UNIVERSITY OF TWENTE.

**Faculty of Electrical Engineering,
Mathematics & Computer Science**

Breathe with me - Designing and Evaluating Wearable Visual and Vibrotactile Displays for Colocated Breathing Synchronization

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" People are all we've got "
- Phoebe Waller-Bridge

Preface

"शब्दावाचुन कळले सारे, शब्दांच्या पलिकडले" - मंगेश पाडगांवकर व पु.ल. देशपांडे

A few years ago, I got the chance to act in a play which was performed more than 25 times. Me and my co-actors had a pre-show ritual where we held each other's hands, looked into each other's eyes and tried to synchronise our breathing before going onto the stage. The days where we were in perfect sync, was when we got the best reactions from the audience, whereas the days where we felt something was off, we couldn't perform well. Over the course of twenty five plays, I found it fascinating how synchronising my breathing with my co-actors for less than five minutes before the play can have such a big impact on connecting with them as well as with more than three hundred members of the audience.

Although there is no direct correlation to the same, it got me thinking about breathing synchronization. I started observing all my interactions to understand that often when meeting someone, we constantly gauge how we are feeling and also how the other person is feeling. And sometimes, something just clicks. We just start to *vibe* with each other. We understand exactly what the other person is trying to say, or empathise exactly what the other person is feeling or going through. There are multiple verbal as well as non verbal cues that we consciously and subconsciously pick up to feel connected to each other. This sophisticated way that humans have evolved to communicate with each other was extremely fascinating to me.

This thesis is an attempt to further explore this idea with the help of wearable technology. This thesis was conceptualised during the COVID-19 pandemic. While I was thinking about connecting people through breathing synchronization, there was a second wave in India in which many people were struggling to breath properly. The irony is not lost on me. I hope that bringing this concept into reality would help people connect better with each other during good times and bad.

I also find it ironic that although this work is made to enhance colocated interactions, most of my communication with everybody involved in the process was remote and yet I felt totally comfortable during the entire course of the thesis. It is all thanks to my supervisors Dr. Angelika Mader, Prof. Dr. Ir. Kaspar Jansen, and Dr. Abdallah El Ali who helped guide me throughout this thesis. I would also like to thank Linda from TU Delft lab who helped me with the stretch sensor.

I dedicate this work to Rajendra Palande who I thank for always watching over me. I would like to thank Deepa Palande and Janhavi Palande-Lakhe who encouraged me to complete the work, patiently listened to all my rants, and yet totally understood what I wanted to say while being on three different continents. I also thank Sweta Balamurali who made me feel less alone during the difficult times when I was away from home.

I wish you a good reading,

Shalvi.

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Chapter 1

Introduction

Humans as social creatures have created sophisticated ways to connect with each other to form communities over thousands of years. Right from language to all other forms of non verbal communication which leads to us understanding each other better. One such non verbal communication mode is using our breath to showcase our emotions. Breathing is a physiological process intricately related to our cognition, emotions, and behaviour and which can be voluntarily manipulated. The better understanding that one gets from understanding their own breath and that of others leads to forming strong bonds within the community. In a social interaction, the interacting partners show engagement by gradually synchronizing their breath. Sharing of breath as biofeedback using wearable technology is of increased interest as seen by the various studies related to mindfulness, telecommunication, healthcare, etc. This study aims to contribute to this growing area of research by exploring the possibility of using wearable technology to aid breath synchronization. The goal of this study is to understand the role of different modalities on certain body locations to facilitate breath synchronization by designing a wearable device. In this thesis, I motivate the use of respiration as the physiological signal in the context of enhancing colocated social interactions.

Goal of the assignment

The aim of this work is to enhance the social interactions between humans, through the use of mindfulness on one's own breathing as well that of the interacting partner. The goal of this thesis is not to replace colocated social interactions as in the case of current information and communication technologies, but to enhance and augment the social interactions, so as to make people mindful of their own self as well as the other.

The research questions answered through this thesis are the first steps into understanding how showcasing one's physiological signals through different modalities can affect the social interactions in a colocated setting. RQ1 : What is the effect of visual and vibrotactile modalities in facilitating breath synchronisation in a colocated social interaction in a dyad?

This includes designing a wearable device and evaluating it's use with the help of various pairs of participants. RQ2 : How to design wearable on-body visual and vibro-tactile displays that can accurately represent human breathing for facilitating breathing synchronisation?

Report organization

The thesis is divided into six chapters to answer the research questions. The motivation behind creating wearable for a colocated setting by underlying the current state of communication and the effects of the same on humans is discussed in Chapter 2. This chapter also discusses the importance of breath sharing, intent and the senses of sight and touch. Chapter 3 focuses on the current state of the art devices that deal with using various physiological signals for social interaction. The research questions and the sub questions provide the basis of the rest of the report. Chapter 4 has been broadened to include the design considerations used to develop the wearable device that consists of hardware and software components of the wearable prototype. Chapter 5 elaborates on the study conducted with participants and the tasks created to test out the wearable device in a lab setup. Chapter 6 is more scientific as it discusses the analysis of the collected data in terms of breathing synchronization for the visual and vibrotactile modalities, along with the discussion for the use of such a device. Chapter 7 concludes the report with recommendations and the future scope of the wearable device.

Chapter 2

Background

2.1 Communication Technologies today

In recent decades, the world has gone through radical and transformative changes due to the advent of different information and communication technologies. Some technologies can be considered more intrusive than the others. Gergen(2002) [1] proposes that technologies such as the radio, television and cinema have a unidirectional communication flow and can be categorised as *monologic* communication technologies. Without allowing any interaction with the users, these technologies are often used and experienced collectively (For eg: watching the television with family). Whereas telephones, smartphones, and social media can be categorised as *dialogic* communication technologies. *Dialogic* communication technologies have an interactive communication flow and often require instantaneous connection with the user. Although not requiring users to be in a physical colocated space, they do share a virtual environment which demands constant attention [1]. Over the course of a few years, these types of technologies have transformed our access to information along with revolutionizing our communication. We can now connect with people, collaborate with coworkers, and communicate in different time zones and to different places on earth. The power of technology has given us the ability to be *anywhere at anytime*, which raises the possibility of harnessing this power of technology to enhance our social interaction *here and now*?.

2.2 Negative impact of Communication Technologies

Monologic and especially *dialogic* communication technologies are the cause of an ”epidemic of distraction” as coined by Weksler et al. [2]. We are constantly surrounded by devices begging for our attention. People are now in a perpetual state of contact. The need to be tuned in to instantaneous information access and communication exchange at all times seems to be the preferred state of being. With the internet being the main medium for a multi million dollar advertising industry [3] having the sole purpose of making sure that people are hooked to their screens. Smartphone usage has seen a steep increase [4] with the help of easy access to unlimited internet, various text-based communication channels along with rich multimedia applications to keep the user constantly connected, informed and entertained. There are various studies [5] [6] suggesting that virtual connections do help people overcome loneliness and in increasing social ties. For example, elderly people participating in virtual communities, avid users of social networking sites strengthening their familial and friendship ties, or socially anxious online gamers practicing their social behaviours to better equip themselves for face to face encounters. Although communication technologies have transformed our lives for good, it might not be for the best. Robins (1995) [7] argues that this virtual empowerment encourages a sense of self containment and self sufficiency and creates a desire to avoid social contact. People tend to seek individualized and self contained pleasures through electronically mediated social life. Various studies [8], [9] show that people choose to neglect those whom they are physically interacting with, only to indulge themselves in their smartphones to connect with their virtual communication partners. The ease of access to internet communication encourages people to spend more time interacting with strangers, or forming superficial relationships with online friends at the expense of more meaningful face to face interactions with their friends and family in a shared physical space [8].Even though people try to indulge in face to face conversations, the mere presence of a smartphone hinders the quality, as seen in the study conducted by Misra et al. [9]. Smartphones represent a portal to people's wider social network and immense information always at an arm's length, which has the potential of dividing their attention from the proximate space to an invisible virtual network. This persistent state of being *absent present* [1], or the split consciousness of being physically present in a location while focusing on the technologically mediated world elsewhere, has led to the deterioration of quality of interactions. Impoverished online conversations displace better quality face to face interactions, as people tend to omit social niceties which are important to maintain relationships. Obligatory and pragmatic responses are the norm in online conversations, while rarely leading up to personal expressions. Gergen [1] contextualized "relational multiplicity" wherein in person interactions are deemed less important than online conversations. Wherein, even without active use of smartphones, the mere presence of these devices have the potential of diverting users from face to face conversations. People are potentially more likely to miss facial expressions, and subtle cues such as changes in the tone of their conversation partner's voice and have less eye contact, when their thoughts are diverted by the presence of the device. These nonverbal and verbal elements of in-person communication are important for a higher quality of social interaction. *Horizontal relationships* [1] are preferred due to the ease in communication which emphasises a broader range of contacts than a *vertical relationship* which requires time, effort and attention. The clear way forward seems to be adding the *dialogical* aspect of technology to enhance colocated social interactions which will entice humans to focus on building *vertical relation-*

ships.

2.3 Enhancing colocated social interaction

Current technology largely focuses on remote connectedness, which leaves the area of enhancing communication in colocated social interaction less unexplored in comparison. Olsan et al. [10], identified two broad wicked problems for the need for better technology in colocated social interactions. As explained in 2.2, the first being the use of current technology that disrupts ongoing social interactions. In the past decade, with the increase in the use of social media and online communication applications, there has been a steady decrease in colocated social interactions. Ironically, the communication with remote others is often the disrupting factor in a colocated interaction. Although remote communication has opened new avenues for social possibilities, it has also introduced various social issues such as loneliness and disengagement from a community [10]. The second wicked problem is the lack of social interaction where it is desirable. From a societal point of view, social interaction is desirable for productivity, safety, belonging, and security. Colocated social interaction increases social connectedness, empathy, builds a sense of community, and positive attitude. Many papers [11]–[13] argue that interaction can be initiated by revealing details about the other person. The increased awareness leads to better understanding and appreciation between people. Currently interacting partners decipher the social situation with the help of social signals and cues such as body language, facial expressions, and intonation of the voice. By adding a technological element, physiological signals can be accentuated and augmented to be used as social signals of communication. Through this research, I would like to explore if representation of breath and breath synchronization can be used as a medium for enhancing social interactions.

2.4 Breathing

Breathing is the only physiological process that is reflexively controlled but can also be voluntarily manipulated. The exchange of information inside and outside of our body through breath is the basis of social and biological signaling between humans to interact with each other. Current research in smart wearables shows that understanding signals, verbal or non verbal, backed by physiological output can be viewed as an indicator in deciphering a person's intent [11], [14], [15]. Various studies [10], [16], [17] suggest that the different aspects of breathing such as the respiration rate, patterns, depth of breath are conducive in understanding a person's emotional and cognitive state thereby helpful in understanding the person's intent in the social interaction. As compared to other physiological signals, the advantage of breathing is that it can make the interacting parties in any social setting voluntarily regulate their own physiological function either consciously or subconsciously to indicate their intention and interest in the social interaction. Previous research [18], [19] has established that breath synchronization occurs in interacting partners over a period of time. By synchronizing physiological signals communication, cooperation, coordination and collaboration is fostered which is important for community building and social bonds. Of all the physiological processes, breathing can be manipulated voluntarily, hence breath synchronization can easily be achieved through conscious or subconscious means. According to Konvalinka et al [20], interpersonal synchronization between multiple people can be described as overlapping of movements or physiological signals in time and form. We subconsciously tend to synchronize most with related individuals, however conscious synchronization with others induces feelings of similarity, relatedness and closeness. Thereby giving humans the advantage of voluntary synchronization to foster better social bonds.

2.5 Intention

Intention plays an important role in boosting synchronization between interacting partners. Studies [19] [18] show a close relation between attention to breath and entrainment. A shared intentionality to synchronize increases attention provided towards the interacting partners which blurs the self - other boundary [21]. When humans are interested in interacting with one another, they often synchronize their movements and physiology, thereby amplifying their social connection and improving the quality of the interaction. Research shows that heart rates and breathing patterns of partners synchronize over time, while watching an emotional movie, singing together, taking a walk, and for romantic couples simply by spending time together [18], [22], [23]. Entrainment [24] can be achieved by voluntarily or involuntarily coordinating behavior by attuning a physiological rhythm to another person's rhythm. Reciprocal entrainment occurs when all the interacting partners deliberately synchronize their actions [21]. The deliberate synchronization of breathing patterns can be used as an approach to convey the intent and interest in a social interaction. Intentional interpersonal synchronization can contribute to increased understanding, togetherness, empathy, and intimacy. If the intentionality is established, synchronization is an ideal marker for the extent of cooperation in a group setting [18], [22].

2.6 Breath sharing and synchronisation

Intention along with interpersonal similarity is the goal for any social interaction, be it personal, professional or merely social. Synchronised movement [25], [26] [27] can be enhanced by breathing together which in turn improves attention towards the partners behaviour. Mimicking posture, vocal as well as facial expression and breathing patterns can trigger experiences felt by the mimicked person. The ability to notice the partner's emotional state requires considerable physical as well as mental effort. Physical effort can be more recognizable than mental effort. Intention matters significantly in the desire to affiliate with the interaction partner. Even if this intention is at a non conscious level, it impacts the effort put in mimicking the breathing patterns of the interacting partners. Lang et. al. [28] suggest that the effects of synchrony in socio-cognitive processing are driven by the perception of successful cooperation, which improves confidence and trust, and then transfers to future cooperative tasks.

2.7 Sight Vs Touch

When the intention to affiliate, be it at a conscious or a nonconscious level, is reciprocal from each of the interacting partners in a real time social interaction, both the interacting partners tend to corregulate their behaviour thereby affecting each other and the social encounter. This intention is conveyed with the sharing of eye contact where each of the interacting partners understand the intention at a psychological level.

Humans are social creatures. The fundamental mechanisms of social interactions that guide our social relationships have deep evolutionary roots, it is the foundation of our life and we measure the quality of our life by the quality of the social interaction we have with the other members of the group. Valuable social information about each other's identity,dominance, fertility, emotions, and likely intent is received by paying attention to the other members of the social group. The sense of sight through observable gaze and emotional expressions is used to learn the intentions and dispositions about other members of the social group. Where sight is primarily used to convey attention, intention and disposition, the sense of touch is used to convey intimate emotions and is essential for our emotional and mental well being. As touch implies direct physical interaction and colocation, it inherently has the potential to elicit feelings of social presence. In the digital age where human social interaction is usually mediated, touch is rarely supported by the current communication systems popularly used by the masses(such as video conferencing). Thereby lacking a convincing experience of actual togetherness.

Chapter 3

Related work

3.1 Research questions

The above literature review provides motivation for designing a wearable for respiratory synchrony to improve and enhance colocated social interactions. This raises two research questions.

RQ1

What is the effect of visual and vibrotactile modalities in facilitating breath synchronisation in a colocated social interaction in a dyad?

To answer this research question, a wearable device needs to be designed to evaluate respiratory data that can be showcased through visual and haptic modalities.

RQ2

How to design wearable on-body visual and vibrotactile displays that can accurately represent human breathing for facilitating breathing synchronisation?

The above question can be further categorised into sub questions to understand the depth of the topic.

SQ1 : What are the user needs and interests in sharing biofeedback? (Refer section 3.2)

SQ2 : What are the design criteria to be considered designing wearables for collocated social interactions? (Refer section 4.1)

SQ3 : Out of visual and vibrotactile modalities, which on-body location is effective for each modality to facilitate breath synchronization? (Refer sections 4.1 and 4.1)

SQ4 : What are the different factors of visual and vibrotactile modalities? (Refer section 4.3)

SQ5 : What is an effective way of sensing breath on individuals? (Refer section 4.2)

SQ6 : How can breath signals be processed to detect synchronization? (Refer section 4.3)

3.2 State of the art

To answer SQ1, the current state of the art technologies were studied.

In recent years, there is a steady increase in the use of multiple smartphone and wearable technological devices to track physical activity, and physiological data. As sensors and actuators decrease in size and increase in the computational abilities, users are interested in obtaining physiological, cognitive and emotional data through modalities beyond traditional touchscreen output [29]. User needs are based on the utility, connectivity and the feedback mechanism of the wearables to better understand their physiological data. The user needs are related to acquiring their own data, sharing their own data to others and receiving data from others. Hassib et al. [29] show that people are more comfortable with receiving other's data(close relations) than sharing their own. As physiological information is extremely personal, technology that encourages mutual sharing is accepted better than sharing one's own information. Valence plays an important role in exchange of data as users are more comfortable with sharing positive emotions publicly and negative emotions privately. In a certain context, the social interpretation of physiological data can affect trust, mood, reliability and dependability [15] [30]. The current state of the art wearable devices deal with various physiological signals as cues for social interactions ranging from skin conductance, heart rate, respiration rate, and emotions such as laughter etc.

