very technology that is designed to increase the well-being of that same user.

The literature review indicates that personal preferences play a vital role in how the user feels about the technology. That is why this thesis uses a semi-guided open approach. The main part of the user tests features four and five patterns in the first and second user test, respectively. After each pattern, the test participant is asked to fill out a questionnaire with basic aspects of the patterns, as well as share their feelings towards the patterns. This questionnaire is seamlessly followed by a loosely guided open interview, where the test participant can talk freely about their thoughts and feelings about and towards the haptic pattern that they just had experienced. Here, the participants can also explain why they gave the scores they gave.

The results of the interviews and the questionnaires will provide valuable insight in how certain aspects of a haptic pattern or the prototype influence their experience. The aspects are Comfort, Clearness, Interactivity, Effectiveness, Naturalness, and Timing. Each of these aspects are evaluated using a Likert scale ranging from 1 to 7, where 4 is neutral. The 1 is a very negative, and 7 very positive, evaluation of an aspect. Each aspect has accompanying questions to make the definition of the aspect clearer for the test participants, such that the scores across all participants and patterns are consistent. The aspects and accompanying questions are as follows:

- Comfort
  - “How did the vibrations of this pattern feel?”
- Clearness
  - “To what extent did you understand what this pattern was ‘telling’ you?”
- Interactivity
  - “To what extent did this pattern adapt to your breathing?”
- Effectiveness
  - “To what extent did you feel this pattern helped you to breathe slower?”
- Naturalness
  - “To what extent did this pattern feel natural and intuitive?”
- Timing
  - “To what extent was the timing of the cues of this pattern appropriate and helpful?”

The flow of the project is as follows: in Chapter 4, the prototype code is explained, after which four patterns for the first user test are presented. These are made by the author of this thesis, using their own tinkering skill that was developed in the Creative Technology program. After four useful patterns are found, they will be evaluated on six user test participants in Chapter 4.2. The feedback from this test allows for more improvements to both the prototype and the haptic feedback patterns, which will be covered in Chapter 5. Finally, the results of both user tests are discussed in Chapter 6.

Testing on actual individuals requires good ethical considerations. The next section will inform about the ethical aspects of this project.

3.7 Ethical Approval

For the user testing phase of this project, the EEMCS Ethics Committee has approved the testing procedure under application number 230446. The participants will be asked for their consent, and it is made clear they can quit the user test at any time without any repercussions. No medical or health data is collected since the focus is on the experience of the vibrational patterns. After the test participant is presented with a brochure informing them about the test structure and other aspects of the test, they are asked to give their consent via the consent form that can be found in Appendix A.

4 Ideation

This chapter is divided in two sections. Section 4.1 will present the thought processes behind the first selection of four haptic feedback patterns. These will be evaluated in a user test with six participants. The results of this test will be presented in section 4.2. The feedback of the test participants will determine the direction of the next chapter, where a new selection of patterns is evaluated on, again, six test participants.

4.1 Exploring Haptic Patterns

In this section, the patterns that are used for the first user test are described. They are designed to be simple and target fundamental aspects of a wearable haptic breathing assistant. Feedback possibilities are time-cue-giving, concurrent feedback of the breathing behavior, guiding feedback, and terminal feedback. Terminal feedback would be a positive or negative signal only after the breathing cycle is completed, which can inform the user if they are breathing 'well' enough or whether there is room for improvement. For the first user test round, the timing and concurrent feedback is given priority over the terminal feedback. The prototype WHBA at this stage is not accurate enough in registering the fine details of someone's breathing behavior, which makes it unreliable for giving suitable terminal feedback. Before the patterns are explained, a description of the code is provided in the next sub-section.

4.1.1 The Code

The ESP32 can be programmed in C++ using, for example, the Arduino IDE or Visual Studio Code with the PlatformIO extension. There are four components of the software operation. The SerialManager class retrieves serial information from the computer and the sensor. After the information is processed, the sensor readings are sent to the DataManager class, where the information is analyzed and interpreted. This class can report the breathing rate in cycles per minute and dynamically calibrate the abdominal expansion, such that a full inhale results in '255' and (comfortably) fully exhaled results in '0' as a mapped value. This mapped value is useful to assign motor intensity values.

The next operation is the PatternManager class that executes the selected pattern. The pattern can be selected by typing a digit in the console of Arduino IDE or Visual Studio Code, which is caught by the SerialManager and will assign it to the 'selectedPattern' variable of PatternManager. The PatternManager has classes of the actual patterns and can execute the selected pattern. Each pattern class generates an array of new motor intensity values that are passed back to PatternManager.

Finally, the MotorManager will take those motor intensity values and apply it to the GPIO pins. Before the signal is applied, it is remapped to at least ‘50’, because during testing it was found that a vibration intensity of below ‘50’ are not perceivable. The upper limit of this remapping is determined by a potentiometer, such that the user can set it to a maximum intensity level that they find comfortable, with a maximum of ‘255’.

4.1.1.1 SerialManager

The SerialManager waits for new inputs on either Serial or Serial2. New information on Serial comes from the USB connection to the console and can be for example ‘1’ to start Pattern 1. The motors can be stopped using ‘0’. New information on Serial2 comes from the sensor connected to the Rx pin of the ESP32. The sensor sends a string of data that contains numerous values. The first two are relevant for this project because they are the abdomen and chest arbitrary unit values. The Serial2 buffer is read until the \n character. Here, the parsing often went wrong because of interference in the circuit. This was solved using a ceramic and an electrolytic capacitor between the positive 5V and the ground, as well as to ignore \r characters. The documentation did not show the presence of \r characters, but without filtering for those, the strings kept being parsed wrongly.

The string from the sensor, consisting of characters, is then parsed such that an abdominal and chest value can be used as numbers. These are put into a SensorReading object that holds the value for abdomen, chest, and timestamp in microseconds, as well as the speed and acceleration that are later determined by DataManager.

4.1.1.2 DataManager

The DataManager receives the SensorReading object and adds the object to a vector of the type SensorReading. It can determine the first and second derivative to calculate the speed and acceleration. The acceleration is not used in the pattern generation, but it was interesting to see during the testing how the acceleration, speed, and position changed during breathing. The SensorReading objects are averaged and added to another vector with the timestamp of the most recent one. A breathing phase (exhale or inhale) is determined and added to the AirFlow field—which is an enumerator—of the SensorReading object. The AirFlow fields are analyzed by a function that checks for the exhale-exhale-exhale-inhale-inhale-inhale pattern (here, the last inhale is the most recent inhale). Once it found such a sequence in the last few readings, it saves the start time of the first inhale in that sequence.

When it encounters the next EEEIII pattern, it can use the new start time to calculate the duration of the completed breathing cycle. A breathing cycle consists of an inhale, followed by an exhale, until the new inhale. By dividing sixty seconds by the cycle duration, the breathing rate can be determined. This breathing rate is reported on the console output, alongside the arbitrary value of the sensor, the speed, the minimum and maximum value of the breathing cycle, and the dynamically mapped value.

4.1.1.3 PatternManager

The PatternManager contains the Pattern classes of the patterns themselves. These have a function that can be executed. A switch is used with the selectedPattern variable (which gets updated by SerialManager). For example, if selectedPattern is ‘1’, it executes the main function of the class Pattern1. When the selectedPattern is ‘0’, the motor intensity array is completely set to ‘0’, essentially stopping all motors from vibrating. Each Pattern class contains functions that generate motor intensity values, which are returned to the motor intensity array of the PatternManager. This motor intensity array is accessed by the MotorManager.

4.1.1.4 MotorManager

Every cycle, the MotorManager checks the values in the motor intensity array of PatternManager and assigns these values to the GPIO pins. The literature indicated that haptics is very personal, and the experience of comfort and intrusiveness varies from person to person. Therefore, a potentiometer allows the user to set the maximum intensity of the vibrations. The potentiometer is read on an analogRead pin. Then, the motor intensity values are remapped to ‘50’ and the maximum potentiometer value between ‘50’ and ‘255’. Below intensity ‘50’, the vibrations are not perceivable.

The motor intensity values are essentially the duty cycle of a Pulse Width Modulation (PWM) operation on the eight GPIO pins. Here, ‘255’ would be a full duty cycle, which would equate to a 5V potential being across the motors. Each GPIO pin has its own ‘LED’ channel, meaning the motors are individually addressable. The breadboard is also designed to support the individual addressable motors.

For both user tests, all the motors will play the same intensity. This is because the motors used in this project are unreliable, and programming gradual patterns is resource intensive. During testing, it was noticed that some motors randomly turned on or off, because of the very vulnerable electric connections of the motors. Therefore, it was decided to focus only on patterns where all motors share the same intensity value.

4.1.2 The Patterns

To establish a baseline on how the prototype performs, four patterns are used. Two of these patterns involve the aspect of time-giving cues, and two involve real-time haptic feedback on the breathing behavior. Even though the WHBA prototype is designed to control eight unique PWM channels, the patterns in the user tests will use one intensity signal for all motors, because of three reasons: 1) the motors are too unpredictable in when they work or not; 2) programming directional patterns is much more resource-intensive; 3) to establish a baseline in haptic stimulation and feedback characteristics, it is useful to focus on one modality.

The motor placement is then less important. With directional patterns, it is beneficial to have the motors spread apart like a square or diamond figure on the abdomen and lower back. However, because the motors often stop working temporarily, the motor setup used in the user test was focused on being symmetrical left and right, with two motors per side close together. So, when one motor temporarily stops working, the other one probably is working, letting the test participant still feel a signal both left and right, on the abdomen and the lower back.

4.1.2.1 Pattern 1

The first pattern is designed to be as basic as possible. This pattern does not use the information of the breathing sensor. Rather, it gives a pre-determined slow-breathing signal consisting of four seconds inhale, a one-second hold, and an eight-second exhale. This would result in a breathing rate of around 4.6 cycles per minute. The vibration increases linearly for the inhale phase, and decreases linearly for the exhale phase, spread for the duration of that specific phase block.

The idea behind this pattern is that when the vibration increases, so does the inhalation. When the vibration fades away, the user can exhale. It is hypothesized that the test participants feel comfortable to follow this pattern, since they do not have to count themselves how long they inhale and exhale. However, because the pattern does not act on their breathing behavior or breathing preferences, some participants may find it annoying and therefore not comfortable.

4.1.2.2 Pattern 2

The second pattern aims at figuring out of well the prototype can give adequate feedback, in real-time, of the breathing behavior. The pattern uses the dynamically mapped abdominal expansion value from DataManager and assigns it as the new intensity value for each motor. That means on a full inhale, the mapped motor intensity value ideally would be ‘255’, thus the motors would be fully turned on. When the user exhales, the vibration fades away.

The idea behind this pattern is that the user is being made aware of their abdominal breathing by simulating the idea of ‘breathing something away’, like a therapist’s hand or a balloon. It would be interesting to couple this with the chest sensor to determine the ratio between chest and abdominal breathing. During the design of this pattern, an abdomen and chest ratio was determined. But an effect was encountered where proper abdominal breathing caused the chest to expand as well near the peak inhalation. Given that the vibrations get deeper the more the user breathes with their abdomen, regardless of a chest sensor being present or not, resulted in the decision to not use the chest sensor at all, for all the patterns. Namely, trying to breathe with the chest would result in much less activity of this pattern, persuading the user naturally to try to breathe more with their abdomen because more vibrations are felt that way.

It is hypothesized that the test participants will relatively enjoy this pattern, as it reflects their own behavior and makes them aware of their own breathing.

4.1.2.3 Pattern 3

The third pattern is the inverse of Pattern 2, meaning that when the user is inhaling, the vibration fades away. This pattern is included in the first user test to establish how the test participants viewed the relationship between inhale-exhale and the vibration being on or off during those phases.

It is hypothesized that this pattern will be less-well received by the test participants, because it may feel ‘punishing’ when the vibrations are fully on while exhaling. Namely, a key component of slow breathing is that the exhale is longer than the inhale, but during testing, the motors being on felt like it was not correct to breathe out so long.