Skin conductance is used as a biosignal display to understand the human interpretation of affect in a social interaction [11]. By designing a wearable Hint [11], the study shows that there is an increase in emotional engagement, and humans tend to use the display of their physiological signal as a form of validation for the interpretation of the particular interaction. The biosignal display was viewed as a part of social performance along with other social cues such as facial expression and tone of voice. The Laughing Dress [13] is a wearable responsive garment that provides a visual and auditory display of laughter. The findings of the study showed that revealing the body state can promote self presence, interpersonal behaviour while also transcending the social norms for a positive connection in a colocated space. Various wearable technology uses breath as a medium to foster social connectedness, empathy, telepresence. Remote sharing of breath as a bio signal can be seen in Breeze [14] which offers a wearable pendant which conveys the physiological signals of breathing through breathing patterns shown by 3 different modalities of visual, vibrotactile and auditory stimuli. The device is designed and developed to understand the interaction partners' emotions, where the results also show that the participants modify their own breathing patterns in some instances. Another remote biosignal sharing device is BreathingFrame [31]. A portable inflatable frame is a breath signal sharing device which improves conveying of emotions over long distances. The users can share their breathing patterns through intentional breath signal delivery which in turn increases the feelings of sentimental connectedness.

In the Same Boat [32] is a two-player game intended to foster social closeness between players over a distance. The synchronisation of both players' physiological data (heart rate, breathing, facial expressions) is leveraged and mapped to an input scheme to control the movement of a canoe down a river. Breath sharing and synchronization is only explored in the following research. Exhale [33] is an installation where a breath is shared between participants with a perceptible breeze. There are two systems which explicitly design for breath synchronization for multiple participants in colocated settings. JeL [34] is a virtual environment with coral-like structures which start growing and pulsating depending on the breath synchronization of the participants interacting with the environment. ExoPranayama [35] is a tent-like structure that will light up with an "Om" sign once breath synchronization occurs in the meditating participants in a colocated setting. From the current wearable technologies, it can be assessed that visual and vibrotactile stimuli have been effective in actuating the process of breath.

Most of the above mentioned technologies emphasize on remote sharing of breath, a few technologies make use of an accessory to aid breath synchronization either through games or visualizations. The breath synchronization using wearables in colocated settings has not been explored thoroughly. Through this thesis, I would like to explore how accentuating breathing patterns through visual and haptic stimuli can facilitate breathing synchronization within friends in a colocated social interaction.

Chapter 4

Method

4.1 Design considerations

To answer SQ2 and SQ3, literature review was performed to study wearability, comfort and feasibility. The conventional methods of drawing a wearer's attention to a wearable technology are visual, vibrotactile and auditory stimuli. As explained in the previous section 3.2, visual and vibrotactile are the preferred modalities in breath sharing. The insights for on-body locations of wearables for visual and vibrotactile feedback can be seen below.

Visual actuation

Dagan et al. [36], suggests that visual modality is easiest to catch attention as people are highly used to interpreting visual cues through movement, shape and light. Harrison et al. [37] have researched the optimal on-body location to place visual stimuli to understand the attention demand and reaction time characteristics. The results were gathered for the self-perception of the visual stimuli by the participants. The highest reaction time for visual stimuli was observed for the wrist, arm whereas the least reaction times were seen on the upper thigh and shoes. A comprehensive study was conducted by Zeagler [38] which provides the functional, technical considerations for on-body location. The findings can be seen in figure 4.1 below.

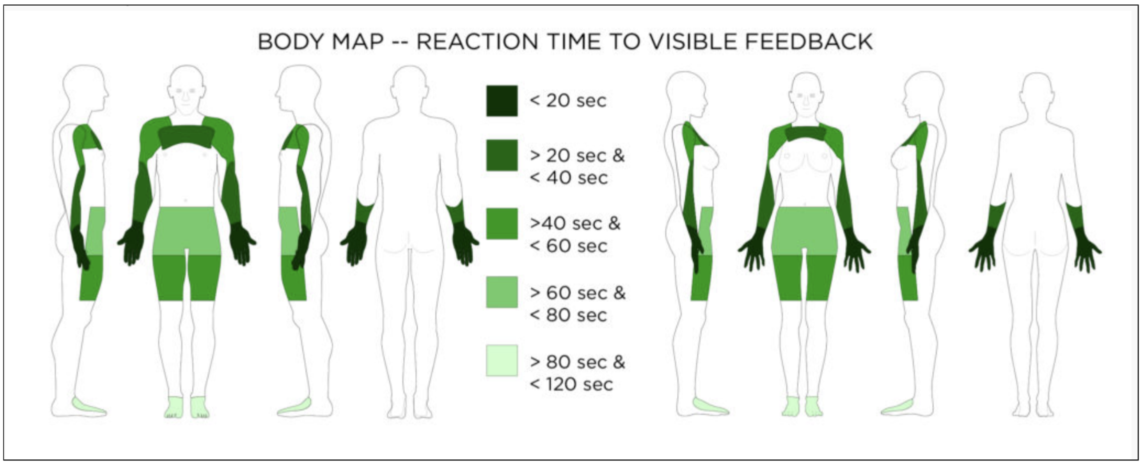

Figure 4.1: Body Map of Reaction Time to Visible Feedback

For this research, a direct mapping [39] between the breathing and visual actuation would be made. The visual representation of one's own physiological signal would be portrayed using a led pattern display. For a maximum unobstructed view, the on-body location of the chest will be studied. As the breath of the individual is represented by the visual modality on one's own self, the context of wearability is personal and comfortable. The intended audience to view the breathing pattern would be the interacting partner. As the premise of the experiment is to explore if an unobstructed view of interacting partners' breathing patterns can facilitate breathing synchronization, the visualization of the breathing patterns will not be viewed by the individual but by the interacting partner, hence the preferred location is the chest.

Vibrotactile actuation

Related work shows that to showcase breathing pattern, the most common form of haptic feedback out of temperature, pressure and vibration was vibrotactile feedback. Stimulus detection of vibrotactile feedback depends on multiple aspects such as intensity of vibration, comfort/pain threshold of the user, temporal patterns of vibration. Depending on the acuity, the ideal on-body location for tactile actuators is the fingers, arms and face [38]. As can be seen in the figure 4.2

below.

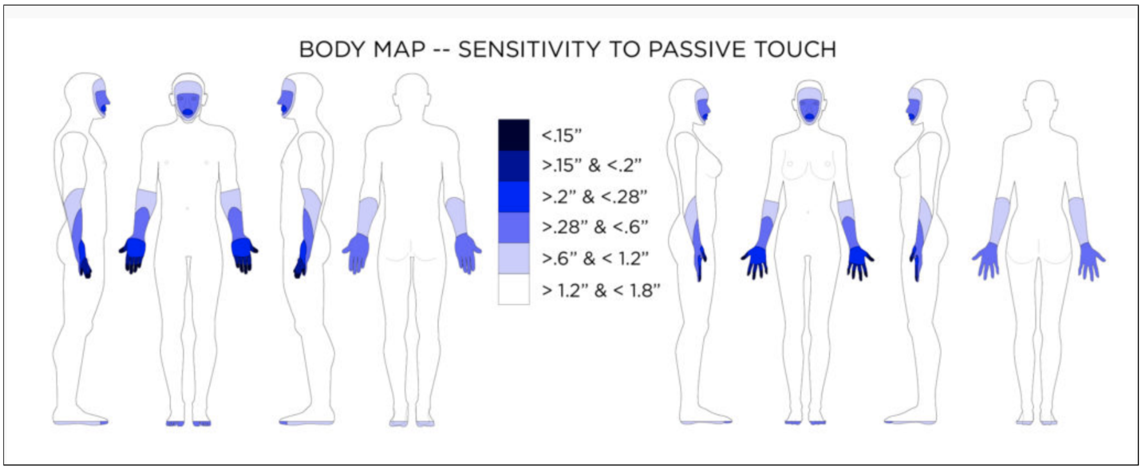

Figure 4.2: Body Map of Sensitivity to Tangible/Haptic Feedback

The context in which the biofeedback is shared between users is as important as the technology itself. The relationship between the interacting partners affects the perception of the physiological signals in question. Suvilehto et al. [40], suggests that subjective experience and processing of social touch depends on the dyadic relationship. Appropriate social touch between dyads fosters mutual positive emotions such as trust and affection by maintaining the individual's proximity to the other and modulating interpersonal behaviour. The body region where one is permitted to touch is dictated by the relationship that is shared between the interacting partners. According to Suvilehto et al., in the social network of friends, social touch on the head, shoulders and arms is acceptable for male as well as female friends. As seen in the figure 4.3, the areas which are acceptable and taboo can be viewed through the difference in colour.

For this study, a direct mapping [39] between the breathing and vibrotactile actuation would be made. For breathing synchronization, in a dyad, the portrayal of a person's breathing data would be actuated on the interacting partner's haptic device. The haptic device is tested on the upper arm and forearm [41] in the preliminary study.

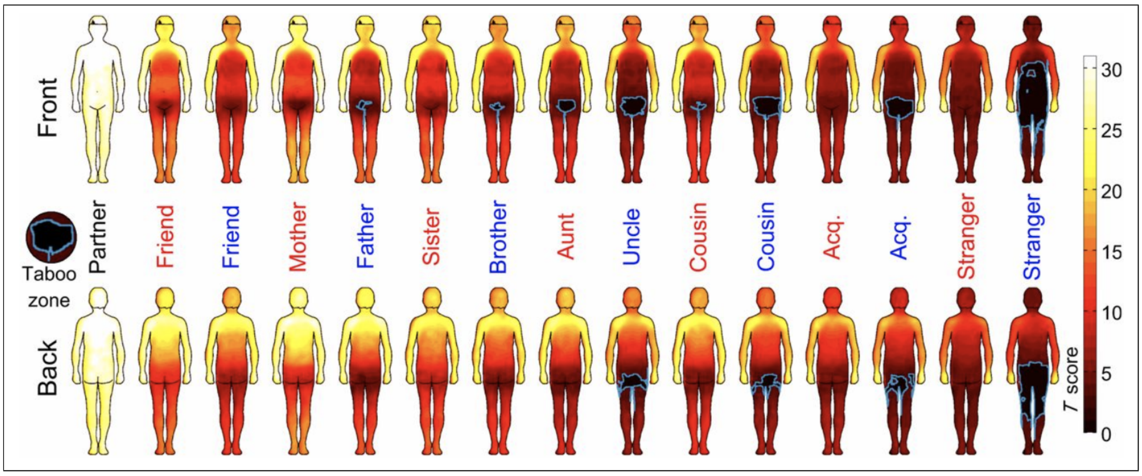

Figure 4.3: Acceptable areas for social touch in various relationships

4.2 Hardware prototype

The prototype consists of two aspects namely the sensor and the actuators.

SENSORS

To answer SQ5, different types of sensors were tested to find the optimum way of sensing respiration data.

Single conductive yarn and Arduino Nano

Initially, a knitted stretch sensor with a single conductive yarn was tested on two body locations namely lower chest and abdomen to collect the breathing data. To collect the breathing data, the change in resistance of the conductive yarn during the expansion and contraction of a person's inhale and exhale action is measured by the stretch sensor. The initial idea was to make the prototype compact by using Arduino Nano stitched onto the stretch sensor belt worn by the participant. I tested the single conductive yarn stretch sensor on myself (See figure 4.4) and collected breathing data patterns for normal, shallow and long breaths.

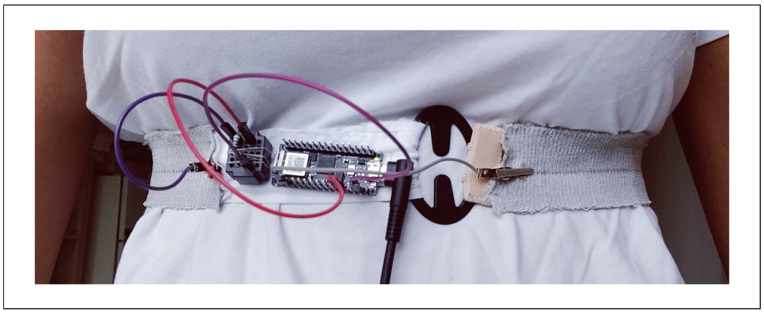

Figure 4.4: Single conductive yarn sensor belt with Arduino Nano

The signal received with the single conductive yarn sensor was too noisy (See figure 4.5).

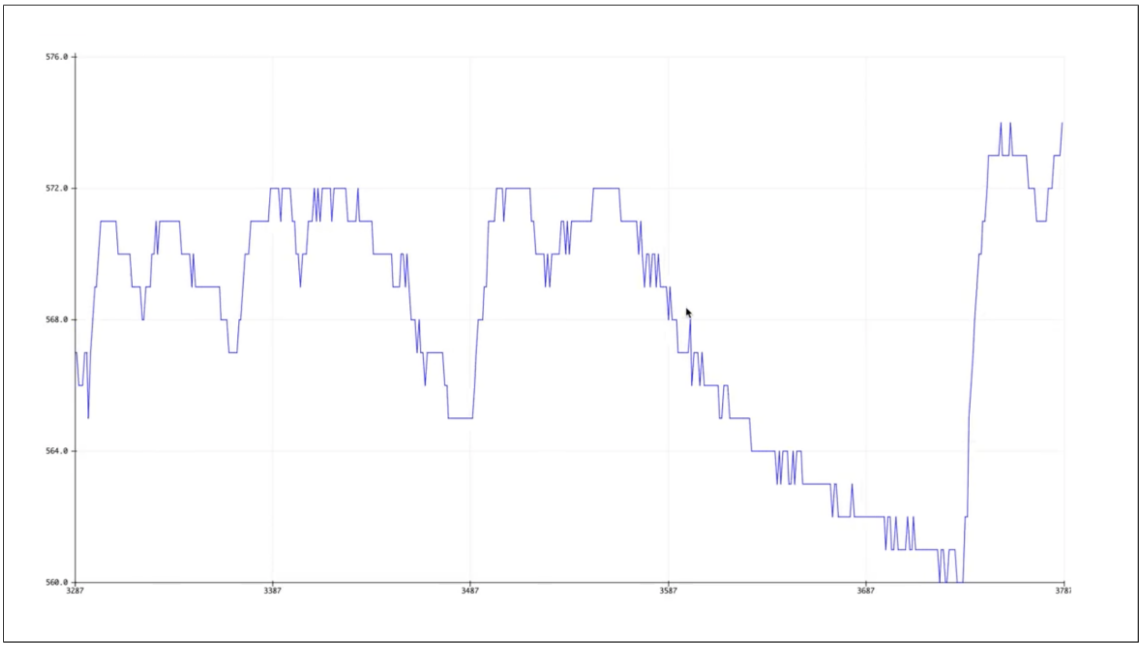

Figure 4.5: Noisy Data for Single Conductive Yarn sensor belt

As real time breathing data needed to be recorded and mapped onto the visual and vibrotactile actuators, this type of a noisy signal was not ideal for the prototype. As multiple other elements such as the visual and vibrotactile actuators were to be added to the prototype setup, Arduino Nano was discarded as a choice of microcontroller as it did not offer enough pins required for all the component connections.

Single conductive yarn and Arduino Mega

As this project required more I/O pins for the sensor and actuator components, Arduino Mega 2560 was selected. Along with multiple pins, the Mega microcontroller offers significantly more RAM which is required for the functionality of the prototype. To collect a refined clean signal, a knitted stretch sensor with a double band conductive yarn connected in a U-shaped was tested (See figure 4.6).

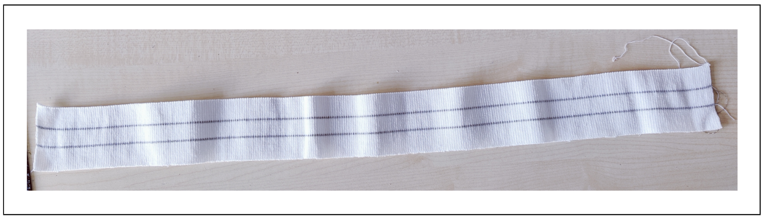

Figure 4.6: Double band conductive yarn sensor belt

The conductive yarn is soldered onto copper wires using metal clasps (See figure 4.7) for connecting the stretch sensor to Arduino Mega.

Figure 4.7: Soldered wire connections to sensor belt

One wire of the conductive yarn is connected to the GND pin, while the other is connected to input pin A10 through a (180 ohm) resistor. The voltage supplied to the sensor is 5V. The circuit diagram for the sensor connection can be seen in figure 4.8.

For the on-body attachment of the belt, metal clasps are connected

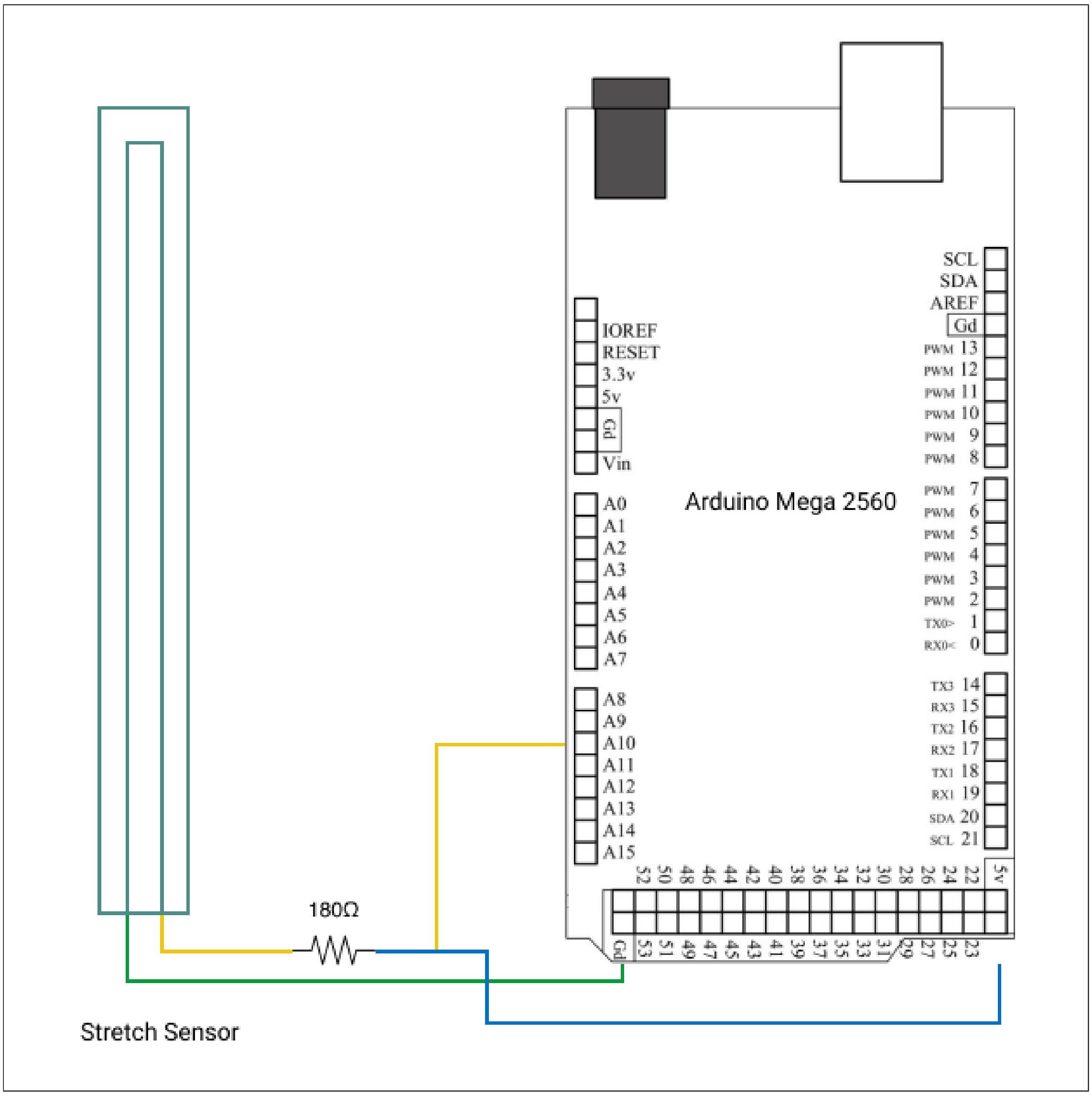

Figure 4.8: Circuit diagram for stretch sensor

with a strip of cotton fabric to avoid contact of the metal clasps to the conductive yarn. I tested the belt on myself to understand how the breathing data collection would differ from the previously used stretch sensor (See figure 4.9).

The signal received is much cleaner with prominent peaks and troughs indicating the inhalation and exhalation of the breathing pattern (See figure 4.10). This signal is ideal as the project requires real time mapping of this breathing pattern to visual and vibrotactile

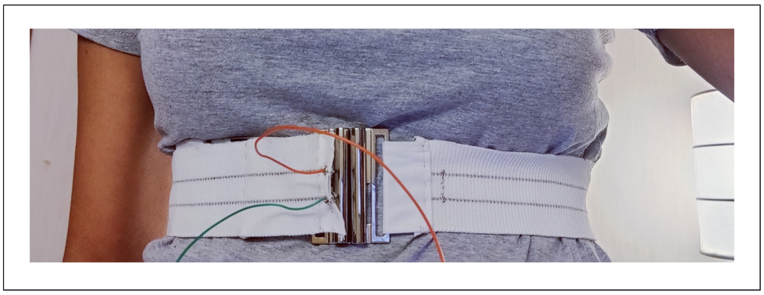

Figure 4.9: Testing for double band sensor belt

actuators.

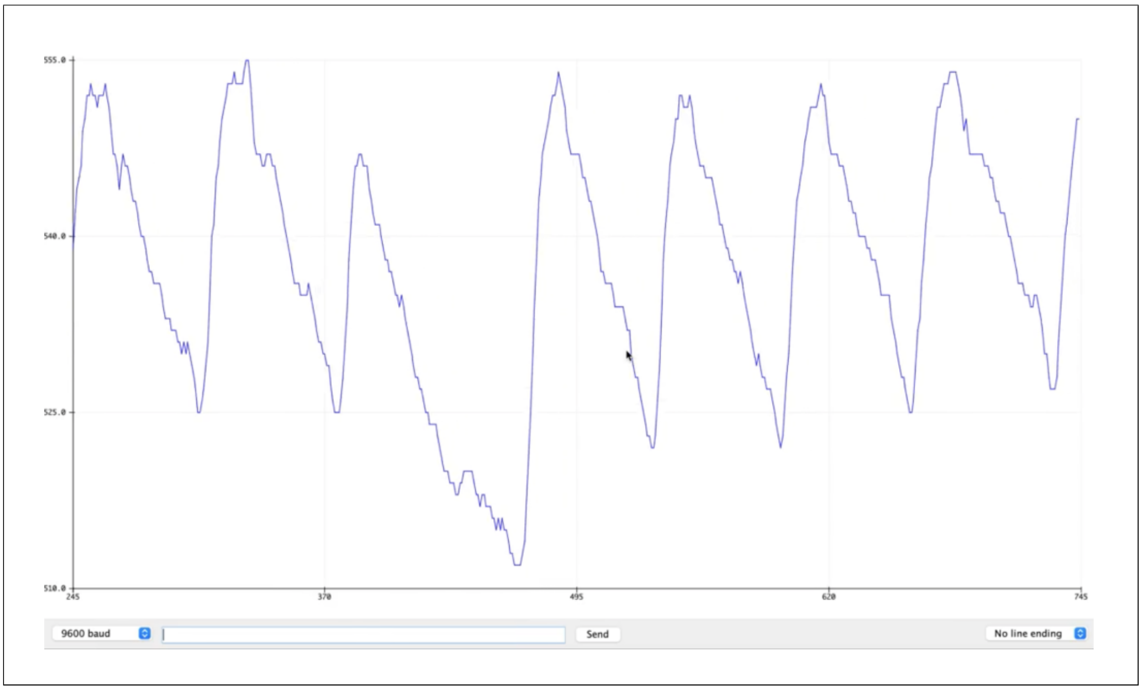

Figure 4.10: Breath signal for double band sensor belt

To collect a prominent signal using the resistance change, the stretch sensor needs to be tightly fit onto the lower chest of the participant. As the stretch sensor belt will be worn by multiple participants with different body types, the sensor belt is extended by using cotton strips. Furthermore, velcro strips are affixed to the cotton strips for size adjustment. The detachable metal clasp can be fastened at three different points on the belt to achieve a tighter fit (See figure 4.11).

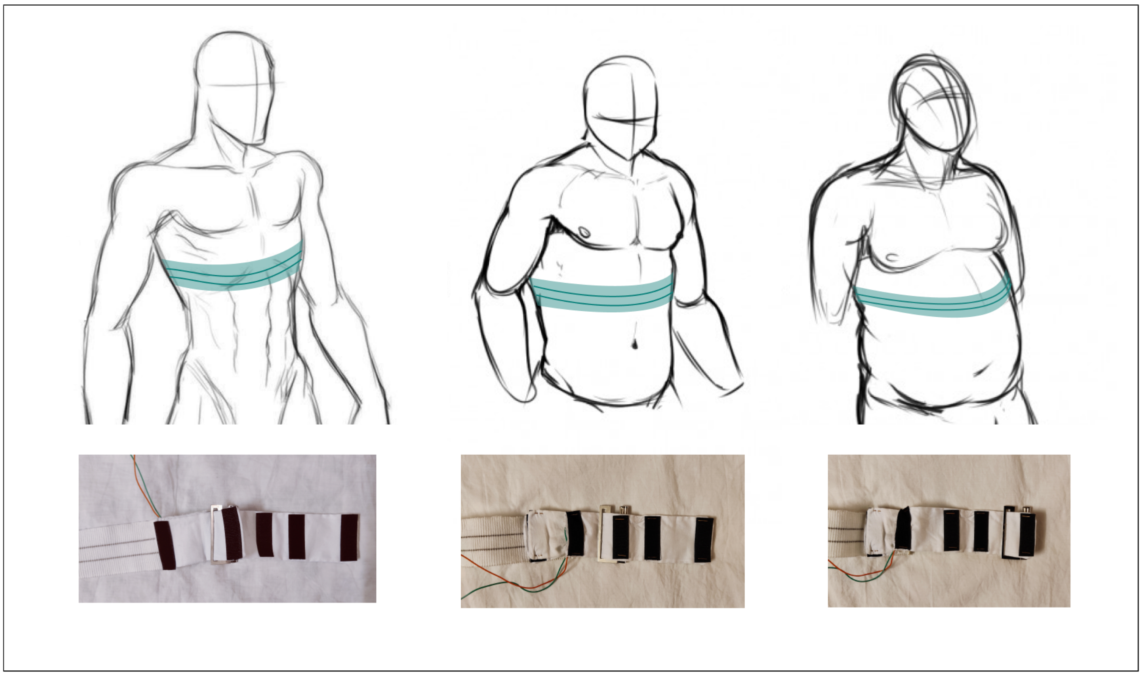

Figure 4.11: Belt adjustment for three different body types

ACTUATORS

Visual actuator

Dot Matrix

The breathing pattern collected by using the stretch sensor is represented on the visual modality by using LED matrix. Initially, four MAX7219 dot matrices were selected to represent the breathing pattern (See figure 4.12). MAX 7219 LED dot matrices have a clock pin which showcases display patterns, although for this project real time analog signal of the breathing pattern was to be represented. Hence using the dot matrices for the visual display of the breathing data was not possible. Along with that, the prototype needed to be robust for multiple usage by different participants and as the connection of four dot matrices involved connecting multiple wires to the microcontroller with the possibility of connection detaching during the experiment, the use of dot matrices for visual actuation was discarded.

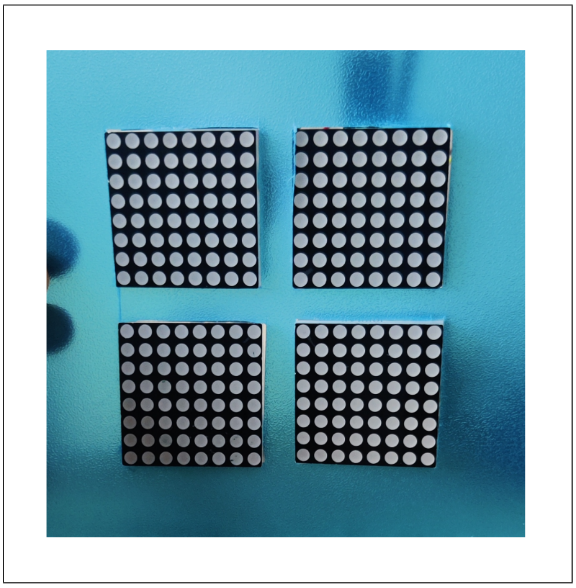

Figure 4.12: Dot matrix visual actuator

NeoPixel LED matrix

Neopixel LED matrix consists of sixty four RGB LEDs arranged in an 8*8 matrix. Each pixel is individually addressable and can be controlled by a single DIN pin. The Neopixel LED matrix is configurable for real time analog input displays such as breathing patterns. For the purpose of this project, the LEDs were configured to light up depending on the breathing input received from the resistance change of the stretch sensor. The NeoPixel matrix is connected to Arduino Mega 2560 by three pins namely GND, 5V and DIN as seen in figure 4.13. As the NeoPixel LED receives a varying power supply depending on the breathing data change, a capacitor of (1000 mu F) is added to the circuit. Using the Neopixel Arduino Library the DIN pin is connected to Pin 6 of Arduino Mega 2560.

The NeoPixel LED matrix was tested along with the stretch sensor to map the real time breathing pattern (See figure 4.14). The intensity, colour of the LED matrix can be manipulated using the Neopixel Arduino library. A circular pattern is selected to represent the breathing data, where the expanded circle illustrates inhalation and contracted

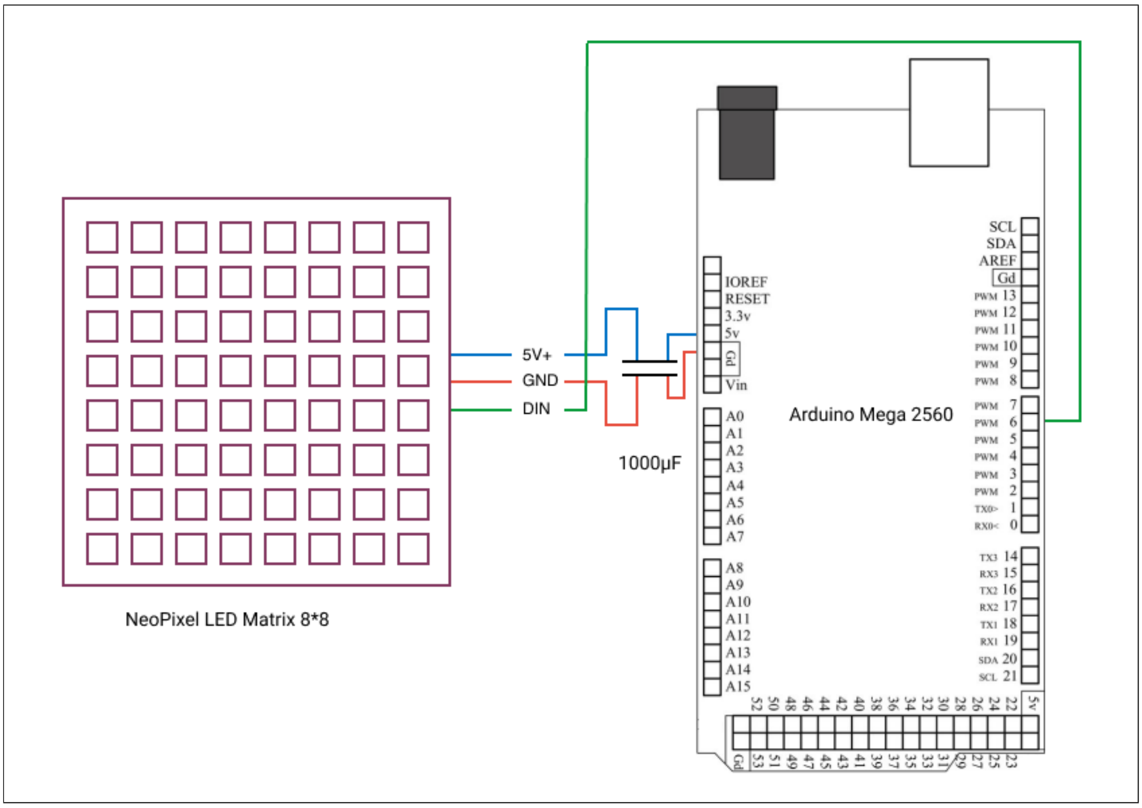

Figure 4.13: Circuit diagram for Neopixel LED matrix

circle illustrates exhalation. The breathing inhalation and exhalation is mapped to the Neopixel matrix according to the peaks and the troughs in the real time sensor data.