4.1.2.4 Pattern 4

The last pattern of the first user test incorporates both time-cues and feedback in a way that shows the potential of such a haptic breathing assistant system. It was featured in Zepf et al. [47], which was covered in section 2.2.1.14, where it did not show significant results for their study. However, when paired with auditory cues it did indeed show significant results. The idea of serving cues at a slightly lower rate than the user is breathing at that moment, persuading the user to breathe slower and slower, fits well with a haptic breathing assistant. With this pattern, the system will serve as a time-giver, as well as an informed coach that responds to your own behavior.

Following the pattern that was used in the study of Zepf et al. [47], Pattern 4 will also offset the actual breathing rate by -2 cycles per minute. That means that when someone is breathing thirteen times per minute, the vibrational cues play at a rate of eleven times per minute. The upper boundary was set to thirteen, such that someone breathing at fifteen or twenty times per minute would have a starting point to match their breathing to. Then the system gradually, based on the user's breathing rate, drops all the way to a minimum of three cpm. So, if you are breathing at five, four, three, or two cpm, you would just feel the vibration of three cycles per minute. That equates to one breathing cycle taking twenty seconds.

Not everyone can breathe at such a slow pace. It would be a good improvement to let the prototype settle on a breathing rate when it registers the user is not lowering their breathing rate anymore. However, during this first user test, Pattern 4 will be tested without this settling behavior, because of limited resources to spend on additional programming. Given this, it is hypothesized that it can be perceived as annoying if the system keeps pushing you to breathe even slower than you are comfortable with.

4.2 First User Test of Haptic Patterns

The first user test aims to establish a baseline for how the current WHBA prototype operates. An eye will be kept on how well the system is able to keep track of the breathing behavior, and how well the vibrations are played in response to the participants' breathing or the time cues of Pattern 1.

The six participants taking part in the first user test are between the age of 25 and 32, and are either students or alumni of the University of Twente and Saxion. The participants have different body types and have different experiences with breathing exercises. Participant 1 is a diver and can hold their breath for more than five minutes. Participant 2 has some experience with what they called 'Fire breathing', which seems to be similar to controlled hyperventilation (covered in section 2.1.6.5). The other four participants did not really have experience with breathing exercises. There are four biological males and two females.

The participants tested the four patterns on the campus of University of Twente. The initial steps took about twenty to thirty minutes, where the participant was briefed, gave consent, had the prototype installed on their body and calibrated the vibration intensity. For each of the four patterns, the participant was instructed to breathe for five minutes to the provided haptic cues in the way they felt was right. Once the five minutes were over, the participants were asked to fill out the questionnaire, and comment on their experience in a short interview.

4.2.1 Results

In this section, the evaluation of the patterns in the first user test is presented. For each pattern, a quick description of its action is given, followed by the overall feedback from the participants, and the evaluation per aspect. Every pattern has a radar plot to visually show the scores for each aspect. For Pattern 1, the aspect Interactivity is left out, since the pattern had no interactive elements.

The average score of each pattern is calculated by averaging the average scores per aspect per participant. Based on this score, Pattern 2 scored the best, with 7.1/10, followed by a shared second place for Patterns 4 and 1, both 6.5/10. Pattern 3 scored slightly insufficient, with its score being 5.4/10.

4.2.1.1 Evaluation of Pattern 1

Pattern 1 is the most basic pattern of the first user test. It is a time-giving cue with four seconds inhaling, a one-second hold, and eight seconds of exhaling. This was working during the creation of the pattern. However, after deploying the prototype setup in the user test environment, the pattern produced cues at a higher pace than it was programmed to do. The cues were given at a rate of about nine cycles per minute, instead of the intended 4.6 cpm. Participants 1, 2, and 3 noticed this effect and it was annoying to them. The researcher detected this faulty behavior too when investigating the claims of the cues being faster than expected. A reason for the faster cues could not be found, and it was decided to leave the prototype as-is to maintain consistent research conditions for all the participants in this first user test.

Participant 4 and 5 were optimistic about the faster cues: even though the cues were faster than intended, it felt comfortable and it gives a “hand to hold” (P4) and was experienced as a suggestive rhythm that helped with the overall attention to the breathing (P5). Sometimes it helped them with breathing in, and sometimes it helped them to breathe out longer. They had rated Naturalness and Timing slightly better, tempering the negative scores of the other participants. In the radar plot in Figure 9, the average scores by all participants for each aspect of Pattern 1 is visualized.

Participants found the vibrations to be comfortable. The pattern was somewhat clear and somewhat effective in lowering the breathing rate. Because of the tempo difficulties, the pattern felt slightly unnatural and had poor timing. The scores per participant, per aspect, can be seen in Table 2. For each participant, their overall score is shown in the bottom row, and for each aspect the average score is shown in the last column. The right bottom corner shows the overall rating of the pattern. All scores are on a Likert scale from 1 to 7.

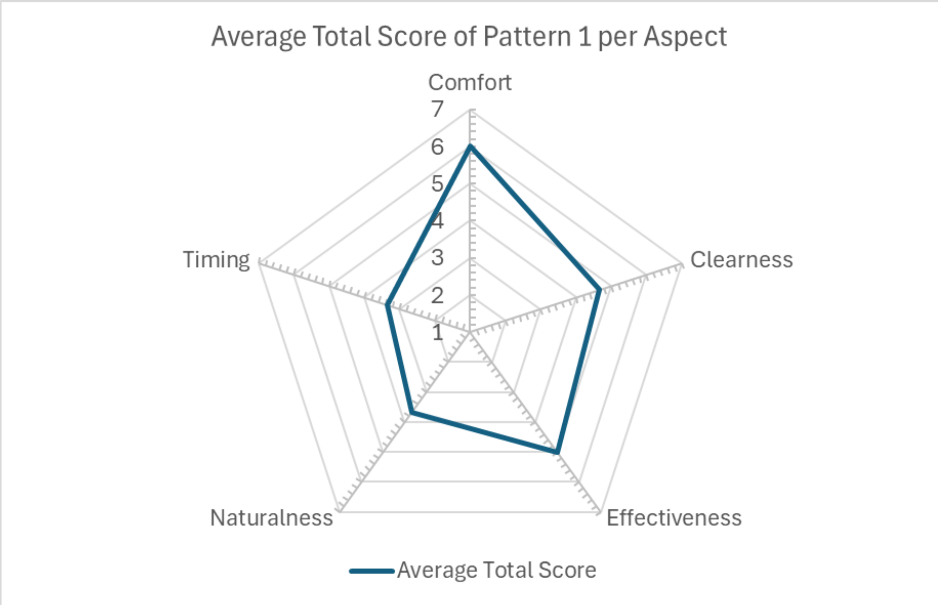

Figure 9 - Radar Plot of Pattern 1

Table 2 - Scores per Aspect per Participant of Pattern 1

Pattern 1	1	2	3	4	5	6	Score per Aspect
Comfort	6	7	5	6	6	6	6.00
Clearness	5	3	5	6	4	5	4.67
Interactivity (not applicable)							
Effectiveness	6	5	2	7	6	4	5.00
Naturalness	3	1	4	7	6	1	3.67
Timing	4	1	2	6	6	1	3.33
Score per Participant	4.80	3.40	3.60	6.40	5.60	3.40	4.53

4.2.1.2 Evaluation of Pattern 2

Pattern 2 features a directly proportional increase in vibration as the user inhales. When the user exhales, the vibration fades away. This effect is achieved with the dynamic remapping of the sensor values, while detecting the minimum and maximum values for each cycle.

This pattern was well received by the participants, having an overall score of a 7.1 out of 10. This makes it the best rated pattern of the first user test. Most participants were annoyed by the technological problems of the prototype. Oftentimes, the dynamic calibration would fail, which caused the pattern to lose track of the participant's breathing rhythm. When the system would work, it was found to be "very interactive" (P2) and as a "good reward" for successfully completing a breathing cycle (P3). Participant 6 found it ineffective, stating: "[The pattern] didn't do much, but it did make me more aware of my breathing.". Because of slight delay in the real time feedback of the prototype, Participant 1 felt the need to breathe faster, to match the vibrations again. Similarly, Participant 5 felt as if they had to play catch-up with themselves. Participant 4 also experienced this: “I felt the need to really do my best.”.

Participants found the vibration of this pattern to be comfortable and clear in what it tried to convey. The interactivity was good when the technology worked, but far from perfect when it randomly stopped. That is also why the pattern’s effectiveness was rated to be neutral. The increase and decrease in vibration felt unnatural to some (P1, P4), but to others it did feel natural, leaving the average score to be neutral as well. When the technology was working, the timing of the feedback was somewhat good.

The radar plot of the aspects is presented in Figure 10, and the scores awarded per participant per aspect can be seen in Table 3, For each participant their overall score is shown in the bottom row, and for each aspect the average score is shown in the last column. The right bottom corner shows the overall rating of the pattern. All scores are on a Likert scale from 1 to 7.

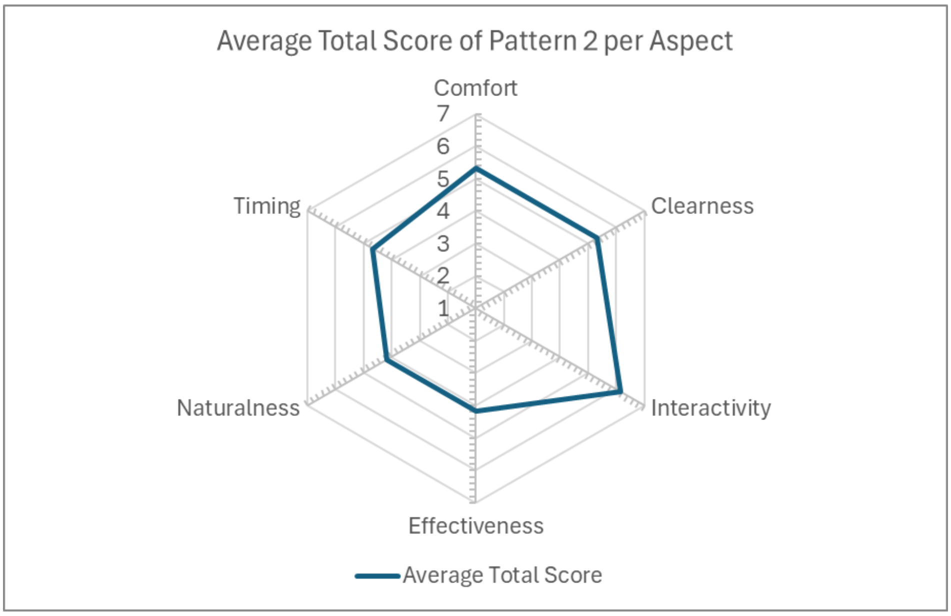

Figure 10 - Radar Plot of Pattern 2

Table 3 - Scores per Aspect per Participant of Pattern 2

Pattern 2	1	2	3	4	5	6	Score per Aspect
Comfort	5	7	3	6	4	7	5.33
Clearness	4	7	4	7	6	4	5.33
Interactivity	5	7	5	6	7	7	6.17
Effectiveness	5	6	5	4	3	2	4.17
Naturalness	3	6	5	2	5	4	4.17
Timing	5	5	5	4	3	6	4.67
Score per Participant	4.50	6.33	4.50	4.83	4.67	5.00	4.97

4.2.1.3 Evaluation of Pattern 3

Pattern 3 has a vibration that disappears as the user inhales. When the user exhales, the vibrations gradually build up again. That means that when the user has not inhaled, the motors are on full intensity. The participants did not fancy this effect, having received a score of 5.4 out of 10.

The participants found the nature of this pattern too stressful and annoying: it felt like “go go go!” (P3). Participant 6 started this pattern of with a remarkably high breathing rate that was nearing that of controlled hyperventilation. The researcher intervened, to instruct the participant that this is a slow-breathing exercise. Participants 4 and 5 mentioned to prefer Pattern 2 to this pattern. Not all ratings were bad: “It felt like the pattern was telling you to exhale some more.”, said Participant 2 positively.

The only positively rated aspect is that the vibration itself feels comfortable, but overall the participants found the pattern vague, lacking in responsiveness (due to the faulty hardware), ineffective, and unnatural.

The radar plot of the aspects is presented in Figure 11, and the scores awarded per participant per aspect can be seen in Table 4, For each participant their overall score is shown in the bottom row, and for each aspect the average score is shown in the last column. The right bottom corner shows the overall rating of the pattern. All scores are on a Likert scale from 1 to 7.