The Neopixel LED matrix is placed in a plastic container wrapped with a textured fabric paper to diffuse the intensity of the light (See figure 4.15). As the Neopixel LED matrix is to be used in a well lit room for the experiment, the intensity of the matrix is kept at seventy five percent. The intensity of the matrix is configurable and the ideal intensity was checked during the preliminary study experiment using participant feedback. As multiple participants would be handling this component, the entire component was then wrapped in plastic foil for the ease of sanitation as a precautionary measure against COVID.

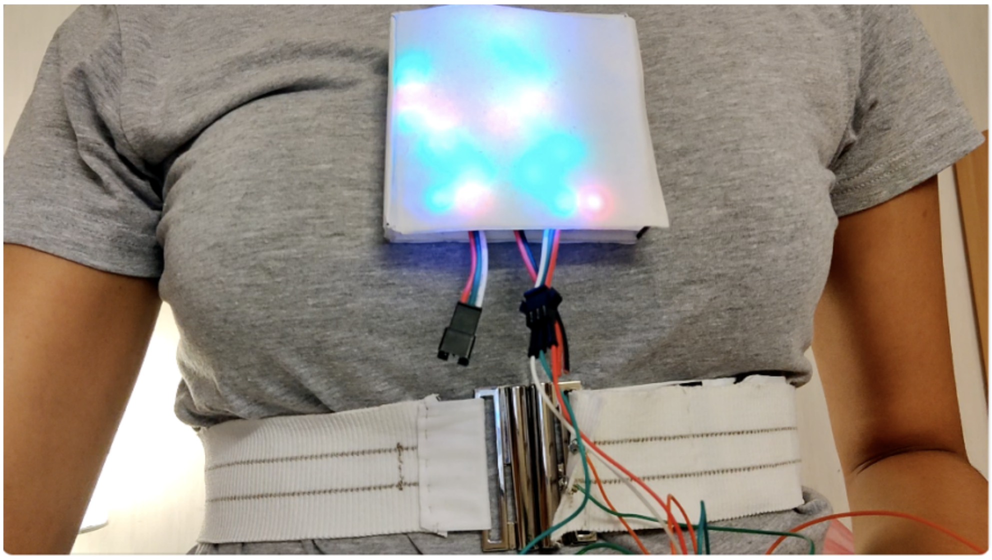

Figure 4.14: Testing for Neopixel LED matrix

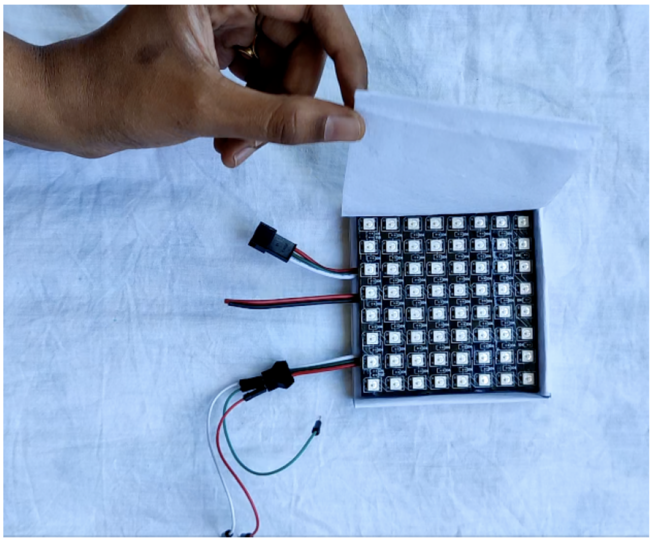

Figure 4.15: Diffusion for Neopixel LED matrix

Vibrotactile actuator

The vibrotactile actuator consists of a LRA vibration motor attached to a DRV2605L driver. The DRV2605L driver. The LRA vibrators are driven by an AC current preferably a sine wave. Amplitude modulation is possible for the LRA motors making it an ideal component for representing breathing pattern data which is an analog sine wave signal. The DRV2605L driver is used with LRA motors for a high quality tactile feedback which can be controlled using the haptic effect library. The LRA motor is soldered onto the DRV2605L driver which in turn is connected to Arduino Mega 2560 using the five pins (See figure 4.16).

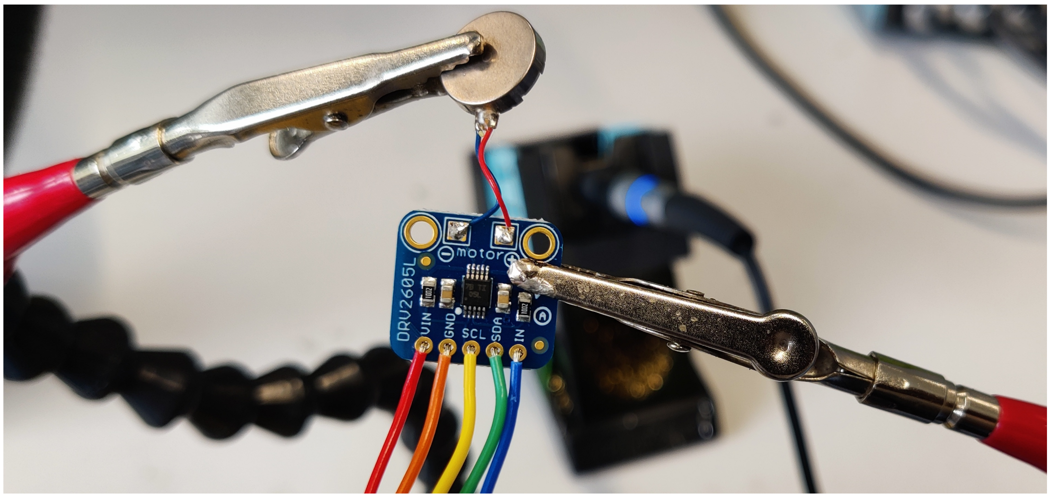

Figure 4.16: Soldering of LRA to DRV2605L

The circuit diagram can be seen in figure 4.17. GND and VIN are connected for supplying voltage to the vibrational motors whereas SDA and SCL are used for serial communication between Arduino and the driver. The Input pin connected to pin A0 of Arduino Mega provides the driver with the breathing data signal received from the stretch sensor.

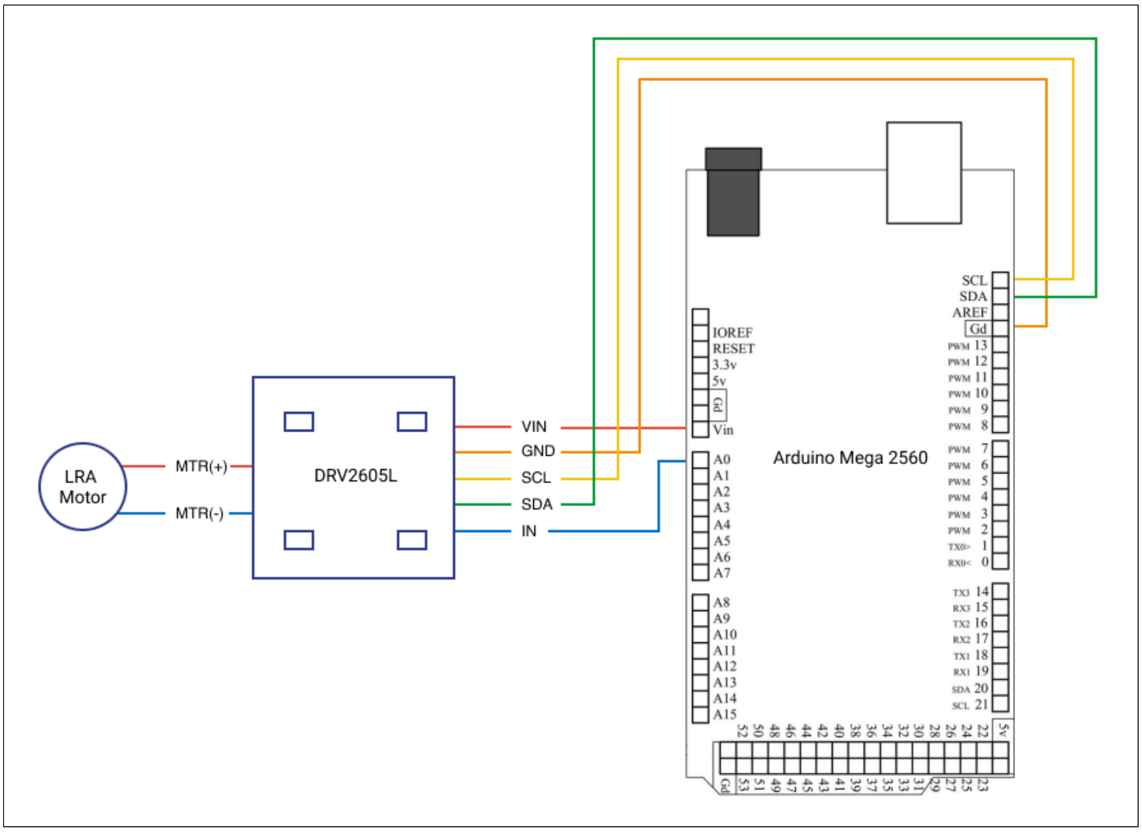

Figure 4.17: Circuit diagram of vibrotactile actuator

As the LRA wires are fragile and can be easily detached from the soldered points due to the vibrational motion, the LRA motor and DRV2605L driver are secured to a piece of felt fabric (See figure 4.18). This in turn is covered with plastic and fixed to a velcro strap which can be used to attach to the participants during the experiment. As the component will be handled by multiple participants, it is covered in plastic for ease of sanitation for precautionary measures against COVID.

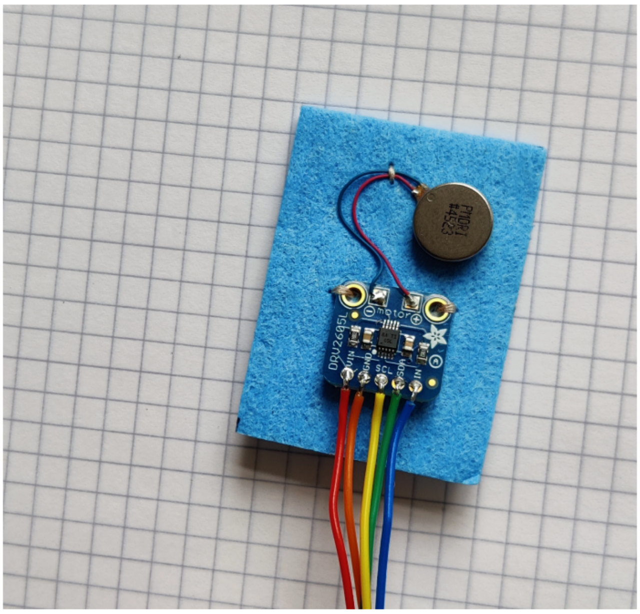

Figure 4.18: Vibrotactile actuator fixed on felt fabric

Hardware architecture

The experiment requires breathing data collection from two participants simultaneously. This breathing data would be actuated using the visual and vibrotactile actuators in real time for both the participants. Therefore the final prototype setup consists of two sets of Arduino Mega 2560 microcontrollers, stretch sensors, visual and vibration actuators connected to a single laptop(Macbook Pro : 2 GHz Dual-Core Intel Core i5 Processor). A protoshield is used to fix all the connections of the three components namely the stretch sensor, visual actuator i.e Neopixel LED matrix and the vibrotactile actuator i.e DRV2605L and LRA motor. The wires are soldered onto the protoshield which is then placed on the Arduino Mega (See figure 4.19). To ensure that the wires do not move during the handling of the prototype, the wires are fixed onto the protoshield using hot glue. This reduces the tensile stress onto the solder points of each of the connections. Finally for bidirectional exchange of breathing data, both the microcontrollers were connected with each other using jumper wires.

The connections numbered in figure 4.19 are as follows.

1. Stretch Sensor
2. Visual Actuator (NeoPixel LED Matrix)
3. Vibrotactile Actuator (LRA)

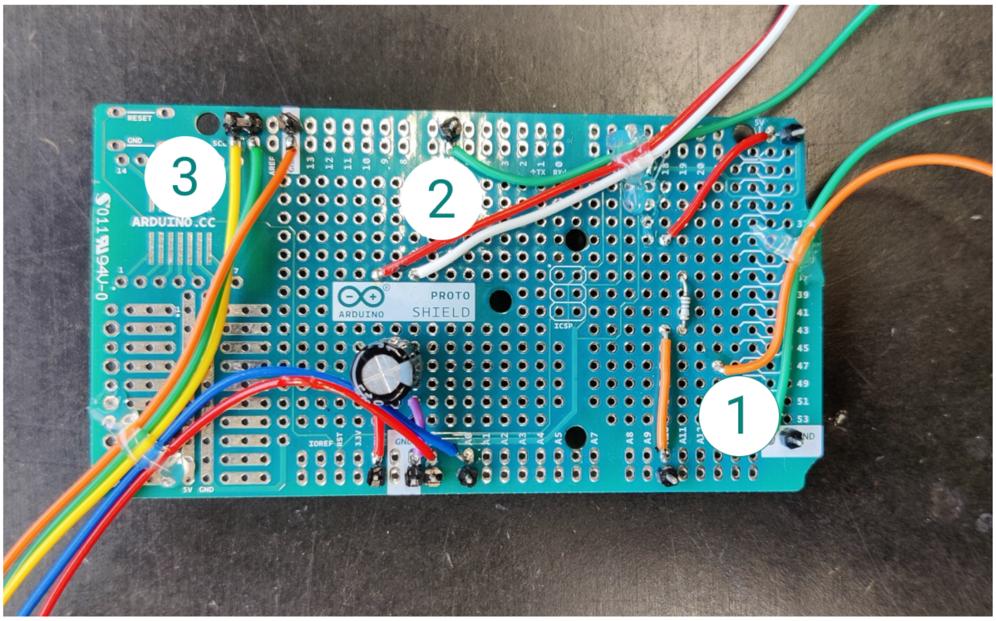

Figure 4.19: Soldering on protoshield

The circuit diagram of the hardware architecture can be seen in figure 4.20 below. The final hardware prototype can be seen in figure 4.21 below.

The components of the hardware prototype as numbered in figure 4.21 are as follows.