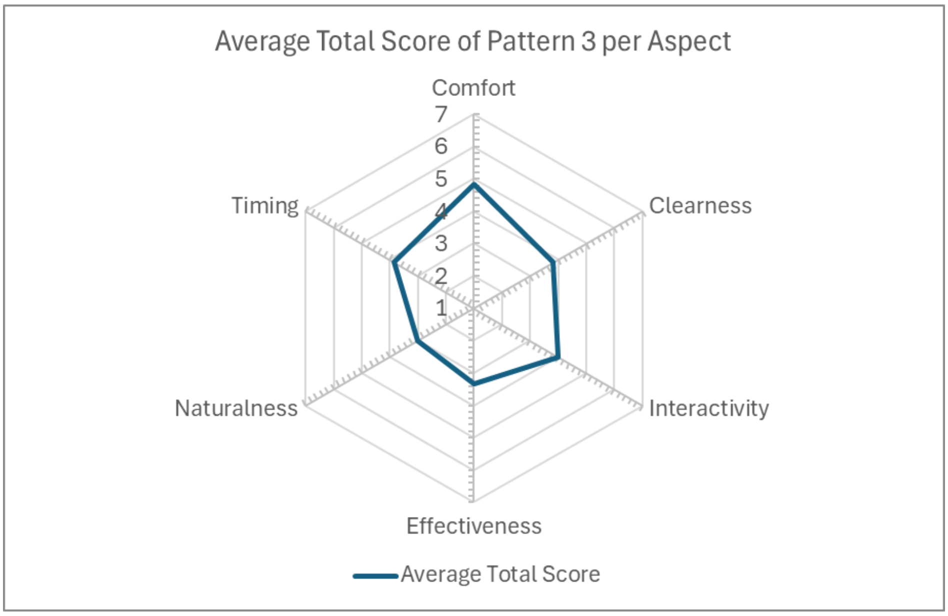

Figure 11 - Radar Plot of Pattern 3

Table 4 - Scores per Aspect per Participant of Pattern 3

Pattern 3	1	2	3	4	5	6	Score per Aspect
Comfort	5	7	2	2	7	6	4.83
Clearness	3	7	1	7	2	3	3.83
Interactivity	7	2	3	1	5	6	4.00
Effectiveness	3	6	1	6	2	2	3.33
Naturalness	2	5	4	1	3	3	3.00
Timing	4	6	4	4	4	1	3.83
Score per Participant	4.00	5.50	2.50	3.50	3.83	3.50	3.81

4.2.1.4 Evaluation of Pattern 4

Pattern 4 is the pattern that serves the vibrational cues at -2 cycles per minute slower than the actual breathing rate of the user.

This pattern was received relatively well with a score of 6.5 out of 10. Thanks to the guiding nature of this pattern, it was more consistent in its performance. Participant 1 says: “It felt constant and easier to follow than Pattern 2 and 3.”. Participant 3 remarked that they would like to use it more often if they could. However, due to the pattern updating its tempo based on the participant’s breathing rate, it was also confusing to most of the participants. Participant 5: “Sometimes there was no vibration, and sometimes two vibrations in one cycle.”. Especially Participant 6 was not content about the intermittent adjustments, commenting annoyed: “What do I have to do now?”.

Even though the participants felt confused about the sudden jumps in the cues of this pattern, their scores were overall positive. The vibrations felt comfortable and somewhat clear in what it tried to tell the participants. It felt somewhat interactive and slightly effective in reducing the breathing rate. Also the naturalness and timing were slightly good.

The radar plot of the aspects is presented in Figure 12, and the scores awarded per participant per aspect can be seen in Table 5, For each participant their overall score is shown in the bottom row, and for each aspect the average score is shown in the last column. The right bottom corner shows the overall rating of the pattern. All scores are on a Likert scale from 1 to 7.

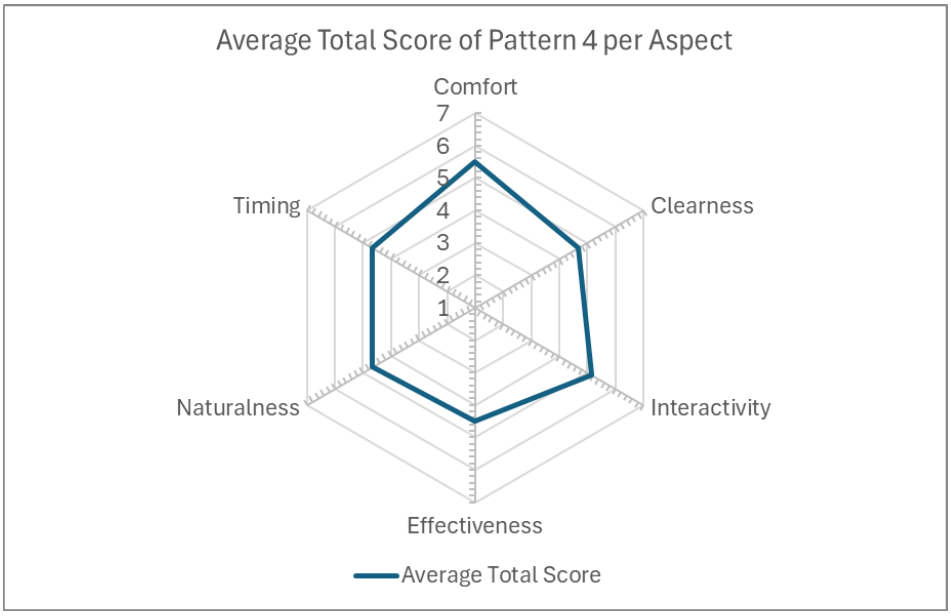

Figure 12 - Radar Plot of Pattern 4

Table 5 - Scores per Aspect per Participant of Pattern 4

Pattern 4	1	2	3	4	5	6	Score per Aspect
Comfort	7	6	6	3	6	5	5.50
Clearness	6	3	3	5	6	5	4.67
Interactivity	5	4	5	6	5	6	5.17
Effectiveness	6	7	5	1	6	2	4.50
Naturalness	4	5	6	2	7	4	4.67
Timing	6	3	5	7	5	2	4.67
Score per Participant	5.67	4.67	5.00	4.00	5.83	4.00	4.86

5 Specification

In this chapter, the feedback of the first user test round is used to improve the WHBA prototype in two ways: the hardware/software aspect, as well as a new set of haptic stimulation patterns. A similar structure as Chapter 4 is used: in section 5.1, the prototype's improvement are discussed and a new set of haptic patterns are created. After that, a new user test is performed, covered in section 5.2.

5.1 Improving the Prototype

The prototype was improved in two ways. First, the technical side has been made more accurate and consistent. Second, a new set of patterns were created with both upgraded patterns from the previous test, as well as new patterns.

5.1.1 Technical Improvements

The prototype received both software and hardware improvements. First the changes in software are discussed, followed by a sub-section on the sensor strap length.

5.1.1.1 The Code

There were two aspects of the code that needed improvement. The first was the cycle detection function, which could detect when a new cycle has started. This was dependent on the speed of the incoming readings, which was troubled by the inclusion of a 'holding' flag when the speed was zero.

The second improvement is the refinement of the dynamic remapping function, which uses the minimum and maximum encountered sensor values across breathing cycles to map the abdominal expansion from '0' to '255'.

5.1.1.1.1 Breathing Phases and Cycle Detection

The logic that determines when a breath cycle started was improved by omitting the 'hold' status of a new reading. Previously, when the speed between incoming readings was zero for four out of the last the seven most recent readings, the readings would get a 'HOLDING' flag instead of 'INHALING' or 'EXHALING'. The values between the readings never were a big change, especially when the readings come in ten times per second. The speed would often be zero, which could not be handled properly by the cycle detection code. The improved code assigns either 'INHALING' for a positive speed, or 'EXHALING' for a negative speed, without any 'HOLDING'. When the speed of an incoming reading is zero, this reading will get the phase of the reading before it. This means that all the readings will remain their correct phase until an actual phase change occurs, which would lead to an inverse speed value and get assigned their corresponding AirFlow tag.

For example, the user is nearing the end of their exhale: a lot of zero-speed readings are registered. With the new logic, the phase of all these incoming readings will remain EXHALING until a reading comes in with a positive speed, confirming the user is inhaling again. This change in logic increased the accuracy of cycle detection significantly during testing.

5.1.1.1.2 Dynamic Remapping

Another improvement in the code revolved around the dynamic calibration of minimum and maximum encountered arbitrary sensor values. The lowest encountered value of the measured abdominal expansion equates to a not-inhaled state, and the maximum value equates to peak-inhalation. When the maximum or minimum could not be updated based on the last breathing cycle, the old code would take the minimal value and set the maximum value thirty arbitrary units higher. This was a too big of a range, since Pattern 2 failed repeatedly to reach its peak intensity of ‘255’ when someone inhaled while the remapping failed. Setting that value to +15 instead of +30 was a noticeable improvement.

During personal testing, this improvement felt more natural in Pattern 2. The motors reached their full intensity quicker compared to the old situation, and therefore felt more responsive. It is expected that this improvement will lead to a higher score of Interactivity in the second user test.

5.1.1.2 The Sensor Strap

In the first user test, the strap was slightly too long for three participants. This was a big contributor to the failure of the dynamic calibration. Due to limited resources, new bands could not be made in time. The supervisor of this thesis allowed the bands to be shortened by folding them and tightening them with safety pins. The creator of the BreathPal sensor, Ben Bulsink, advises against shortening the cable in the manual: “If the strap is too long or too short, a different length must be ordered. Do not fold the strap to shorten it, this will largely influence the measurements”. However, during testing the sensor, the sensor behaved very well. Since this research project focuses on qualitative feedback, super-precise measurements were not needed. Only the ESP32 needed to know the arbitrary value to calculate the speed and for that purpose it was accurate enough with the shortened sensor strap. It was chosen to use this method for the second user test, and it is expected that the system will perform more consistently and accurately.

5.1.2 The Patterns

5.1.2.1 Pattern 5

The first user test showed the potential of Pattern 4, which was the second-best rewarded pattern. One of the main criteria revolved around it being confusing, which took away from the effectiveness of the pattern. To improve this pattern, a short ‘bump’ cue was placed before the main cycle of inhale-hold-exhale. The bump was programmed to be 500ms, but the inconsistent behavior of the motors led to the bump being hard to perceive sometimes.

It is hypothesized that the bump will help the user to understand when to start breathing in again, which would bring a higher score for clarity and effectiveness.

5.1.2.2 Pattern 6

An observation that was made in the first user test, is that some test participants started looking around during the breathing exercises, looking at ‘things’ and thinking day-to-day thoughts, while slow-breathing and experiencing the patterns. Pattern 6 aims to explore the time-dimension of haptic feedback patterns. The writer of this thesis wondered what would be the result of—instead of using many cues with precise timing or even feedback—just using one, continuous, soft vibration playing on its own.

It is hypothesized that the users will find it easier to return their focus on the slow-breathing exercise with this pattern playing.

5.1.2.3 Pattern 7

A direct copy of Pattern 2, but now it is named Pattern 7, so it fits in the order of how the patterns are tested. With the improved technical aspects of the prototype, it is hypothesized that Pattern 7 will feel more consistent and natural. Namely, the over-all rating of Pattern 2 was positive, but Naturalness and Effectiveness scored lowest (sitting between 4 and 5 on the Likert scale). The technological improvements directly address these two aspects, and it is expected that both Naturalness and Effectiveness see an increased positive rating, as well as the pattern over-all.

5.1.2.4 Pattern 8a

Pattern 8a involved terminal feedback, giving a ‘positive’ cue that only played when the user was breathing slow enough. The pattern was set to play a cue when the breathing rate is equal to seven cycles per minute or lower. The positive aspect of this signal is the upwards inflection of the second ‘beep’ in the beep-beep cue. The cue lasts 300 milliseconds and 450 milliseconds for the first and second tone, respectively. Because it is valuable to only test terminal feedback, no other vibrations were playing during the exercise; just the beep-beep cue if the user was breathing slow enough.