1. Arduino Mega 2560 microcontroller

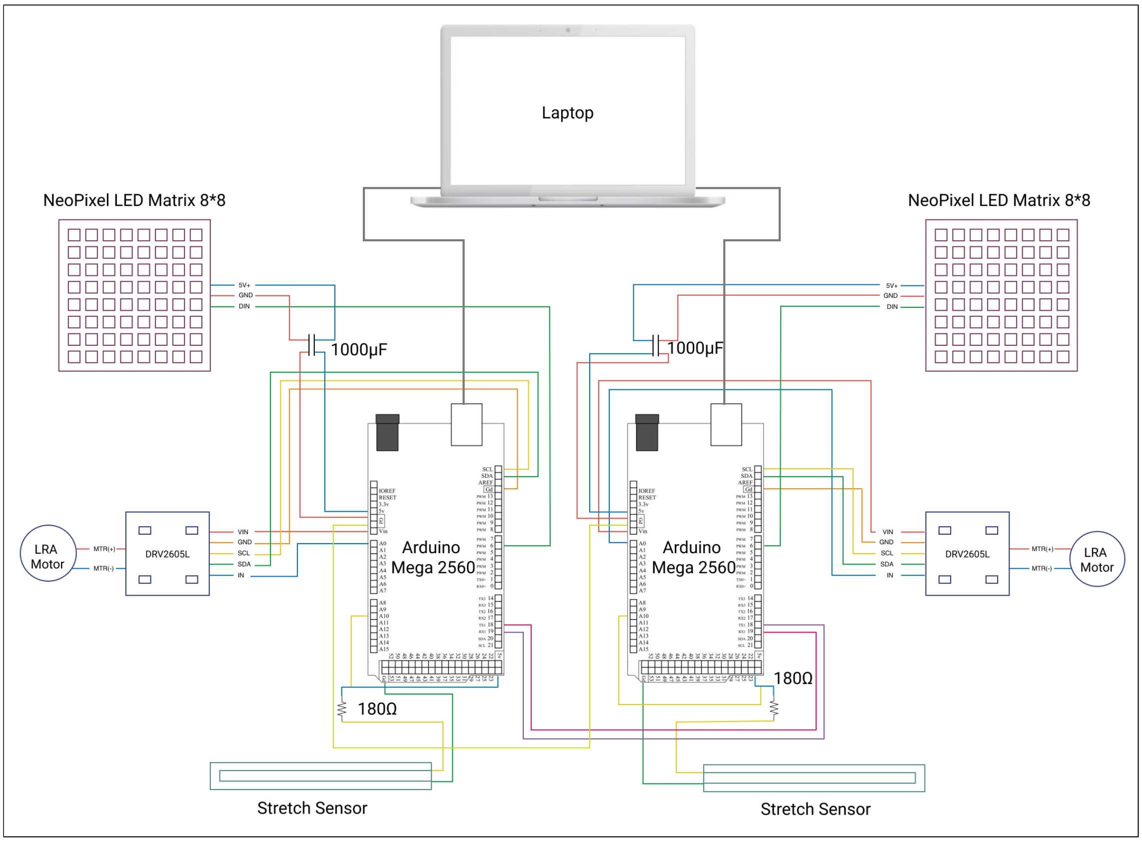

Figure 4.20: Circuit diagram of prototype

2. Stretch Sensor
3. Visual Actuator (Neopixel LED matrix)
4. Vibrotactile Actuator (LRA)
5. Protoshield in top of microcontroller

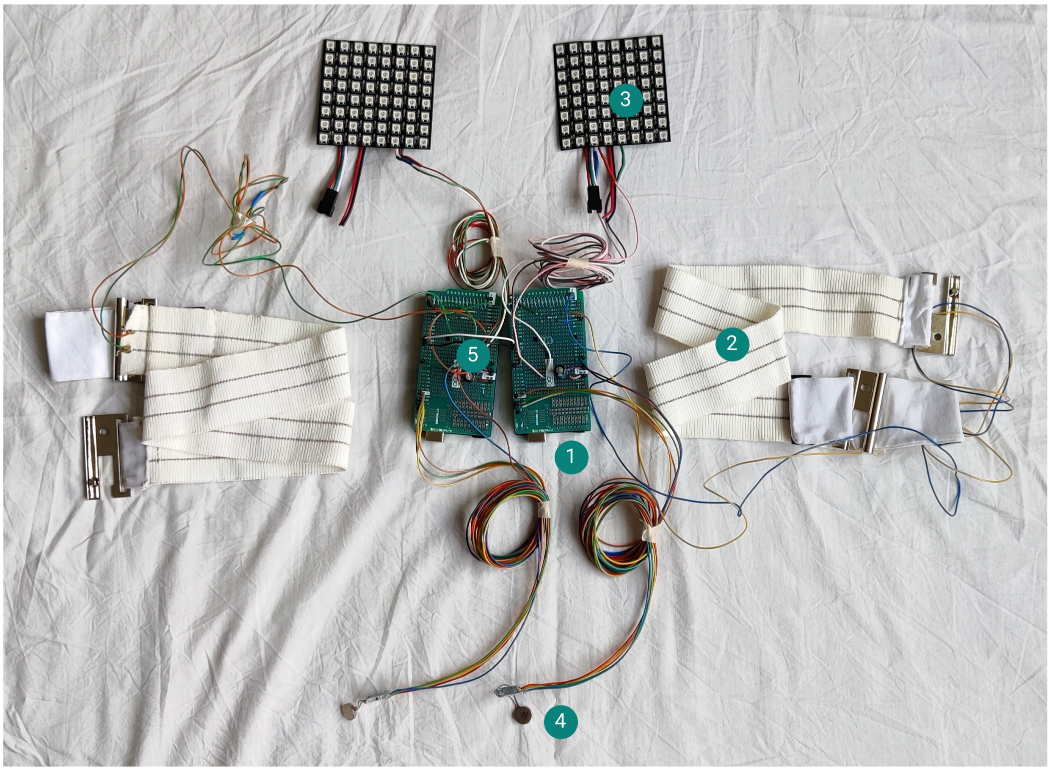

Figure 4.21: Hardware diagram of prototype

4.3 Software prototype

This section expands on SQ6. The codes for the sensing and actuation can be found on github using link : Wearable for Breathing Synchronization

Python data logging and condition selection

The study has five conditions namely Baseline, Visual, Vibrotactile, Visual and Vibrotactile and InSync. These conditions are selected from the python code and sent to the Arduino using serial communication. The sensor data from each of the Arduino microcontrollers is logged into separate files for each of the conditions. Upon finishing the data logging, the next condition can be selected. The data logging consists of timestamp, the raw value of resistance change and the type of condition selected. *Link for Condition Select and Data Input*

The amplitude, phase and respiration rate calculation is performed retroactively after all the breathing data is collected to keep the time lag for actuation to the minimum. *Link for data processing*

Arduino breath mapping and actuation

Arduino IDE is used to read breathing data from sensors and map the breathing signal to the visual and vibrotactile actuators.

The sensor data read from each of the two microcontrollers is transferred to the other microcontroller for vibrotactile mapping and synchronisation. *Link for Arduino Codes*

The breathing position(Peaks or Troughs) for each user is compared with the breathing position from the other user, and when the condition is true, the actuation of the breath pattern is changed on the visual and vibrotactile actuators to the SyncValue. The breath value for normal as well as sync condition is passed to the visual or the vibrotactile actuator depending on which condition is selected from the python code.

Chapter 5

Study

An experimental study was conducted to understand and evaluate the wearable device. The goal was to collect real time breathing data of pairs of participants while asking them to perform collaborative tasks. The collected data is then analysed for instances of breath synchronization and the modality which aids the same.

5.1 Participants

Participant recruitment was done by approaching people in person, posting participant requirements on social media, along with word of mouth recruitment. A google form along with a link to a schedule selection page was created from which a feasible time suitable for both the participants of the experiment could be selected. The participants were current masters students and ex-students of TU Delft. Fifteen pairs (thirty participants) were invited to perform the experiment. Each participant received a 10 eur voucher. The age demographic of the participant ranged from 22 years to 29 years. There were eleven pairs of male-female participants, three pairs of male-male and one pair of female-female participants. Out of the fifteen pairs, two pairs were married, four pairs were colleagues, three pairs were classmates, four pairs were housemates/roommates, and two pairs were friends.

5.2 Tasks

As mentioned in section 2.5, intention can be generated in the participants by providing them the common goals. Hence using the task models suggested by Palanque et al. [42] tasks based on cooperation and collaboration were chosen to understand the overview of respiratory behaviour in these different types of interactions. Participants were requested to play games which focus on balance, concentration and collaboration between two people. The materials required for the tasks are Mikado sticks, narrow mouthed bottle and sponge cubes. All the materials were sanitised with alcohol wipes and a sanitizer spray before each experiment as a precautionary measure against COVID. For the tasks of Mikado, modified Mikado and high tower, the feedback conditions were visual, vibrotactile, and combination of visual and vibrotactile. The tasks were split into five parts for each testing condition. These feedback conditions were randomised and counterbalanced for each experiment. The materials can be seen in figure 5.1 below.

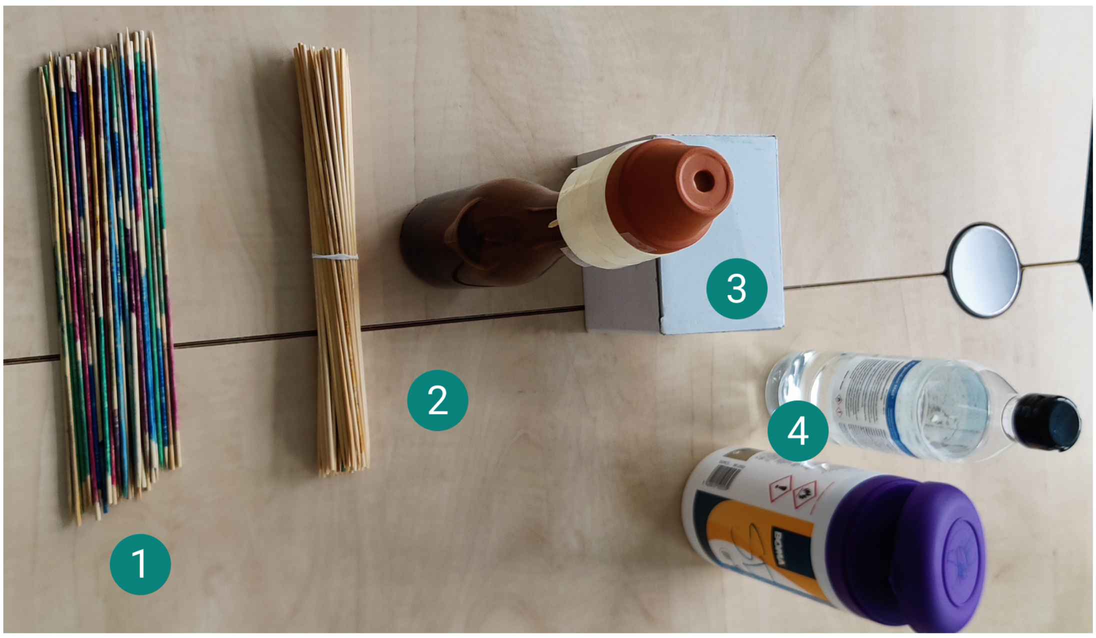

Figure 5.1: Task Materials

Number in Figure	Material	Task
1	Coloured Sticks	Mikado
2	Sticks and Narrow Mouthed Bottle	Modified Mikado
3	Sticks and Sponge Cubes	High Tower
4	Sanitizer and Wet wipes	To clean all materials before next experiment

Table 5.1: Task materials contents

Icebreaking questions

The first condition was to collect Baseline data for which the participants were required to breathe normally. The task consisted of ten ice breaking questions, and lasted for five minutes. For this task, the researcher and the participants got familiar with each other by answering each question. The purpose of this task was to get the participants familiar and comfortable with the setup and with each other [43]. The set of questions can be seen in the table below.

What do you like about yourself?	What do you like about your partner?
Tell us a story of the first time you met.	What was your first impression of your partner, and what do you think of them now?
What is your favourite thing to do together?	Tell us a story of the last interesting thing that you did together
Name 3 things that you and your partner have in common.	Name 3 things which a quite different for you and your partner.
Given a choice of anyone in the world, who would you invite for a dinner for 3?	Which was your favourite meal that you had together?

Table 5.2: Icebreaking questions for self and other

Mikado

The second task consisted of playing Mikado. Set of wooden sticks are randomly placed on the table. The rules of the game are each participant takes a turn to pick up a stick from a pile of sticks without moving the other sticks while doing so. For the sake of the experiment the participants were requested to pick up the sticks at the same time. The participants could discuss and decide which sticks to pick up. The task lasted for five minutes. Figure 5.2 illustrates participants performing task two.

Figure 5.2: Participants playing Mikado

Modified Mikado

The third task consisted of playing a modified version of Mikado where similar to the second task a set of wooden sticks were randomly placed on the table. The rules of the game are each participant takes a turn to pick up a stick from a pile of sticks without moving the other sticks while doing so. Along with the sticks this task also consisted of a narrow mouthed bottle. The modification for this task was that each participant had a single stick in their hand, which they could hold with their dominant or non-dominant hand, whichever was comfortable for them. Using the single stick, both the participants had to pick up a third stick from the pile of sticks on the table and place this third stick in the narrow mouthed bottle. The participants were informed that task four depends on the number of sticks that they collect in task three. The participants could discuss and decide which stick to pick up. The task lasted for five minutes. Figure 5.3 illustrates participants performing task three.

Figure 5.3: Participants playing modified Mikado

High tower

After the completion of the third task, the number of sticks collected in the bottle were counted. Using double the number of sticks from the bottle along with the sponge cubes, the participants were requested to build a high tower together for the fourth task. The task lasted for five minutes. The rule was to create a tower which would remain stable at the end of 5 mins. The participants were encouraged to discuss and decide on creative ways to create the high tower. Figure 5.4 illustrates participants performing task four.

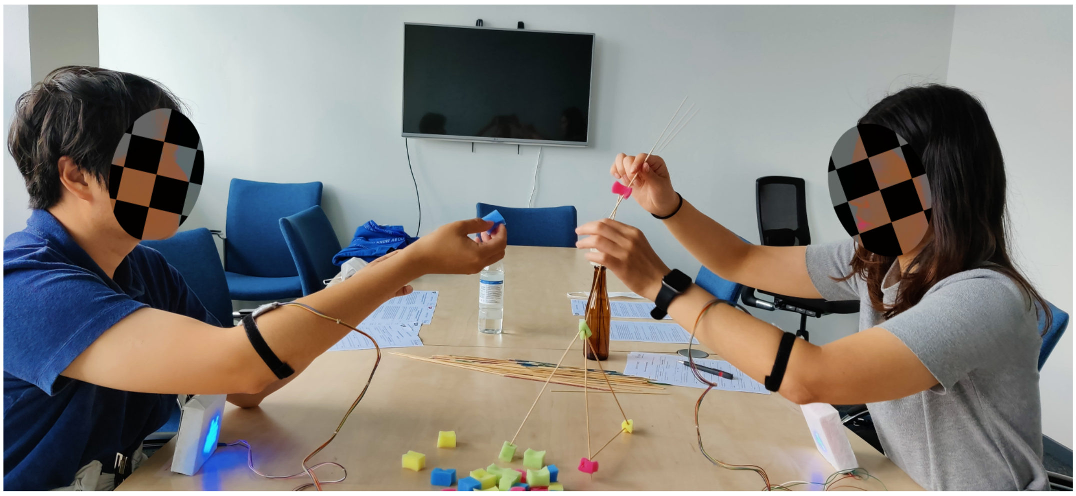

Figure 5.4: Participants playing high tower task

Music clip

For the fifth task, a music clip (Nature by John Ocean) was played. The music clip was selected for the soothing effect. Participants were requested to deliberately synchronise their breathing. They were encouraged to maintain eye contact, nevertheless they could also engage in conversation while synchronising their breath. This task lasted for 5 mins. Only the breathing data was recorded using the stretch sensors while all the actuators were turned off for this task.

5.3 Lab setup

The experiment was conducted in a room in TU Delft IDE department over the course of two weeks. The setup consisted of a control circuit comprising of two sets of microcontroller, sensors and actuators (visual and vibrotactile) which were connected to the laptop. Paper forms included the consent forms, instruction pamphlets which were filled at the start of the experiment along with the Network minds questionnaire and Comfort assessment form which were filled after every task. The real time breathing data was monitored throughout the experiment for each of the five selected conditions. The setup of the experiment is shown in figure 5.5.

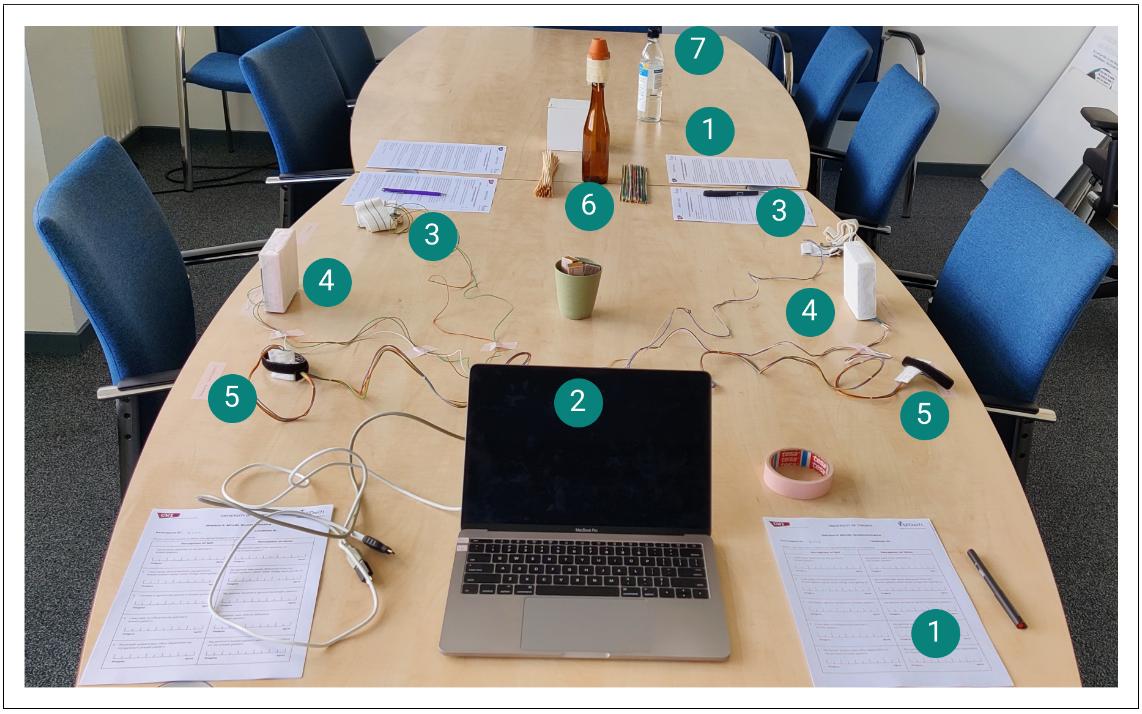

Figure 5.5: Experiment setup

The components of the experiment setup as numbered in figure 5.5 are as follows.