It is hypothesized that this terminal feedback would function as a comfortable reward for each breath that was slow enough, essentially creating a personal rhythm of breathing with the prototype. When the user would breathe slightly too fast, no cue will play, after which the user is expected to slow down their breathing rate to find the cue once again.

5.1.2.5 Pattern 8b

Similar to the terminal feedback implementation in Pattern 8a, this pattern features a negative cue (downwards inflection) whenever the user was breathing too fast. Just like 8a, the slow breathing threshold was set to seven cycles per minute. When the user was breathing faster than the threshold, the ‘disappointing’-sounding beep-beep cue would play. During this pattern, no other vibrations played.

It is hypothesized that the user would maybe feel a few cues in the beginning of the exercise, but once settled on a comfortably low breathing rate, no cues would play anymore for the rest of the pattern.

5.2 Second User Test of Haptic Patterns

This test was carried out with six participants. Five participants had also participated in the first user test. Participant 1 could not participate in the second user test, which created the opportunity to test the improved prototype on someone who had not tested it before. Participant 7, a female student at the University of Twente, volunteered to be a test participant of the second user test. This was discussed with and approved by the supervisor of this thesis. Participant 7 was presented with the brochure of the user test. The other five participants were already familiar with the testing procedure. The participants were asked for their consent, and the prototype was installed on their body.

Unlike the first user test, the participants were fully informed about what the pattern was going to do before each pattern would play. In the first user test, the participants were instructed to breathe along with the pattern as they saw fit, without an additional explanation of what the pattern would do. To have the second user test fully informed was instructed by the supervisor, ensuring the participants could perform to the best of their ability, with less confusion and guessing.

5.2.1 Results

Below, the evaluation of the patterns that were tested in the second user test can be found. Like the structure of the first user test patterns’ evaluations, the evaluation of each of the five patterns in the second user test is presented in numerical order. Already it is clear that the patterns are awarded higher scores compared to the first user test. Terminal feedback especially received high scores: Pattern 8b was rated 8.3/10, followed by a shared second place of Pattern 7 and 8a, both having 8.1/10. The soft, continuous vibration of Pattern 6 received a 7/10, and the improved Pattern 5 scored a 6.8/10. No insufficient scores are present. The only negatively rated aspect was found in the interactivity of Pattern 5, of which more is written in the next section.

5.2.1.1 Evaluation of Pattern 5

The second user test started with an improved pattern of the first user test. Pattern 4, which guided the participants to breathe -2 cycles per minute slower, now has a 500ms ‘bump’ cue at the start of every cycle that should indicate when the participant is expected to breathe in.

This bump only made the pattern more confusing; Participant 4 said: “It felt more stable, but the bump was slightly annoying.”, which was shared by Participant 6: “The gradual vibrations were interrupted by a bump”. Remembering the hardware troubles of the first user test, Participant 6 asked themselves whether the prototype had not just malfunctioned. Participant 2 remarked that the bump was too quick to perceive. The participant placed their hand on their abdomen, to feel the vibrations better. This led to inaccurate behavior of the dynamic calibration, which the participant had noted as well. Even though it went out of phase, it did not trouble them. Other participants (3, 5, and 7) noticed their signal drifting out of phase too: “Felt continuously a bit out of phase.” (P5). Also not troubled by the out of phase cues was Participant 7: “The vibrations felt inspiring and helpful.”.

The improved prototype performed more stable and consistently compared to its performance in the first user test. It was more consistent in tracking, and keeping track, of the breathing behavior of the participants. This caused the system to accurately change the played cues based on the breathing rate of the participant. It updated the tempo of the cues after every breathing cycle—which annoyed some of the participants—resulting in a slightly negative-to-neutral score on the interactivity of the pattern. Other than that, the vibrations were comfortable, clear, effective, natural, and were served with relatively good timing. Overall, the pattern received a 6.8 out of 10 and is the lowest rewarded pattern in the second user test.

The radar plot of the aspects is presented in Figure 13, and the scores awarded per participant per aspect can be seen in Table 6, For each participant their overall score is shown in the bottom row, and for each aspect the average score is shown in the last column.

The right bottom corner shows the overall rating of the pattern. All scores are on a Likert scale from 1 to 7.

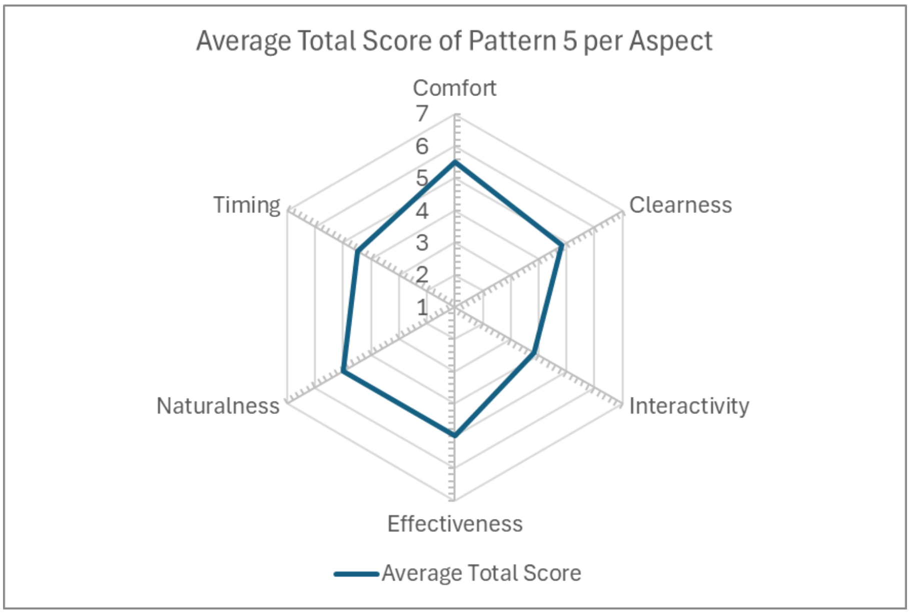

Figure 13 - Radar Plot of Pattern 5

Table 6 - Scores per Aspect per Participant of Pattern 5

Pattern 5	2	3	4	5	6	7	Score per Aspect
Comfort	7	4	5	6	5	6	5.50
Clearness	6	6	7	3	2	5	4.83
Interactivity	6	2	3	2	7	3	3.83
Effectiveness	7	5	7	3	3	5	5.00
Naturalness	7	5	6	4	2	6	5.00
Timing	5	3	6	3	5	5	4.50
Score per Participant	6.33	4.17	5.67	3.50	4.00	5.00	4.78

5.2.1.2 Evaluation of Pattern 6

With Pattern 6, the participants were exposed to a soft, continuous vibration. When explaining the pattern to the participants, they felt surprised, with some believing it would not be of any significance.

Participant 7 found the pattern to be “surprisingly helpful for regaining focus”. With ‘regaining focus’, the participant meant that whenever their attention would drift to something in the environment, the continuous cue of this pattern brought the attention back to the breathing. Participant 6 also perceived this effect: “The pattern generated awareness of breathing but felt ‘wiggly’ and not constant.”, indicating they would not like to experience it for an extended period of time. To some participants, the vibration was slightly too soft. Participant 4 leveraged the quiet nature of this pattern to focus even more on their breathing, instead of focusing on what the vibrations are instructing them. Not everyone was positive about this pattern; Participant 5 said only: “It did not do anything.” (This was not a hardware failure. The vibrations were playing successfully).

The continuous vibration was rated good scores. Overall, it received a 7/10. The vibration was soft, but comfortable and somewhat clear. Four out of six participants found it effective in lowering their breathing rate. The timing aspect, meaning the continuous cue, was rated as good by two participants, but others left the aspect neutral, because there was no real feedback or pattern with alternating cues going on. This is also why the aspect of Interactivity was left out of the evaluation. The pattern was found to be unnatural by two participants, whereas the other four rated it somewhat natural.

The radar plot of the aspects is presented in Figure 14, and the scores awarded per participant per aspect can be seen in Table 7, For each participant their overall score is shown in the bottom row, and for each aspect the average score is shown in the last column. The right bottom corner shows the overall rating of the pattern. All scores are on a Likert scale from 1 to 7.

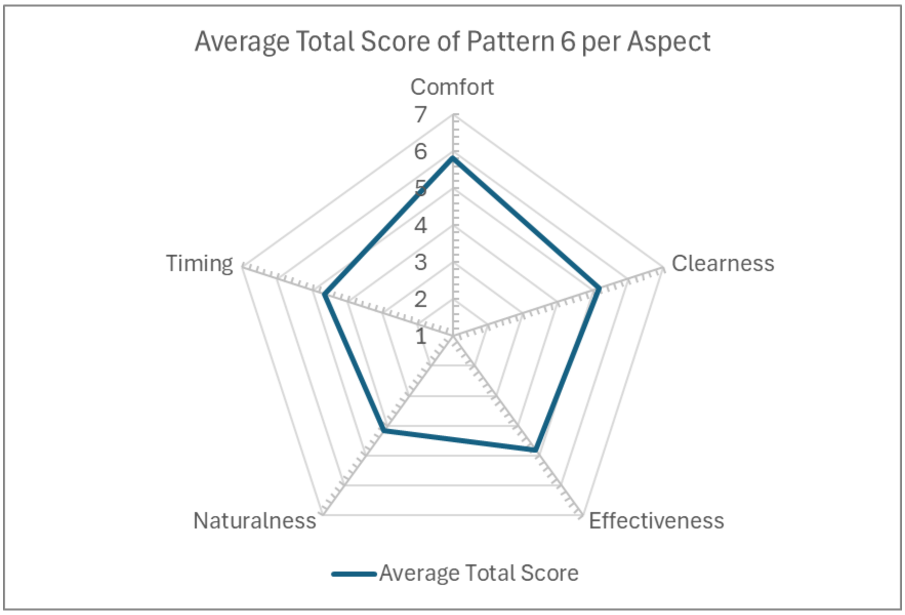

Figure 14 - Radar Plot of Pattern 6

Table 7 - Scores per Aspect per Participant of Pattern 6

Pattern 6	2	3	4	5	6	7	Score per Aspect
Comfort	6	6	7	4	6	6	5.83
Clearness	3	6	4	4	7	7	5.17
Interactivity (not applicable)							
Effectiveness	5	6	3	2	6	7	4.83
Naturalness	2	5	5	2	5	6	4.17
Timing	4	6	4	4	4	6	4.67
Score per Participant	4.00	5.80	4.60	3.20	5.60	6.40	4.93

5.2.1.3 Evaluation of Pattern 7

One of the two recycled patterns of the first user test is Pattern 2. Pattern 7 is a direct copy of Pattern 2. The first user test was plagued by inconsistent tracking of the breathing behavior, but the technological improvements of the prototype resulted in higher scores for this pattern.

Participant 2 stated: “It felt more responsive!”, being pleasantly surprised by the quality and definition of the pattern. Participant 6 liked the tracking abilities as well but noted that it still can benefit from being even more responsive. Participants 3 and 5 were of this opinion too, with Participant 3 saying: “The feedback was just a bit too late, but still effective.”. Only Participant 5 found the pattern to be ineffective. Participant 4 and 6 requested a bit more guidance from the pattern, since they were unsure if they were breathing ‘correctly’.

Overall, this pattern was rated well with a score of 8.1/10, and had the lowest variance in the scores per aspect per participant of the patterns in the second user test. (Pattern 2 had the lowest variance in the first user test, too). The vibrations felt comfortable, and the pattern was slightly clear. The improved prototype had higher accuracy and stability, and this is reflected in a high score for Interactivity. The increasing vibration while inhaling felt natural to the participants. In the end, the pattern was somewhat effective, with somewhat good timing.

The radar plot of the aspects is presented in Figure 15, and the scores awarded per participant per aspect can be seen in Table 8, For each participant their overall score is shown in the bottom row, and for each aspect the average score is shown in the last column. The right bottom corner shows the overall rating of the pattern. All scores are on a Likert scale from 1 to 7.

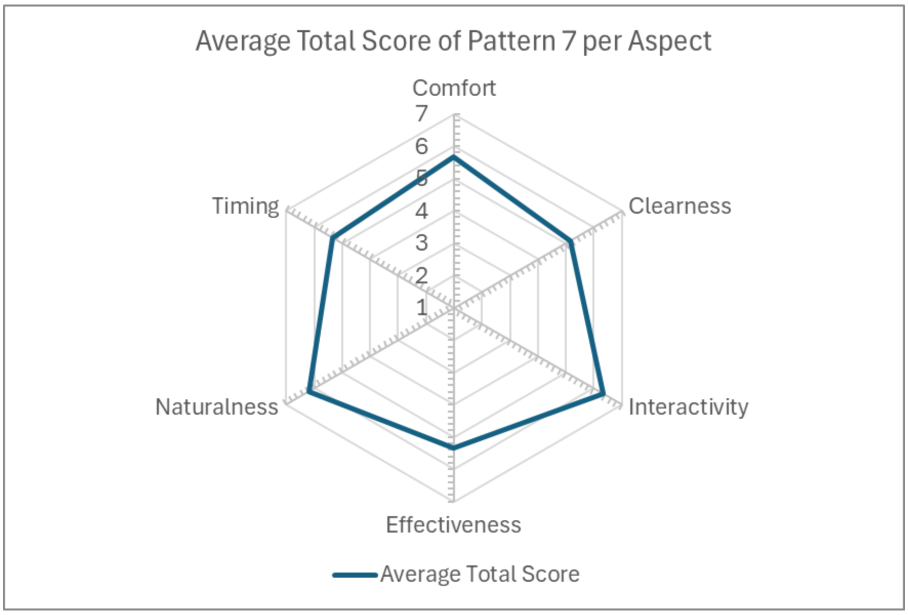

Figure 15 - Radar Plot of Pattern 7

Table 8 - Scores per Aspect per Participant of Pattern 7

Pattern 7	2	3	4	5	6	7	Score per Aspect
Comfort	7	5	3	5	7	7	5.67
Clearness	6	6	7	5	4	3	5.17
Interactivity	7	6	7	5	7	6	6.33
Effectiveness	7	6	4	3	6	6	5.33
Naturalness	7	6	6	5	7	6	6.17
Timing	7	5	7	3	4	6	5.33
Score per Participant	6.83	5.67	5.67	4.33	5.83	5.67	5.67

5.2.1.4 Evaluation of Pattern 8a

In the second user test, two terminal feedback patterns were tested. Pattern 8a, this pattern, rewarded the participants with a positive short cue if their completed breathing cycle was slow enough. If the breathing rate would be equal to seven cycles per minute, or lower, a short upward-inflected cue would play.

Participants were content with this type of feedback. They would slow down their breathing to ‘find’ the cue, and then keep breathing slow enough to feel the cue again. Participant 4 said: “It feels like a reward. Very natural and effective.”, and Participant 5 found it ”easy to appreciate”. Not everyone found the cue ideal, though, with Participant 6 saying: “Sometimes the feedback came too late, taking away focus on the inhale”. That the cue disturbs the inhale phase was also remarked by Participant 7. Not feeling the cue left

Participant 3 asking “Where are you?”, inclined to think the prototype was broken, as opposed to them breathing slightly too fast. The cue was supposed to be a sharp, short, upward inflected ‘beep-beep!’ cue, with emphasis on the second beep. Participant 2 found the definition of the cue to be lacking: “It feels like a ‘zooOom!’ instead of a ‘beep-beep!’”, suggesting a longer break between the two short cues.

The pattern was awarded with an 8.1/10, just like Pattern 7. The terminal feedback was comfortable, clear, interactive, effective, and somewhat natural. The timing was good too, except for Participant 7.

The radar plot of the aspects is presented in Figure 16, and the scores awarded per participant per aspect can be seen in Table 9, For each participant their overall score is shown in the bottom row, and for each aspect the average score is shown in the last column. The right bottom corner shows the overall rating of the pattern. All scores are on a Likert scale from 1 to 7.

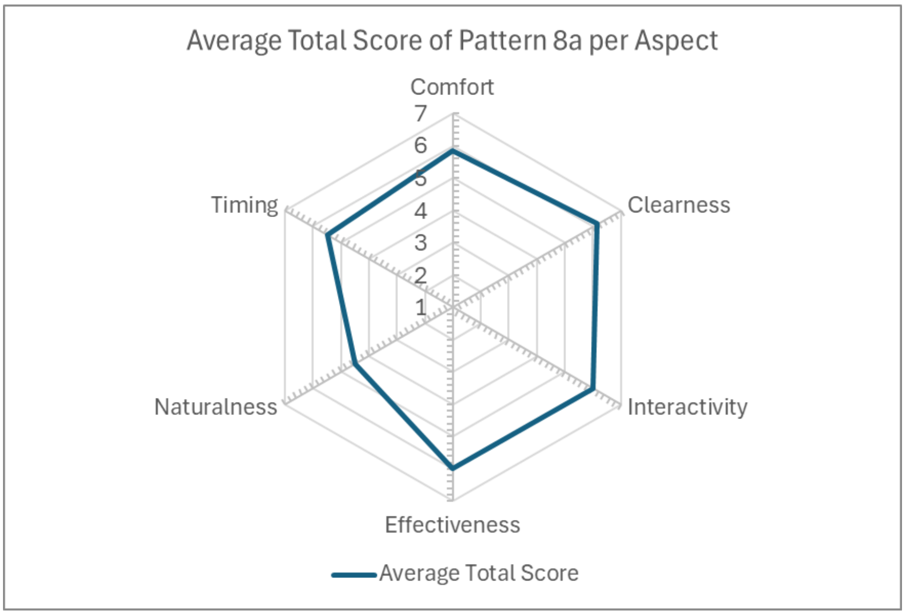

Figure 16 - Radar Plot of Pattern 8a

Table 9 - Scores per Aspect per Participant of Pattern 8a

Pattern 8a	2	3	4	5	6	7	Score per Aspect
Comfort	7	4	7	6	5	6	5.83
Clearness	7	3	7	7	6	7	6.17
Interactivity	7	5	6	6	5	7	6.00
Effectiveness	6	6	7	7	7	3	6.00
Naturalness	5	3	7	4	5	3	4.50
Timing	7	6	6	6	6	2	5.50
Score per Participant	6.50	4.50	6.67	6.00	5.67	4.67	5.67

5.2.1.5 Evaluation of Pattern 8b

The second pattern with Terminal feedback is this pattern. When participants breathe at a rate of more than seven cycles per minute, a disappointing-sounding cue would play. The disappointing aspect is brought forward by the downward inflection. The pattern was rated as the best of the second user test.

It was an interesting test, since the cue only played for about two to three times in the beginning. Once the participants were breathing slow enough, nothing happened. Participant 2 indicated this was “boring”, and Participant 5 found it even annoying to be in the unknown. Participants sometimes wondered if the prototype was still working correctly. During the exercise, the researcher reassured them the technology was still working well. “No news is good news”, said Participant 3. However, when the cue would play, it felt “stubborn and artificial” (P3). Participant 6, who saw similarities with a heartrate notification on their Apple Watch, felt startled by a sudden cue in the middle of the exercise (They were breathing at 7.14 cycles per minute). The disappointing tone was a success according to Participant 7. To Participant 4, it was experienced as a very personal breathing exercise, which felt “more enjoyable than being in the presence of a human guide”.

The pattern was quiet most of the time, since participants were breathing slow enough. But overall, they were very appreciative of this terminal feedback pattern, rating it an 8.3/10. The cue was somewhat comfortable, very clear, very responsive, effective, natural, and had good timing. Participant 7 rated all aspects of this pattern the highest possible score.

The radar plot of the aspects is presented in Figure 17, and the scores awarded per participant per aspect can be seen in Table 10, For each participant their overall score is shown in the bottom row, and for each aspect the average score is shown in the last column.

The right bottom corner shows the overall rating of the pattern. All scores are on a Likert scale from 1 to 7.

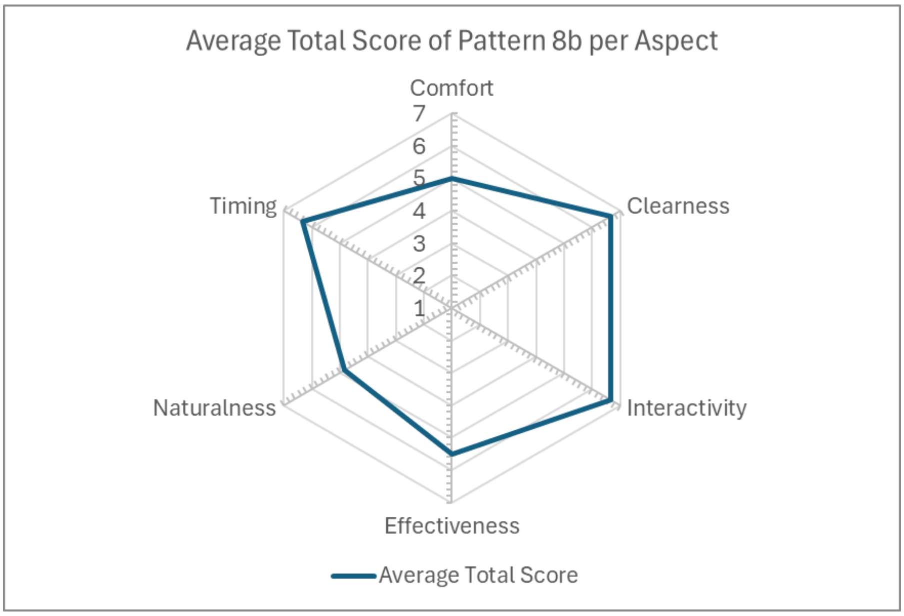

Figure 17 - Radar Plot of Pattern 8b

Table 10 - Scores per Aspect per Participant of Pattern 8b

Pattern 8b	2	3	4	5	6	7	Score per Aspect
Comfort	2	4	7	4	6	7	5.00
Clearness	7	6	7	6	7	7	6.67
Interactivity	7	7	7	5	7	7	6.67
Effectiveness	5	6	7	2	6	7	5.50
Naturalness	7	2	6	4	3	7	4.83
Timing	7	5	6	6	7	7	6.33
Score per Participant	5.83	5.00	6.67	4.50	6.00	7.00	5.83

5.2.2 Generic Observations and Remarks

Participant 7 remarked that they liked the order in which the patterns were tested very much. It felt like the user test first guided the test participant a lot in slow breathing in Pattern 5, then retaining focus in Pattern 6, after which they got the full control in Pattern 7, followed by the terminal feedback of Pattern 8a and 8b. As a test participant who was not experienced in breathing exercises, this structured order felt helpful and comfortable.

6 Discussion

The two user tests are completed, and the results have been presented in the previous two chapters. This Discussion chapter aims to gather insights and attempt to explain certain findings of the evaluation of the haptic patterns. In section 6.2, a statistical test is performed on Pattern 2 and 7, to see if the technological improvements made a statistically significant difference in the evaluation of these patterns. After that, in section 6.3, the Design Questions are answered and the Knowledge Questions are revisited to see if this project's results are in-line with the answers constructed from literature and other relevant research papers. An comprehensive list of recommendations is presented in section 6.4, such that the findings of this thesis project can benefit future research in this specific field of using haptics for guided breathing applications. Finally, a conclusion of this whole thesis is given in section 6.5.

6.1 Interpretation of the Results of each Pattern

Each pattern that was tested in this thesis project will be discussed in this section, each with a short description of the pattern, the general observations of the test participants, the hypothesized effect of each pattern, as well as discussing if these hypotheses turned out to be correct or not.

6.1.1 Pattern 1

The first pattern that was tested is a time-giving pattern. There is not yet feedback involved, meaning the system just produces the vibrations regardless of what the user is doing. The vibrations increased and decreased, and the user is meant to follow this behavior with their breathing: as the vibration rises, the user breathes in, as the vibration decreases, the user breathes out.

The test participants felt comfortable with the vibrations but found the naturalness and timing severely lacking. They had the idea that the signal was out of phase, and the motors could not convey the fine moment of where they were supposed to breathe out again. The participants were correct in their observation of the timing aspect; the pattern behaved, rather unexpectedly, much quicker than was intended. The period of each cycle corresponded to about six seconds (nine cycles per minute), whereas it was supposed to be about thirteen seconds (4.3 cycles per minute). An interesting effect occurred: the users leveraged the out of phase effect in their advantage. One time, they used the rising or fading vibration as a help to breathe in, and sometimes to breathe out longer.