1. Networked minds questionnaire (NMQ) and Comfort assessment form(CAF)

2. Macbook Pro : 2 GHz Dual-Core Intel Core i5 Processor
3. Stretch Sensors
4. Visual Actuator Units
5. Vibrotactile Actuator Units
6. Task Materials
7. Sanitiser and wet wipes

5.4 Procedure

Participants were requested to reach the venue five minutes before the start of the experiment. Upon arrival, participants were welcomed and asked to read the instruction manual and sign the consent forms. During which they were also provided with the basic explanation of the experiment procedure. The participants were requested to be mindful of their own breathing as well as their partners breathing during the entire duration of the experiment. After the consent forms were collected, the participants put on the stretch sensor on the lower chest as well as the vibrotactile actuator on the forearm. Adjustments were made wherever required and the visual and vibrotactile actuator were calibrated for the participants. During this session, they got familiar with the visual and vibrotactile feedback. Any questions about the procedure were answered by the researcher. The main part of the experiment started once both the participants wore the setup. The experiment consisted of breathing data collection for five conditions starting with baseline data and ending with deliberate synchronisation of breathing data. The other conditions were randomised and counterbalanced. Each condition lasted for five minutes during which the participants performed tasks. There was a two minute break after each condition during which the participants were presented with a Networked minds questionnaire on a ten point Likert scale for feedback regarding attention to breath and effect of actuators. At the end of the experiment, they were provided with an additional Comfort assessment form on a twenty point Likert scale assessing the comfort and wearability of the setup. Once they filled out the comfort assessment form, the participants were asked to remove the setup. A semi structured interview was conducted with both the participants together to understand their experience of the overall experiment, task and the wearable setup. Both the participants were encouraged to give open feedback and elaborate on their experience of performing the tasks together. The entire semi structured interview was recorded. After the interview, each participant received a 10 euro voucher for their participation. If the participants had any questions of their own, then they were discussed. The entire experiment process was completed in sixty minutes. The process can be illustrated in the following figure 5.6.

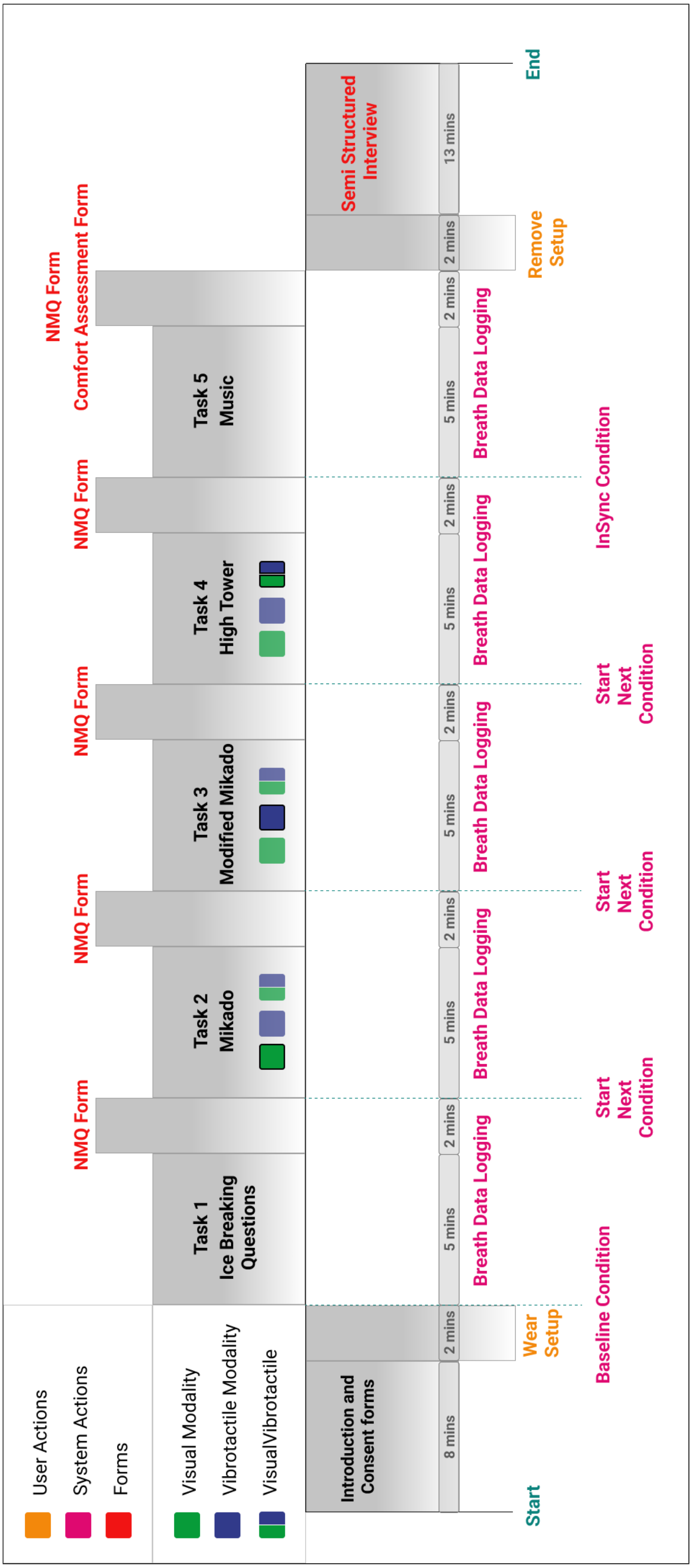

Figure 5.6: Experiment procedure

Chapter 6

Analysis

A total of fifteen experiments were conducted. Each experiment consisted of five conditions. The five conditions were Baseline, Visual, Vibrotactile, Visual-Vibrotactile and InSync. For each condition the breathing data of two participants was recorded simultaneously. To explore the data, the files can be found on Data Files.zip. The objective of the research question RQ1 (See 3.1) was to find the the effect of each modality on breath synchronization. To answer that question, the recorded data was analysed to find how many instances of breath synchronization occured for each of the conditions. Finally, to understand how the users perceived the visual and vibrotactile modality qualitative data was collected by using the networked minds questionnaire, comfort assessment form and semi structured interviews. The figure 6.1 below represents the analysis process to find the synchronization instances.

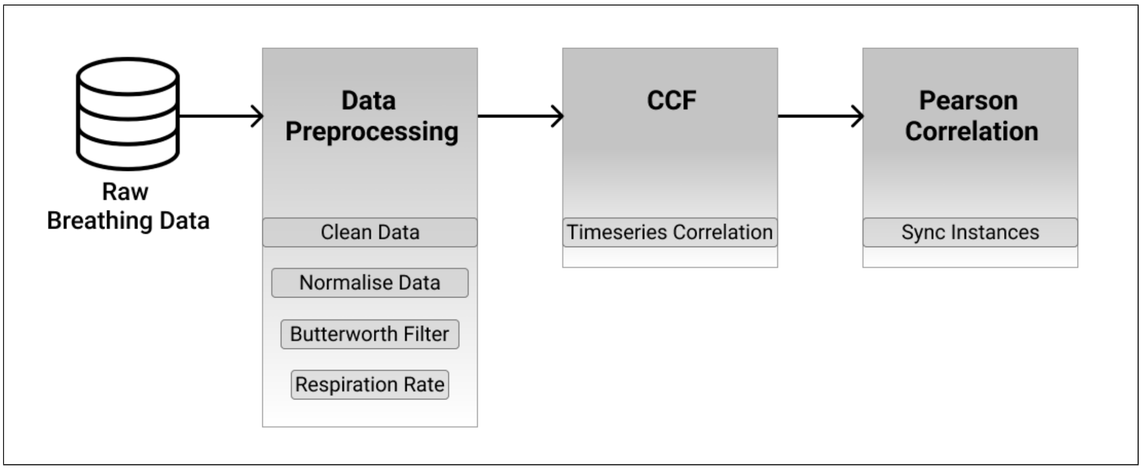

Figure 6.1: Analysis Process

6.1 Data preprocessing

The raw data is recorded with the sampling rate of 50 samples per second. Using Python's Neurokit [44] for the preprocessing of data, the raw data obtained from the sensor was cleaned, normalised and butterworth lowpass filter was applied to the data. Different methods were used to find the optimal way to get the clean data and find different breathing factors. Neurokit offers Khodadad and BioSPPy methods as filter parameters for physiological signals. Khodadad2018 [45] method was selected for signal preprocessing as it uses a fifth order low pass filter. It blocks out any high frequencies from the detected data. Thus it prevents physiologically implausible "overshoots" or "undershoots" in the y-direction. As any breathing signal is pretty consistent and seldom shows high peaks (intense inhale/exhale outliers), this method provided better results without losing out on the required peaks during calculation as seen in figure 6.2.

To find the synchronization in the raw breathing data, at first different breathing factors were calculated. Respiration rate, amplitude and phase were calculated for each of the experiments for user 1 and user 2.

Out of these three factors, respiration rate was selected to be the

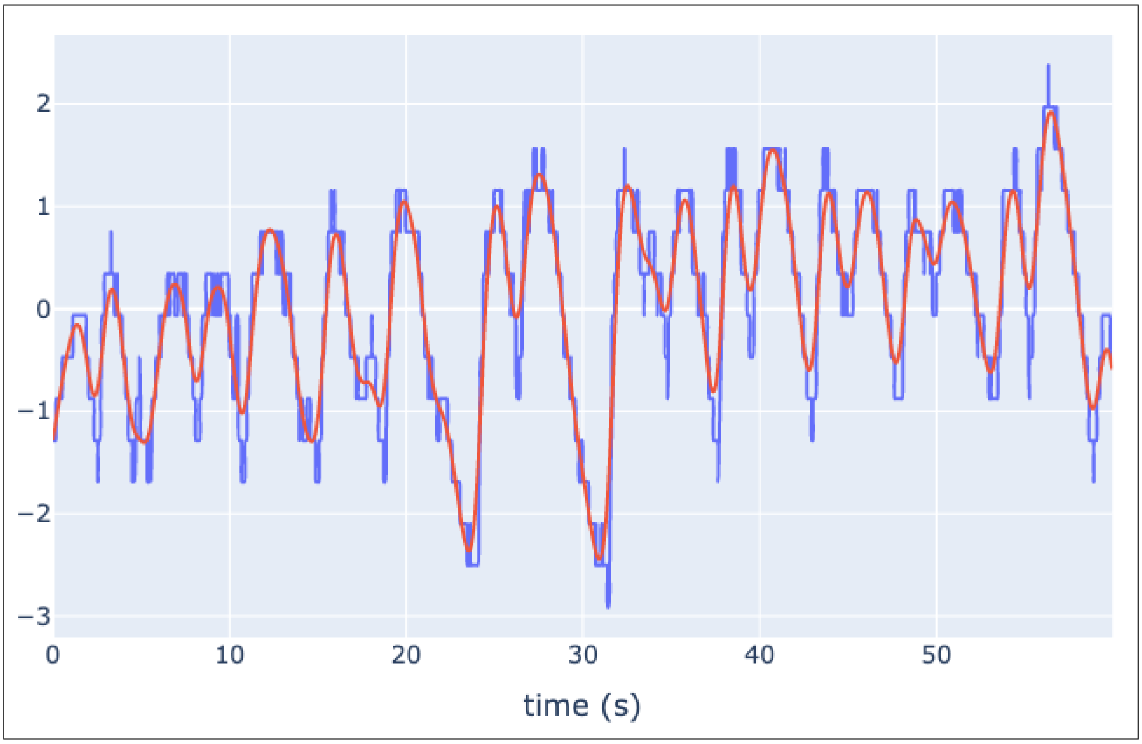

Figure 6.2: Normalised breathing data

factor of concern. Phase was not considered as the user could be breathing along with the interacting partner, although at their own respiratory rates. In phase, where both the partners inhale and exhale together or anti-phase, where one partner exhales while the other inhales. Amplitude was not considered as it highly dependent on the tension created on the stretch sensor. Although the facility of belt adjustment (See 4.11) was provided, it was for the comfort of the wearing the stretch sensor throughout the experiment. Respiration rate is calculated between successive respiratory inhalations. This provides better understanding of synchronization from how fast/slow the users are voluntarily or involuntarily breathing to match each other's breathing patterns.

The respiration rate signals of user 1 and user 2 were then plotted onto graphs to further analyse the data, as seen in figure 6.3.

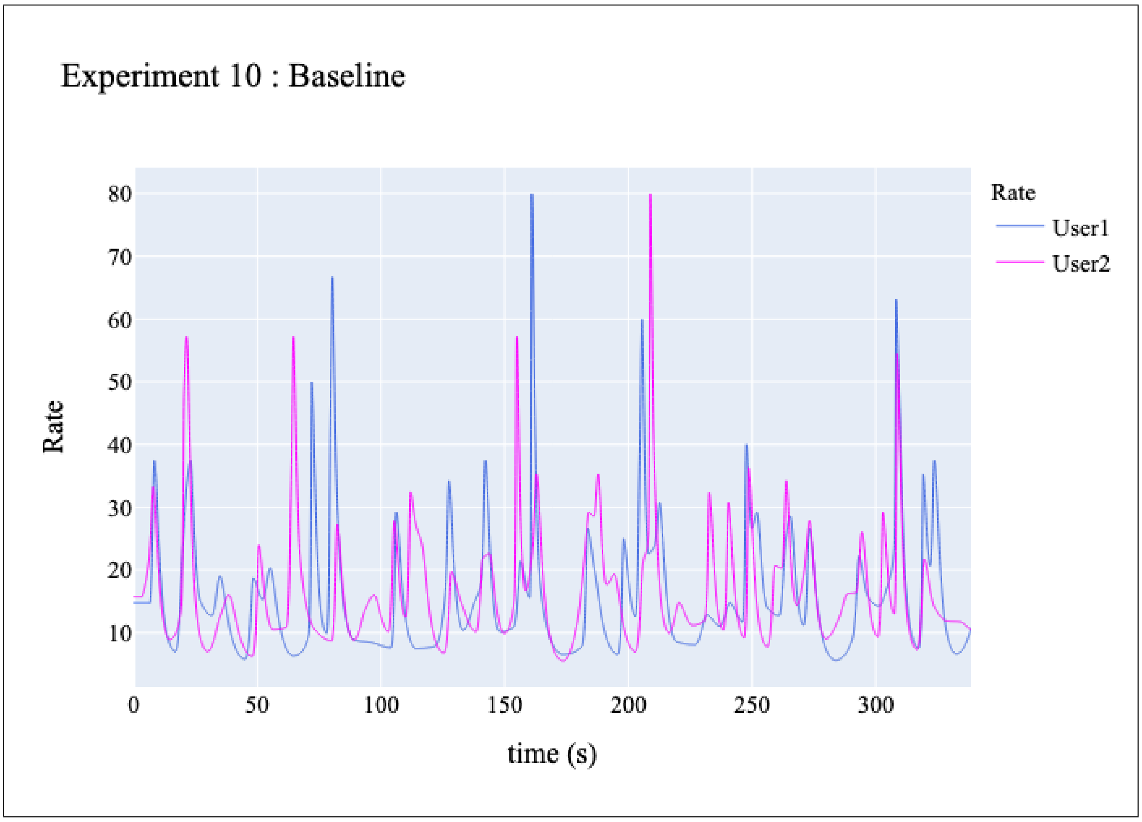

Figure 6.3: Experiment 10 : respiration rate of user 1 and user 2 for baseline condition

6.2 Quantitative analysis and results

Analysis process

To find synchronization, firstly a cross correlation factor(CCF) was calculated from the two data streams for each experiment for all five conditions. As a measurement that tracks the movements of two or more sets of time series data relative to one another, The CCF between user 1 and user 2 respiration rate data signals showcased the movement of two time series data to objectively determined how well the signals matched up with each other.