It was hypothesized that this pattern would be alright to follow, but that because there is no feedback involved, some people may find its unchanging rhythm annoying. This turns out to be in line with what occurred during testing: participants found the vibrations comfortable and somewhat effective, but they disliked the timing of this pattern. It was too quick and did not feel in-phase. Since there is no feedback involved, this pattern does not fully take use of what the prototype is designed to do, and that is to give feedback. Pattern 2 uses only feedback and is covered in the next section.

6.1.2 Pattern 2

The second pattern involved direct mirroring of the abdominal expansion of the test participants. When the participant inhaled the vibrations increased, and when the participant exhaled again, the vibrations would decrease. With dynamic mapping of the sensor values, the WHBA prototype tried to have no vibration at their fully exhaled state, and the maximum vibration at their peak inhaled state.

The participants reported that the system sometimes missed their inhale, or that the motors suddenly stopped working. The latter could be due to the vulnerable motors, but mostly it was caused by the breathing tracking of the prototype that was trying to figure out where in the participants' breathing cycle they were and what dynamic mapping was needed to have the maximum vibration at peak inhale and vice versa for the lowest vibration. This caused some participants to give lower scores to the Effectiveness and Naturalness of the pattern. Participant 6 reported it made them more aware of their breathing, and participant 3 found it to feel rewarding for completing a good cycle.

It was hypothesized that the participants would relatively enjoy this pattern, since it reflects their own behavior and may make them more aware of their own breathing. Participant 6 said as the only participant that it made them more aware of their breathing. Others said it felt like they had to "do the hard work" (P4), the system was inaccurate, or the feeling that they had to play catch-up with the system. These are all points of improvements. Thus, the hypothesis turns out to be partly correct. Even though there were shortcomings of both software and hardware, the participants relatively enjoyed the pattern according to the Comfort and Clearness aspect, but not because it made all participants more aware of their breathing.

6.1.3 Pattern 3

An inverted carbon-copy of Pattern 2 was tested under the name of Pattern 3. Instead of increasing the vibrations with each inhale (and decreasing with exhales), this pattern had the motors on high intensity when not inhaling. When the participants would breathe in, these vibrations faded away. As they exhaled again, the vibrations came back.

The test participants were not content about this pattern. It felt stressful, ineffective, and even “punishing” (P6). Compared to this one, some participants wanted to feel either Pattern 1 or 2 again because these patterns were more comfortable. This stressful “go go go!” (P4) pattern combined with the somewhat inconsistent breathing tracking of the prototype, made the pattern also vague to some participants.

It was hypothesized that the participants would less-well receive the pattern, because it may feel ‘punishing’ when the vibrations were fully on while exhaling. An important aspect of slow breathing is to extent the exhale to be longer than the inhale, but the motors turning on when breathing out may make it feel as if the participant would need to rush to the next inhale again. This turned out to be true, with Participant 6 mentioning the punishing feeling of the vibrations coming on when they wanted to exhale long and calmly. Instead of prolonging the exhale, the participants inhaled quicker to not be stressed by the increasing vibrations during their exhale. Most aspects were given a negative score by the participants.

This is a good find, since it shows that participants clearly liked the softer approach of Pattern 2 better as opposed to the stressful cues of Pattern 3. In essence, the vibrations were not hostile or stressful. With a positive mindset, one can learn to enjoy this mechanic of ‘breathing the vibration away’ and not be stressed when the vibrations return during the exhale. However, with a participant selection who experienced this for the first time, it is understandable that they would feel rushed when they feel the vibrations slowly increasing while exhaling.

Moreover, a more consistent and accurate prototype would help with making the pattern feel more peaceful. Because when the dynamic calibration would fail, the motors suddenly all jumped on, making the participants feel as if they did something wrong. This was because the minimal sensor value corresponds to a motor intensity of ‘255’ in this pattern, so when a shift in body position or an interrupted inhale occurred, there was a chance the prototype could not figure out the proper set-point for the minimal and maximal sensor values.

Concludingly, this pattern might have been received more negative than it deserves. With a solid prototype that can track the breathing very well, combined with the mindset that it is okay to feel these vibrations increasing with the exhale, could make for an effective and enjoyable pattern. But in the state it was tested, the participants indeed were not liking this pattern.

6.1.4 Pattern 4

The last pattern that was tested before the prototype was improved was Pattern 4. In this pattern, a time-cue wave was given that was similar to Pattern 1. However, in Pattern 4, the system used the calculated breathing rate of each completed cycle to downshift the rate of the time-cues. This happened with an offset of -2 cycles per minute, meaning that when the participant breathed at seven times per minute, the provided cue pattern plays at five times per minute. The idea behind this is that the participant would be persuaded to breathe even slower than they are currently.

The test participants were overall positive of this pattern. Participant 1 found the timing to be more constant than Patterns 2 and 3. One participant called the timing even “excellent and helpful” (P4), and yet, even though this participant was successfully guided from 11 cpm to 4-to-7 cpm (observation by the researcher during the test), they still felt it was very ineffective. This, because it did not feel intuitive, and they needed to cognitively think about what they were having to do.

It was hypothesized that the pattern can be perceived as annoying when the system keeps pushing you to breathe even slower than you are comfortable with. With Participants 2, 4 and 6 feeling confused and annoyed, this turned out to be partly correct. However, others were more positive towards this pattern, with Participant 3 wanting it to use more often.

6.1.5 Pattern 5

Pattern 5 to 8b were part of the second user test with the improved prototype using the feedback of the first user test. Pattern 5 was an improved version of Pattern 4. One of the observations with Pattern 4 was that it was confusing. “What do I have to do now?” (P6), and “Sometimes there was no vibration, and sometimes two vibrations in one cycle” (P5). The pattern was updated with an initial bump cue that would help the participants to find the moment where they were supposed to breathe in.

The bump was not a success: it felt slightly annoying (P4) and to others even hard to perceive in the first place. The pattern felt more out of phase than Pattern 4. It felt out of phase to four out of six participants. The bump was either not recognized, or it caused extra confusion by the participants. This was reflected in the negative rating of the Interactivity of the pattern. However, due to more accurate and consistent tracking, all other aspects retained their positive score, and the pattern was rated similar, but slightly lower than Pattern 4.

It was hypothesized that the bump would help the participants to understand the moment when they were expected to start breathing in again, resulting in higher scores for Clearness and Effectiveness. Interestingly, the scores for Clearness and Effectiveness were indeed slightly higher in Pattern 5, but the bump failed in notifying the participants when to breathe in. Most participants reported that the pattern felt consistently out of phase, which at first sight can be considered bad. However, with more argumentation, this is perhaps indicative of the technological improvements.

Namely, the pattern is supposed to feel out of phase, because the cues are essentially leading the participants to a lower breathing rate. The pattern is giving the cues at a -2 cpm lower than the participants' actual breathing rate. Even though the participants were fully briefed about this, it felt to them that the Interactivity aspect was worse than in the first user test. In that sense, the system was doing a very good job in tracking their breathing behavior. However, this exposes a new flaw of this pattern. The software design of this pattern switches from phase to phase, with the phases being 'bump', 'inhale', 'hold after inhale', 'exhale', and 'hold after exhale'. When a new breathing rate is calculated after each cycle, the pattern would basically reset itself to start over, but this time with a slower rate. To implement the breathing rate shift, the phase approach is not suitable. Phases would get interrupted, and the behavior is unpredictable and stammering.

A much better design approach for this pattern would be to be able to adjust the period of the wave, just like a change in period in a sine can fluidly adjust the 'tempo' of the sign. In the current approach with the fixed phase blocks getting another time duration, this was not fluent at all. Improving the fluidness of the pattern, and with the participants knowing it is supposed to feel out of phase, this pattern may be very suitable in down-guiding the breathing rate of the users.

The -2 cpm idea was taken from [47], which used subwoofers integrated in the car seat, as well as using an ambient music track through the car speakers, testing only-auditory, only-haptic, as well as both modalities at once. They could use a sine wave to drive the subwoofers, which is easier to adjust the period of. Seemingly, they did not incorporate a difference in the inhale and exhale duration. So, for Zepf et al., it was easy to gradually change the period of the sine wave generator. However, in the WHBA prototype, the author of this thesis wanted to follow the literature of the fact that extending the exhale is a very powerful aspect of slow breathing, thus, with the limited resources, it was chosen to use phase blocks that could have their own timing characteristics.

6.1.6 Pattern 6

A rather interesting pattern was Pattern 6, which was just one continuous soft vibration cue for the whole exercise. Most test participants were positive towards this idea. For some, it generated more awareness of their breathing, helping them shift their focus back to breathing when their mind wandered off. Others described it as uninteresting, since it does not give any instructions, and "wiggly" (P6), with 'wiggly' meaning the motors turned on and off several times due to their vulnerable nature. Other participants found the vibrations to be soft but handled that in their own way. Participant 2 laid their hands on the sleeve to feel more connected to the technology. Participant 4 accepted the very low intensity and said it gave them more space to focus on their own breathing.

It was hypothesized that the participants would find it easier to return their focus on the slow-breathing exercise while this pattern was playing. This turns out to be partly true. Participants 6 and 7 felt like the constant vibration generated awareness. Some participants missed the instructions the other patterns gave. To most participants it was just an enjoyable intermezzo. “A nice massage”, as Participant 3 describes it. Pattern 6 was enjoyable and indeed generated awareness, but it was not more than that.

6.1.7 Pattern 7

Pattern 7 is a direct copy of Pattern 2 from the first user test. The pattern increases the vibrations when someone is inhaling and decreases them when exhaling. Now, with the improved WHBA prototype, it is a good chance to test if the improvements were effective, and how the participants liked this pattern with more accurate breathing tracking. A statistical analysis on the evaluations of Pattern 2 and 7 is done in section 6.2.

Participants were more positive to Pattern 7 compared to Pattern 2. Participants noticed that it felt much more consistent than in the first user test. Some participants found the feedback to still be slightly “too late” (P3, P5, P6), suggesting the system should be even more responsive. Others expected more guidance from the pattern (P4, P5, P6). For example, Participant 6 wondered if they were breathing ‘right’. Perhaps, a terminal cue could be played to give this guidance. However, a pattern should not become too complex with trying to convey different information points.

It was hypothesized that the Naturalness, Effectiveness, and over-all score would be higher than Pattern 2. This hypothesis is correct: talking in terms of the Likert scale, Naturalness was much higher, going from a 4.17 (neutral) to 6.17 (natural); Effectiveness saw an increase, going from 4.17 (effective) to 5.33 (somewhat effective); and the over-all score went from 4.97 (somewhat good) to 5.67 (good).

6.1.8 Pattern 8a

Terminal feedback was tested in two ways in this study. In this Pattern 8a, a positive terminal feedback cue was played when the users were breathing in the beneficial range of seven-or-less cycles per minute.

Over-all, the test participants liked this pattern. It was hypothesized that the terminal feedback would function as a comfortable reward for each breath that was slow enough. When no cue was felt, the participant was expected to slow down their breathing again to find it. This effect was indeed observed in the tests. Participant 3 asked “where are you?”

when no cue was felt, thinking the technology might be even malfunctioning instead of that their breathing rate was too high. But due to the technological improvements, the researcher could observe that their breathing rate was too high in these cases (7.14 instead of 7.00 cycles per minute). Others said it was easy to appreciate and that it felt like a reward. However, the timing of the terminal cue was slightly annoying to some participants, since it took away focus of their inhalation phase. This is understandable, since the cue was given when a new breathing rate was calculated, which happened 300ms after the users started inhaling.

However, Participant 3 might be on to something: after a review of the code, it appears there exists a flaw in the code logic. An easy approach to give terminal feedback was to only check if a new breathing rate was calculated. So, when a newly calculated breathing rate was not equal to the last calculated breathing rate—and low enough—the cue would play. Here, the author of this thesis believed that it was unlikely that a new breathing rate in two digits after the comma was exactly matching with the last breathing rate. The times of each sensor reading were captured in microseconds for maximum accuracy. Sixty seconds divided by one millionth of a second surely would not lead to the exact same breathing rates, thought the author of this thesis. However, during the experiments, the researcher noticed the comma digits of a calculated breathing rate would often be the same. For example, it was very likely that a breathing rate would land on 7.14, and not 7.13 or 7.15. The period of a cycle would need to be about 8.403 seconds to land on 7.14cpm. For 7.13 cpm on 8.392 seconds and for 7.15 cpm 8.415 seconds. These are very small margins to explain this observation. Why this effect manifested itself is unknown.

Now, it is apparent that with this effect and the flawed code logic, there is indeed a small chance the participant may not have felt a cue where it would have been right. To optimize this, the logic in the code should be redesigned, such that when a new breathing rate is available and it is seven cpm or lower, that the cue would play (instead of checking if the new breathing rate is different than the last, and low enough). This could be done using a function that is triggered after a breathing rate is calculated, regardless of its value, checking if it is low enough to trigger the cue.

6.1.9 Pattern 8b

The negative terminal feedback was tested with Pattern 8b. When the users would breathe higher than seven cycles per minute, a negative cue would play. The participants had a wide variety of feedback for this pattern. Some felt it was boring, since when breathing slow enough, no cues are given. Some were startled by the cue when it suddenly played. Others found it a bit unsettling to be in the unknown, asking themselves if they are really breathing slow enough or whether the system is malfunctioning. Participant 7 found the disappointing tone very fitting. Even though this pattern indicated the participant was doing something ‘wrong’ with a disappointing tone, it was the highest rated pattern out of all patterns that were tested across both user tests. This indicates the users found it rightful and informative to know they were going too fast, and when feeling no cues they were doing a good job. One participant compared it to a heartrate function of a fitness watch, indicating it is too high and one should calm down (P6). “No news is good news” (P4).

It was hypothesized that the users would only feel some cues in the very beginning of the exercise, but once being settled on a comfortably low breathing rate, no cues would play anymore for the rest of the pattern. This turned out to be partly true. Most participants indeed felt only one or two cues in the beginning, and then nothing. But some were hovering around the 7.00 cpm mark, and when landing on 7.14 they would suddenly feel a cue and be startled by it. This was because there was no guidance in this pattern; the users were free to breathe on their own tempo. This tempo was clearly higher than in the guided patterns. In many guided patterns, most, if not all, participants successfully breathed in the 4 to 5 cpm-range, with some even reaching as low as 3 or as high as 6 cpm. But with both terminal feedback patterns, the participants were mostly around 6 to 7 cycles per minute.

To make it more interesting and effective, Participant 6 made an interesting suggestion. They suggested that the pattern could include threshold steps to guide the users even lower. For example, starting off with ‘higher than 7 cpm is too high’, but after a one or two minutes, ‘higher than 6 cpm is too high’, optionally going even lower as time progresses.

6.2 Student-T Test of Pattern 7 against Pattern 2

Using a Student-T test, the scores of Pattern 7 can be compared to Pattern 2, since these are the same patterns with the only difference being the technological improvements of the prototype. The hypotheses for the test are:

H_0: The technical improvements made no change in the score.

H_1: The technical improvements made a change in the score.

This calls for a double-sided T-test, since Pattern 7 can either be better or worse than Pattern 2. The test was conducted using Excel using the following command:

=T.TEST(B12:G17;L21:Q26;2;3)

- The first argument (‘B12:G17’) is the table of the scores per participant (Participants 1 to 6) for Pattern 2.

- The second argument (‘L21:Q26’) is the table of the scores per participant (Participants 2 to 7) for Pattern 7.
- The ‘2’ in the third argument indicates that the T-test is two-sided.
- The ‘3’ in the fourth argument means the test is an ‘independent’ test with unequal variances, since both groups had five participants who experienced both, but Participant 1 and 7 experienced their pattern just one time, which can influence the variance of both patterns.

Excel reports the p-value to be 0.038803737, or around $p = 0.039$. Given a standard significance level of $\alpha = 0.05$, the p-value is lower than the significance value. The H_0 can be rejected, meaning that it is likely that the technical improvements made a significant change in the scores, indicating that Pattern 7 scored statistically significantly higher than Pattern 2.

6.3 Answering the Research Questions

Important in the Creative Technology Design Method is evaluation and reflection. After the tests are completed, we can answer the Design Questions, as well as reflect on the Knowledge Questions’ answers provided in section 2.4 (page 39).

6.3.1 Design Questions

First, the Design Questions (DQs) are answered using the observations and results of the two user tests. DQs aim to answer specific technical and methodological questions of the design process. This thesis has three DQs and they will be answered in the following sub-sections.

6.3.1.1 Design Question 1

“How can the system synchronize with the personal breathing preferences of the wearer, such that the wearer does not feel as if they have to rush their breathing to keep the pace of the system?”

Most importantly, the system and its sensor should support high detail measurements. The BreathPal lacked this precision, making it hard to track the precise breathing behavior in real time. To circumvent this, multiple samples were taken, but this delays the real time operation of the system, making the patterns feel often out of phase for the participants.

Also, the system should support personal breathing preferences. For example, Participant 5 liked to perform the slow breathing exercise by first taking a ‘sip’ of air, followed by a calm inhale. The tracking in the software of the microcontroller did not really understand this behavior, which caused the dynamic calibration to fail often for this participant.

So, for the refresh rate of this BreathPal sensor, it is necessary to be able to measure in the comma digits of these arbitrary values. For even higher refresh rates, which would benefit the real time performance greatly, even more sensitive sensors are needed to still have informative sensor readings (where the speed is not ‘0’ between two new readings, even though the user partly inhaled or exhaled in those 100 milliseconds).

On the topic of the patterns themselves feeling out of phase or unpredictable, the down-guiding patterns like Pattern 4 or 5, which leads the user with a signal that is two cycles per minute slower than they are currently breathing, a wave generator is advised for more fluid transition of the speed of the cues. With a wave generator, it is easy to adjust the period on the fly, because it is a continuous generation of the same wave. In the implementation in this thesis, phase blocks were used. But this caused a confusing bumping behavior because its nature is discrete instead of continuous.

Participants were eager to think along to help solve this problem. Quite some participants suggested to simulate their last successful breathing cycle when the system could not keep track of the current cycle. This way, the users would not feel punished by something that is not their fault. The system should handle the users’ preferences. By temporarily simulating a successful wave, the user is not disrupted in their breathing exercise, and the system can leverage the undisturbed incoming values. This, as opposed to the user being confused, trying multiple cycles to adapt to the system, and the system not being able to find a repeating and consistent breathing pattern. Simulating a wave would also leave room for the participant to quickly change their body position, take an additional inhale, or even talk to someone in the room (which would all cause for hard-to-track sensor values).

6.3.1.2 Design Question 2

“What haptic stimulation patterns are effective in teaching individuals certain breathing techniques?”

This thesis has tested several different haptic stimulation patterns. It became clear that the test participants valued guidance. In patterns with no guidance, like Pattern 2, 3, 6, 7, 8a, and 8b, the users often asked themselves if they were doing their exercises the right way. The terminal feedback was evaluated very positively. It was clear and simple, but not very effective in lowering the breathing rates. Pattern 8a and 8b saw higher breathing rates of about 6 to 7.5 cycles per minute, compared to the guided (Patterns 1, 4, and 5) and the direct feedback patterns (Patterns 2, 3, and 7) with which most participants reached four to five cycles per minute, with some reaching as low as three, or a bit higher like six cycles per minute.

The direct feedback patterns were effective in the sense that users could feel their own breathing behavior. It was mirrored back to them by increasing or decreasing the vibration with their in- and exhalations. Here, it was apparent that the users did not want to feel pressured by the system; Pattern 3 was experienced as stressful and negatively rated. Pattern 2 was the most useful, because the participants felt a stronger vibration the more the deeper they inhaled, which was a feedback loop that automatically slowed down their breathing rate.

The guiding patterns (Patterns 1, 4, and 5) were not very clear, since the participants did not feel the moments where they were supposed to breathe in or out. The participants used this in their own advantage by one time using the vibrations to breathe in longer, and the other cycle to breathe out longer. This also successfully lowered their breathing rate, but the confusion is not desirable in such an application that is meant to relax the user. Pattern 4 was vague, because of the discrete phase blocks that shifted based on their breathing rate. It was thought that a bump (Pattern 5) would help solve this issue, but it may have made it even more confusing. Instead, Pattern 1 could definitely have benefitted from a bump cue, and a better solution for Pattern 4 would have been to use a proper wave generation function that could continuously adjust its period, perhaps with bump cues as well.

Concludingly, for more relaxing or less intensive applications, terminal feedback that notifies whether someone is doing a good job or not is helpful and appropriate. Especially when a baseline breathing rate is set beforehand, and someone driving a car or working in an office gets a vibration when they exceeded their threshold for several minutes. With the small cue, they can focus their attention on their breathing rhythm. Another option here would be to play Pattern 6, a continuous soft vibration, for a few minutes such that the focus can remain on their breathing perhaps longer than a short cue would achieve.

For active breathing exercises, where users dedicatedly want to engage with the system, guiding patterns and direct feedback patterns are useful. They can guide the user in a comfortable but slow breathing pace, as well as ‘challenge’ them to really breathe with their abdomen by mirroring their own abdominal expansion. This can be coupled with a chest sensor to give feedback in such a way that breathing primarily with the chest is not encouraged.

6.3.1.3 Design Question 3

"What characteristics of haptic stimulation patterns make some patterns more preferable to other patterns?"

6.3.1.3.1 Comfort

The vibrations should feel comfortable and not annoying. Physically, it is important that the vibrations can be perceived well enough, both symmetrically from left to right, as well as front to back. Pattern-wise, the vibrations should not feel as stressors. In the evaluation of Pattern 3, participants did not appreciate the continuous vibration that only faded away during inhalation, as it made them feel rushed.

Terminal feedback cues in Patterns 8a and 8b were also seen as stressors by some participants because they disturbed the inhale phase. A better approach would be to provide the cue at another point in the breathing cycle, such as at the peak of inhalation.

6.3.1.3.2 Clearness

A recurring theme across nearly all patterns and participants was confusion. It is important that the patterns are clear and do not try to convey too much information. A simpler approach might involve providing a vibration cue only when the user is supposed to exhale (like in [44]), instead of using one oscillating vibration for both inhalation and exhalation. However, too little information is also problematic, as participants often felt unsure about whether the system was working, if they were performing the exercises correctly, or what was expected of them.

6.3.1.3.3 Interactivity

Interactivity is essential for a real-time feedback system. In direct feedback patterns that mirror the user's abdominal expansion, the system must feel responsive and consistent. Otherwise, it can quickly feel out of phase, causing users to try to compensate. Participant 5 said for Pattern 2 and 3: "It feels like I have to play catch-up with myself.", and many of the participants mentioned often that a pattern felt out of phase.

6.3.1.3.4 Effectiveness

Patterns perceived as most effective by participants were guiding patterns and terminal feedback patterns. However, feeling effective is different from being effective. Even when participants achieved a slower breathing rate (e.g., 4 to 5 breaths per minute), they might still perceive the pattern as ineffective due to cognitive load or annoyance. Direct feedback patterns were the least effective, as they lacked guidance. Specifically, Pattern 3 was considered ineffective because it was too stressful.

6.3.1.3.5 Naturalness

Pattern 7 felt the most natural, as it mirrored the breathing movement of the user back to them, with great accuracy and consistency. The pattern could have been even more responsive, but it already felt natural. The least naturally feeling pattern was Pattern 3, which made the users feel as if they had to rush their breathing.

6.3.1.3.6 Timing

Clear timing is crucial for the system to effectively communicate with the user. In guiding patterns, the moments to inhale or exhale should be unambiguous, which can be achieved with a bump cue or by giving vibrations for only inhalation or exhalation. For terminal feedback patterns, providing cues during the inhale phase was disruptive for some users. It might be more appropriate to give the cue at the end of an inhalation. Patterns 4 and 5, which aim to slow the user's breathing with a -2 cycle per minute tempo, would benefit from a continuous wave generator instead of phase blocks that are often interrupted by updated breathing rate information.