In the table 6.1 below, the CCF range values for all five conditions can be seen.

Condition	Lowest value	Highest value
Baseline	$>$ -0.2	0.2 $<$
Visual	$>$ -0.1	0.1 $<$
Vibrotactile	$>$ -0.15	0.15 $<$
VisualVibro	$>$ -0.15	0.25 $<$
InSync	$>$ -0.2	0.4 $<$

Table 6.1: CCF Value ranges for all five conditions

The CCF plots of all experiments for five conditions can be seen in *CCFPlots.pdf*.

Taking the example of Experiment 4 for InSync condition as a representation for the data analysis The CCF graph for the InSync condition for all experiments can be seen in figure 6.4 below. In the figure below, it can be observed that the CCF value attained ranges from $>$-0.2 to 0.4$<$. The highest CCF value of *0.45* can be seen in Experiment 4, which shows that synchronization occured in Insync condition of Experiment 4.

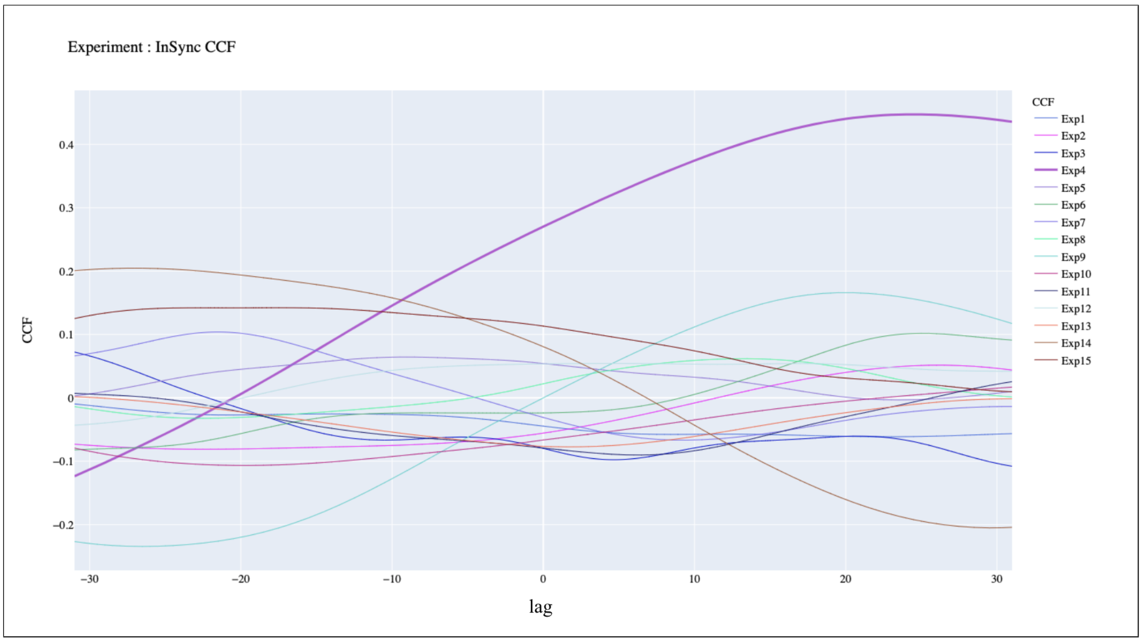

Figure 6.4: InSync condition : All experiments CCF

After CCF calculation, the Pearson correlation coefficient was calculated for each of the modality using a rolling window of 250 samples. Upon examining the graphs for respiration rate, there was visible synchronization seen by the naked eye. The Pearson correlation is showcased for all the data points in light green, whereas the moderate correlation $R >= 0.5$ is showcased in medium green and high correlation instances $R >= 0.8$ are showcased in dark green. Taking the example of Experiment 4, InSync Condition as seen in figure 6.5 below. It can be observed that there was definite synchronization during time *1600-1680*. There is a brief drop in synchronization where the users start breathing in anti phase during *1635-1655* which can be seen in the respiration rate graph and more prominently in the Pearson correlation graph. An interesting result of the study shows that the

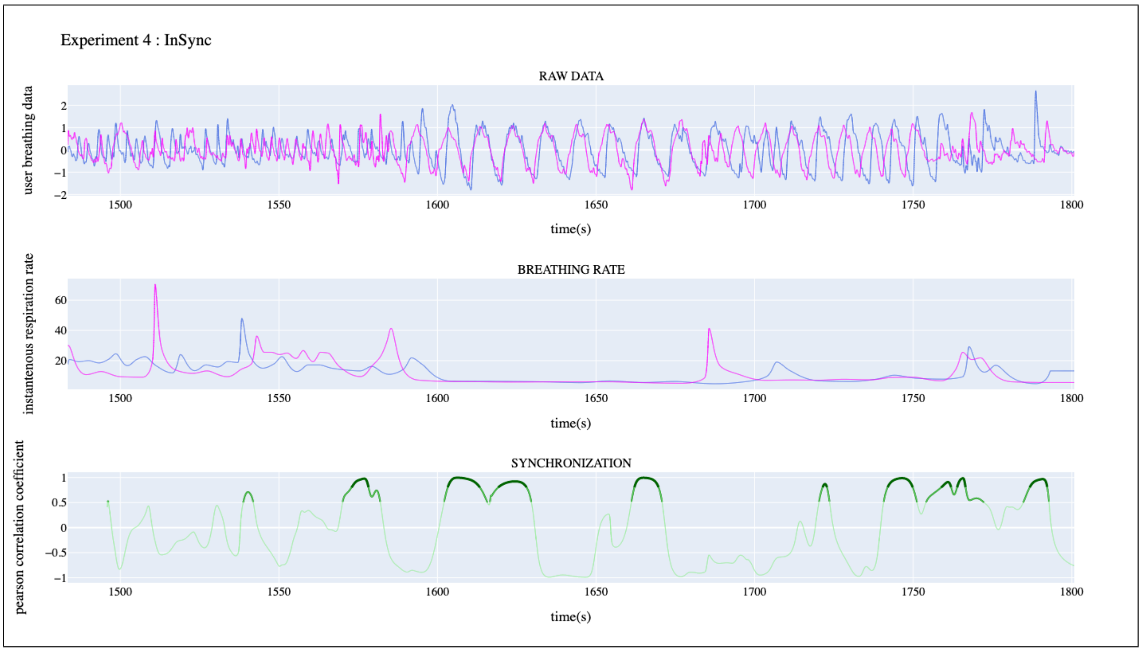

Figure 6.5: Experiment 4 :InSync condition Pearson Correlation

instance of maximum synchronization for InSync condition between a pair of participants(Experiment 4) occurred in the only female-female participant pair of the study. The other pairs were male-female or male-male. This provides further scope to explore how different gendered combinations interact with each other in a social space.

Results

After calculating Pearson correlation of all experiments for each modality, the resulting correlation (R) is divided into moderate and high correlation durations and plotted on a graph. For each modality, the total time duration for synchronization was calculated as follows. (Moderate) $tSync = \sum(Ry(t) - Rx(t))$ where Ry(t) and Rx(t) are timestamps of curve where $R >= 0.5$. (See figure 6.6)

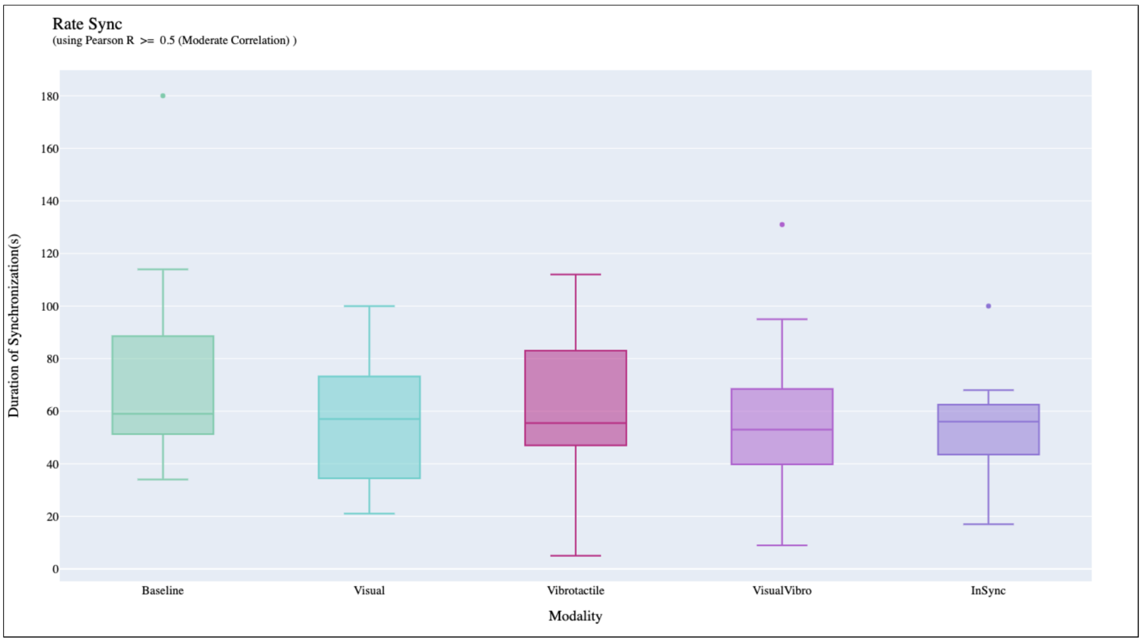

Figure 6.6: Synchronization : Moderate correlation

Whereas for the High correlation, (High) $tSync = \sum(Ry(t) - Rx(t))$ where Ry(t) and Rx(t) are timestamps of curve where $R >= 0.8$.(See figure 6.7

The median Value scores for can be seen in the table below.

The rolling window Pearson correlation coefficient for the high correlation showed that vibrotactile modality showed the highest instances of synchronisation followed by visual-vibro and then visual modality.

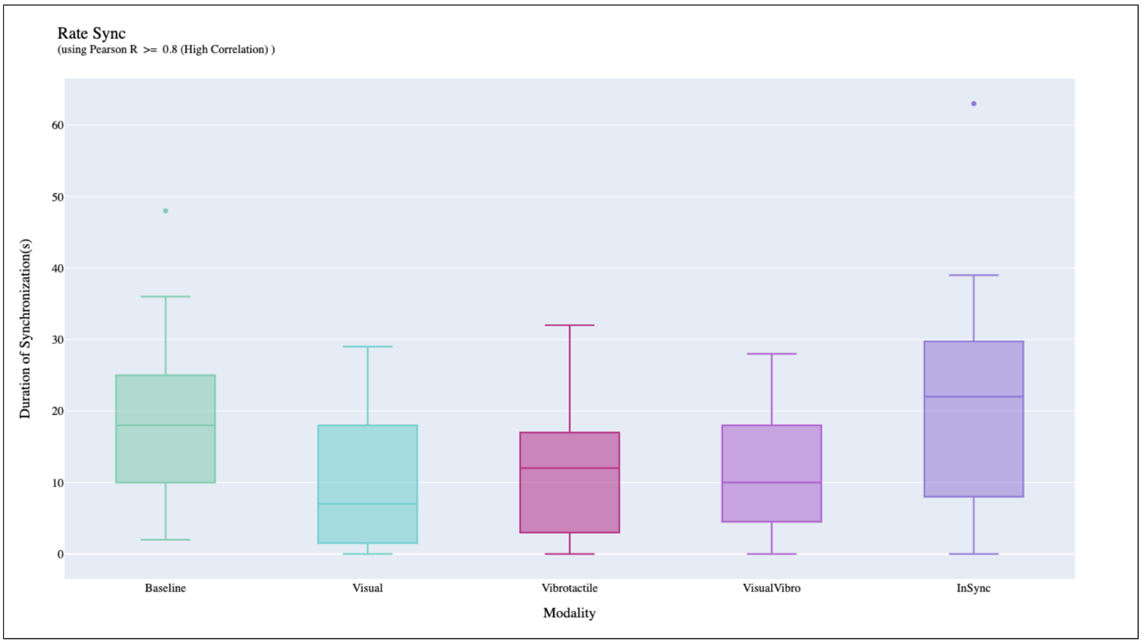

Figure 6.7: Synchronization : High correlation

PCorr	Baseline	Visual	Vibro	VisualVibro	InSync
RR Moderate	59	57	55.5	53	56
RR High	18	7	12	10	22

Table 6.2: Mean values of Pearson correlation for respiratory rate

As expected, the InSync condition has the highest synchronization, although no modality was used in the last task. Through Quantitative analysis we see that the vibrotactile modality is the one which shows maximum instances of definite synchronisation.

6.3 Qualitative analysis and results

During the semi structured interviews, the users provided their thoughts on the wearable device and their preferred modality for sharing breathing patterns. All the interviews can be seen in *FinalInterviews.pdf*. The participant IDs are named as P followed by (Experiment No) followed by user ID(User1 - 001, User 2-002). Using the Networked minds questionnaire along with the empirical data found through semi structured interviews, conclusions regarding the preference of modalities for breath sharing and synchronization can be seen as follows.

Networked minds questionnaire

After each task was completed, the participants answered Networked minds questionnaire B.1 on a ten point Likert scale. The participants answered the questions for the perception of their own breathing pattern and how they perceived their interacting partner was reacting regarding the sub-scales of Close attention, Distraction, Ignorance, Influence, and Dependence.

Close Attention

Perception of Self : *I paid close attention to my partner's breath pattern.*
Perception of Other : *My partner paid close attention to my breath pattern.*
Most of the users preferred the visual modality to understand their interacting partner's breathing pattern. While to showcase their own breathing pattern to their partner, the vibrotactile modality is preferred followed by the visual modality.

The semi structured interviews provided similar insights. Users became more aware of their breathing pattern.

P1002 : "Normally I don't do heavy breathing, But looking at the visual actuator I did take some heavy breaths. Understanding I could see my partners breathing and that he could see my own, I wanted to emphasise my breathing more prominently. "

P4002 : "For me, I was much more aware with the visual actuator, rather than the vibrational actuator...."

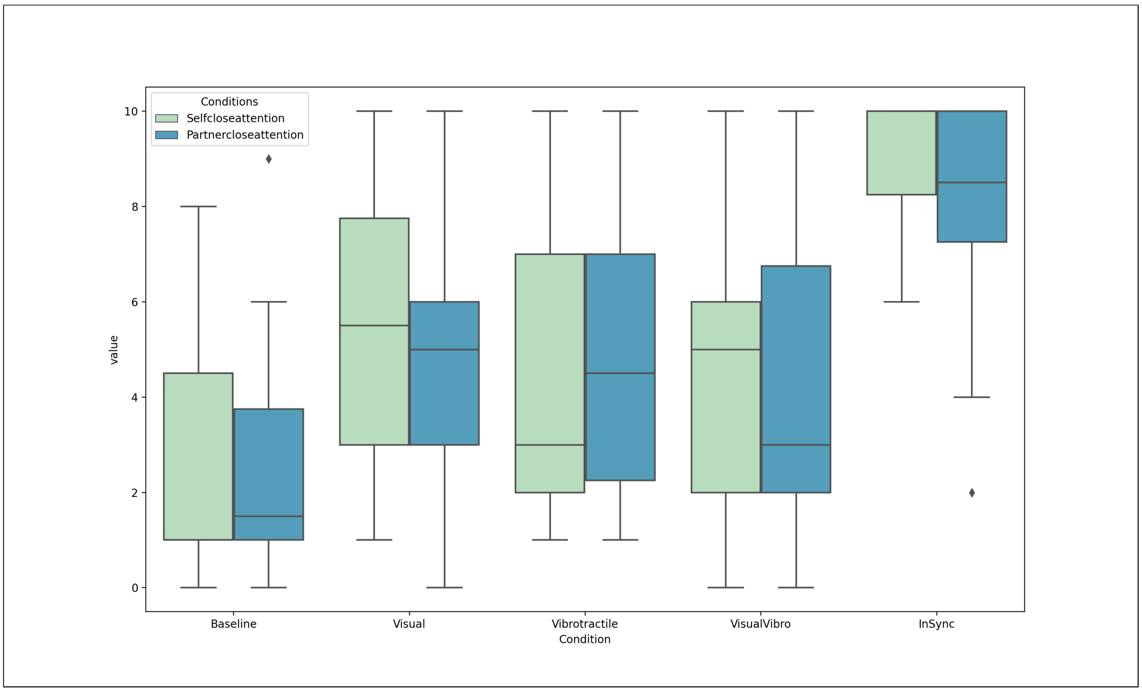

Figure 6.8: NMQ : Close attention

Distraction

Perception of Self : *I was easily distracted from my partner's breath pattern when other things were going on.*
Perception of Other : *My partner was easily distracted from my breath pattern when other things were going on.*
The vibrotactile modality proved to be distracting at first till the users got used to the feeling. While the users were trying to focus on their tasks, they preferred to focus more on the visual modality and body displacement.