6.3.2 Knowledge Questions Revisited

Knowledge Questions were answered in Chapter 2. After having completed the user tests, the answers to these questions are re-evaluated to see if the observation and results of the user tests are in-line with the information from the literature and relevant research papers.

6.3.2.1 Knowledge Question 1

"What breathing techniques may be effective to teach with haptic stimulation patterns?"

The user tests show that slow breathing is indeed an effective exercise for such a haptic breathing assistant. Participant 6 nearly started hyperventilating at the beginning of Pattern 3. This was not the intended breathing rate and the researcher intervened. However, this could be an interesting use case: practicing fire breathing or the Wim Hof Method with assistance of haptic stimulation cues. [33] already tested it in driving sim environment.

6.3.2.2 Knowledge Question 2

"Where on the human body would haptic stimulation be comfortable and effective to teach breathing techniques?"

The location of the motors was good on the abdomen and lower back. This region is naturally involved with the breathing motor movement. Some participants laid their hands on the motors to feel the vibrations better, with which, simultaneously, they could feel their own abdominal expansion. Participant 2 felt more connected to the technology this way, although it made the WHBA prototype struggle with the dynamic calibration of the sensor values. It should be noted that everyone may perceive haptic stimulation differently. Participants mentioned to either feel the front or back motors better, even when all the motors worked. This may be due to clothing type, but also just how they perceive it. It is advised to use stronger motors, since the participants almost uniformly had the intensity at 100%.

According to a study by Celebi et al. [12], using a bHaptics TactSuit X40 haptic vest, the intensity of the motors on the back had to be increased by 12.3% in order to feel equally strong as the abdominal motors. It is recommended that future research focuses on the personal experience of the wearer, with everyone experiencing haptics their own unique way. This leads to the recommendation to add a fader that the participant can use to balance the vibrations in the back and front, such that they feel equal and comfortable.

6.3.2.3 Knowledge Question 3

“How to evaluate the effectiveness of haptic stimulation in teaching breathing techniques?”

Questionnaires and open interviews produced adequate insights in the characteristics of the patterns. The test participants regularly commented on why they awarded an aspect a certain score. The total of seven test participants produced a wide variety of considerations, thoughts, and feelings on the patterns and their aspects, the hardware, and the test methodology. The Likert scale with supportive leading questions helped the participants to accurately convert their experience to a number.

6.4 Limitations and Future Work

With the findings and observations of the user test, as set of recommendations is presented in this section. This is done to help future research in the field of haptic guidance for breathing exercises in choosing their method and what to focus on. First, the limitations of this thesis project will be discussed, after with an extensive list of potential improvements and recommendations is presented.

6.4.1 Limitations

One of the biggest limitations in this project was the BreathPal sensor. It was very difficult to get working, and once it was working reliably, the Arbitrary Units in which the sensor reports its values proved to be tricky to perform calculations on. Namely, one of the challenges was to track the breathing rate of the user. However, the differences in the arbitrary values were so small, that the speed between the readings would often be zero.

Besides that, the dynamic remapping of the minimal and maximum sensor values was hard. It sounds trivial, but how would a computer know, in real-time, what the minimum and maximum expansion is of your abdomen while breathing? It would need to predict on what arbitrary value the user would land when fully inhaled. To do that, accurate speed and acceleration numbers could not be used in this project, because they were not precise and continuous enough. Then, a sub-optimal tracking system was used that tracked the minimal and maximum encountered values between the cycles. Especially any change in breathing pattern, body position, or even placing the hands on the abdomen, disturbed the sensor readings and this dynamic remapping. That lead to inconsistent behavior in the feedback patterns, to the annoyance of the participants.

Another big limitation were the motors. These were not powerful enough to be felt clearly and were too vulnerable, causing them to stop and start working randomly. They also had a spin-up time, making the terminal cues less sharp and precise, resulting in a “zooOom!” instead of a clear “beep-Beep!” (P2), and “wiggly” behavior when the motors stopped and started working randomly (P6).

6.4.2 Recommendations for Future Work

6.4.2.1 Breathing Session Duration

To ensure participant comfort, limit the slow breathing sessions to about twenty minutes to prevent fatigue or loss of focus. Test four to six patterns for four to five minutes each, with breaks in between if more patterns are tested.

6.4.2.2 Flexible Breath Tracking

The dynamic calibration of the arbitrary sensor values was reliant on the user’s breathing directly in-and-out. But in practice, some people interrupted their own breathing by doing a slight double inhale (P5) or breathing in earlier or later to match with the cues again. Some participants wanted to lay their hands on their abdomen too, to feel the motors and their abdomen better. All these factors were troublesome for the WHBA prototype to track the breathing behavior of the participants accurately and steadily.

Future research projects that want to implement direct mirroring feedback (Pattern 2 or 3 for example) will benefit from a more refined approach of registering and keeping track of the breathing behavior of the participants. This would lead to more consistent performance of the system, to the enjoyment of the participants, as well as prevent the participants feeling ‘punished’ for when the system or motors malfunctioned once again. Good Human Media Interaction design requires the technology to be forgiving.

A suggestion from multiple participants was to simulate a successful breathing cycle in the case the system encounters unusable sensor values. That way, the participant can shift their body position, take an additional inhalation, and just continue their exercise. This benefits the tracking system as well, since the more normal the user breathes, the better the information is with which the system can work. Otherwise, when the pattern disrupts itself, the user tries to change their breathing behavior for sometimes multiple cycles to get in line with the system again, but this is confusing to the tracking logic in the WHBA prototype.

To evaluate the breathing behavior of the user, an interesting approach would be to calculate a coefficient of the actual breathing performance of the user and the expected breathing pattern from the system, as seen in [42].

6.4.2.3 Adjustable System

Haptics are very personal, and users would be happy to control certain aspects of the setup. One aspect is the intensity of the motors, which was present in the WHBA prototype. However, with motors that were not powerful at all, basically everyone had it at 100% and wished it could even go stronger. Another thing participants indicated they wanted to control was the balance between the front and back side. People feel the front and back in different intensities due to clothing, but also their own unique body. A fader that fades between the balance of intensity between the front and back is a good choice to implement in a haptic breathing assistant.

6.4.2.4 Suitable Motors

It is important to have motors that are powerful and durable enough to be used in a wearable fashion. It was very annoying for both the participants as the researcher when the motors once again failed to operate. They would randomly engage and disengage because of the weak connectors. The motors used in this thesis project were designed to be used on solid Printed Circuit Boards, not in a soft Sugru enclosure. Potential improvements here could be to choose more powerful motors and choose a more suitable enclosure with tension relief from the power cables. Still, the motor with enclosure should be comfortable, thin, and dynamic enough to be comfortable sitting very close to the body.

The definition of the motors influences what type of cues one can give. Gradual patterns like Patterns 1, 4, and 5, were difficult to interpret; the moment where the user is supposed to breathe out again was not clear at all to the participants. Having a high-power, higher fidelity motor with which the user can differentiate more intensity levels may solve this problem. Another simple way to solve this problem is by using bump cues that indicate when the user should breathe out. But also, for this bump cue it is important the motors have a low spin-up time. Otherwise, when the spin-up takes 100+ms, it may feel like it is part of the gradual cues itself.

6.4.2.5 Breathing Sensor

To get accurate readings with a breathing sensor, it is important that the straps are fitting the wearer. In the first user test, the strap was slightly too long, making consistent tracking of the breathing very hard for the WHBA prototype. The participants were annoyed whenever the pattern stopped working, and having to wait one-and-a-half breathing cycle before the system would be caught up with them again.

The sensor should also be accurate enough to interpret the data in real time. The BreathPal sensor used in this project used Arbitrary Units, which are good for general use, but using these values in real time showed their lack of detail. Within the 100ms updates of the sensor, the difference between of the new incoming value is often zero, even though there was a physical change in abdominal expansion. Perhaps lowering the update time of the sensor would prevent the zero-speed readings, but then it would be even less real time. Better would be to have a more sensitive sensor with at least the same or higher refresh rate, for real time applications.

6.4.2.6 Gradual Patterns

The WHBA prototype of this thesis project features eight individually controllable motors. It would be a great continuation of this thesis' main research question to explore what is possible with gradual patterns. Due to limited resources, it was decided to not explore gradual patterns in this thesis. A time-giving gradual pattern could be one that starts gradually on the lower motors, followed by a gradual increase of the top motors, followed by a gradual decrease of the bottom motors, followed by a decrease of the top motors. This creates a gradual experience that the user can follow with their breath. Gradual patterns were already used in relevant research papers [19, 33, 34, 39, 46].

6.5 Conclusion

This thesis project revolved around how haptics can help with learning breathing techniques. Haptics are an interesting medium and, unlike visual and auditory modalities, allow for a very personal learning experience where the wearer can literally feel what they are doing, instead of guessing. The main objective was to find out what characteristics of a haptic stimulation patterns are useful and helpful, and which rather not.

To test for these characteristics, a Wearable Haptic Breathing Assistant prototype was created, which featured a breathing sensor and eight vibrotactile motors. The motors were tugged tightly in a sleeve around the abdomen, with four motors on the abdomen and four on the lower back.

In the first user test, four patterns were tested on six participants. Using the feedback of this user test, the prototype was improved, and a new set of patterns were tested on, again, six participants. It became clear that users liked guidance and knowing they were doing well. Otherwise, cognitive load gets in the way in the form of questions: “am I doing it correctly? Is the system working? What am I supposed to do?”, taking away from the relaxation one would expect to get with slow breathing exercises.

The system delivering the patterns should be very responsive, accurate, and consistent in its tracking of the breathing behavior of the wearer. Also, to feel clearly what the patterns are ‘telling’, powerful, durable, and high-fidelity motors are needed.

Three knowledge questions and three design questions were answered through a combination of a background research, consisting of a literature review, an analysis of state-of-the-art research papers and commercially available products, and, secondly, the test results of the two user tests performed in this thesis project.

While haptic breathing assistants are continued to get researched, remember that such advanced technology is not necessary to practice it yourself; whenever you feel stressed, remember that slow breathing is free and effective. The benefits will come within minutes. Breathe.

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Consent Form

Short overview of the user test:

1. Briefing.
2. Establish consent.
3. Install and calibrate the wearable device.
4. Eight rounds (two breathing exercises, with each four patterns).
5. After each round, a short questionnaire on a provided paper and a little discussion about your experience. <u>Any feedback is useful feedback!</u>
6. After all rounds are finished, a little discussion about your most preferred and least preferred, and why. Patterns can be repeated in this step if needed.

NOTE This research will ask you to breathe at a certain tempo. It is important that you are okay with breathing slowly, and that you feel fit and confident enough to perform breathing exercises. This is not advised when you have physical or mental problems related to breathing, such as anxiety disorder, PTSD, asthma, COPD, or Covid Syndrome. Please indicate your fitness in Article 5 of the consent form below.

Please tick the appropriate boxes

1. *I have read or have been read the study information and I have understood it. I agree to voluntarily participate in this research.*
   - *Yes*
   - *No*

2. *I understand that this research involves performing breathing exercises, feeling vibrations on my body, filling out eight short questionnaires, and talking about my personal experiences of the haptic patterns in an open discussion.*
   - *Yes*
   - *No*

3. *I understand that at any point, I can withdraw my consent and stop the experiment, without having to give a reason.*
   - Yes
   - No

4. I understand I will wear the wearable device and have the haptic sleeve and breathing sensors strapped to my upper body with a thin layer of clothing (no thick sweater or something similar).
   - Yes
   - No

5. I declare that I find myself fit enough to perform slow-breathing exercises. I understand I can stop at any time if I feel uncomfortable:
   - Yes
   - No

6. *I understand that personal information, such as my name or the city where I live, will not be shared beyond the research team.*
   - *Yes*
   - *No*

7. *I allow the results of the questionnaires and what I say in the open discussions to be used in the thesis of the researcher. I understand the researcher may quote me using a test participant number, like "Participant 5 remarked this and this", but I will remain completely anonymous. I understand that the thesis will be publicly available on the Internet.*
   - Yes
   - No

Date: ____________________________

City: ____________________________

Name participant:	**Name researcher:**
________________________________	Thiemen Doppenberg_____
Signature participant:	**Signature researcher:**
________________________________	________________________

For any questions or requests, please contact me on t.a.doppenberg@student.utwente.nl