P7001: "For the vibration one, for 2 sec I was a bit startled when the vibrations started and once I got used to it, it was fine." P9002 : "... I didn't feel the haptic was distracting either. Like the first time it started I did feel it, although later it was just going on in the background. Because I was not focusing on it. Maybe it was distracting so I just blocked it out. I was focusing more on the visual and his body language."

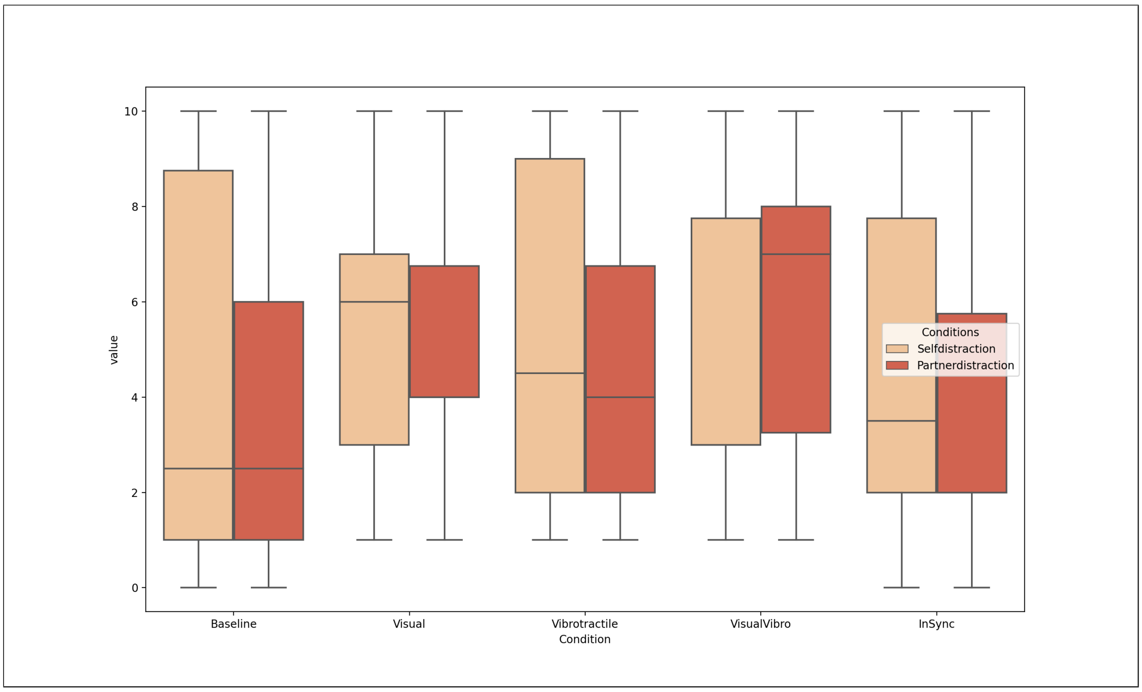

Figure 6.9: NMQ : Distraction

Ignorance

Perception of Self : *I tended to ignore my partner's breath pattern.*
Perception of Other : *My partner tended to ignore my breath pattern.*
On average, the visual modality was more ignored than the vibrotactile modality. Most of the users mentioned that ignored the breathing patterns as they were focused more on performing the tasks. *P11001 : "I tried noticing if his breath was synchronising, but as the tasks went on I focused more on the tasks themselves...." P13001: "Nothing substantial related to her breathing pattern. When we were focusing on the task, the whole attention was for the task."*

Influence

Perception of Self : *I was able to influence my partner's breath pattern.*
Perception of Other : *My partner was able to influence my breath pattern.*
Users found it easier to be influenced by their interacting partner's breathing pattern with the visual modality. They were better able to

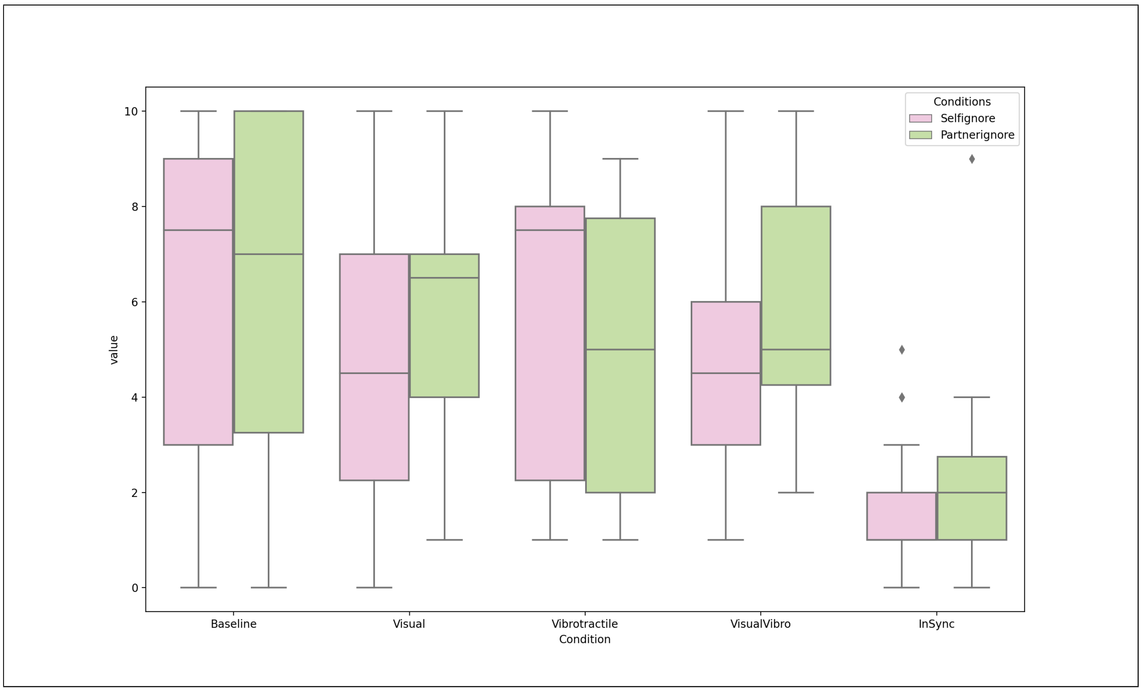

Figure 6.10: NMQ : Ignorance

influence their interacting partner's breathing pattern using the vibrotactile modality. When visual and vibrotactile modality were used together, the user were influenced by their partner's breathing pattern. Users preferred to change their own breathing pattern to match with their partners rather than deliberately trying to influence their interacting partner's breathing pattern.

P2002 : "Yeah, I consciously tried to match with it, so that we would get on the same cycle. For that last one. And also for the stick dropping into the bottle one(Task 3). "

P15002 : "I wouldn't say I was influenced because we definitely have different breathing patterns but it was easy to change my breathing pattern. It's just holding my breath for a few seconds longer than I would have normally done."

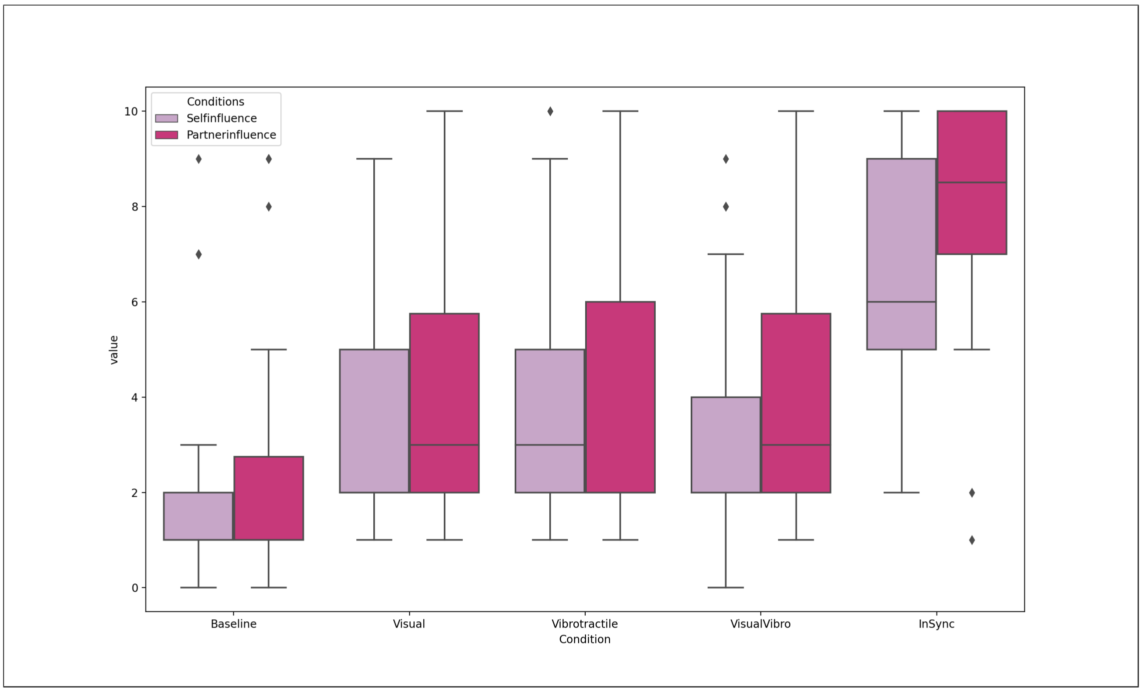

Figure 6.11: NMQ : Influence

Dependence

Perception of Self : *My breath pattern was often dependent on my partner's breath pattern.*
Perception of Other : *My partner's breath pattern was often dependent on my breath pattern.*
The users deliberately made efforts to change their own breathing patterns to match with their interacting partner's breathiong pattern to achieve the common goal of completing the task. *P13002 : "I was trying to sync with him.Like if he took a long breath, I observed that he's exhaling now and in some seconds he is going to be inhaling so even I inhaled at that moment." P10001 : "Yeah I did. It was hard though. Because it sounds weird, but I breathe differently. He takes really long breaths and I take fast and shallow breaths, so I was breathless."*

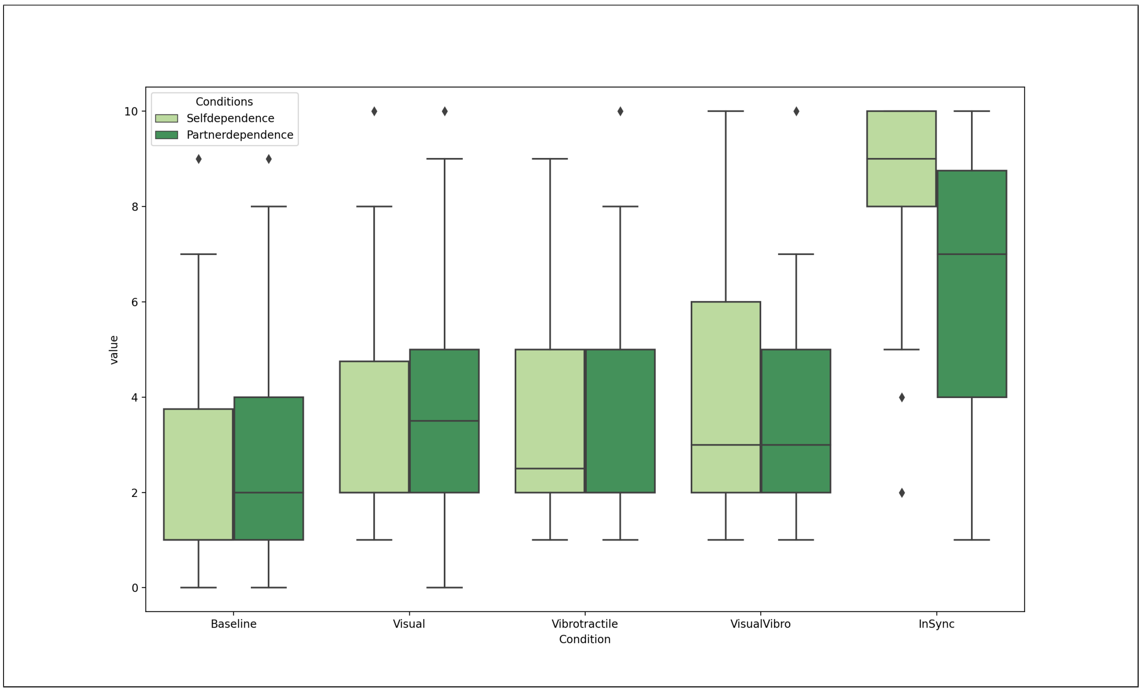

Figure 6.12: NMQ : Dependence

Comfort assessment

After the experiment users were asked to fill out a comfort assessment form [46] (See Appendix B.2) on the wearability of the device on factors of Emotion, Attachment, Harm, Perceived Change, and Anxiety. Users were comfortable and receptive of the wearable device. As seen on the Likert scale, the consensus is low for Emotion, Harm and Anxiety. Users did perceive the device to feel strange as seen in the Perceived change section. This provides more scope for improvement on the wearability of the device. The result of which can be seen in the figure 6.13 below.

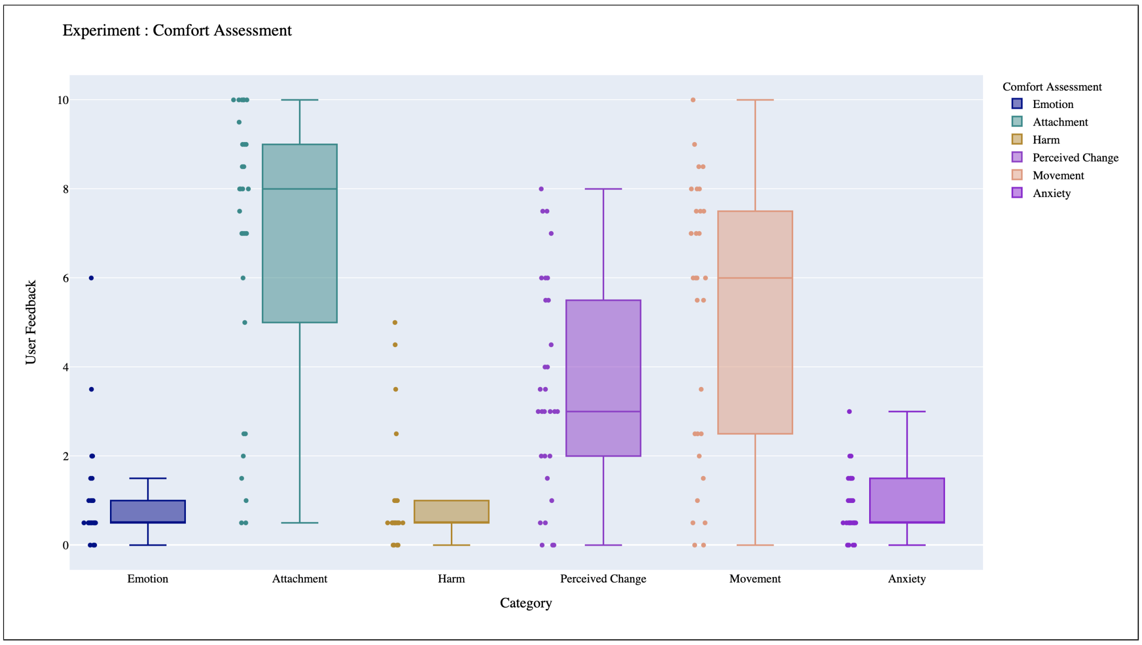

Figure 6.13: Comfort assessment results

Semi structured interviews

Connectedness

Most of the participants expressed feeling more intimate and connected with their interacting partner by understanding their breathing patterns.

P12002 : "I agree, it's more information and you can understand people better with breathing. It's more intimate. You are more aware of their existence and their breathing. "

P5001 : "Actually, normally I can hear his heartbeat as well. So both his heartbeat and breathing. If I can catch some irregular pattern or some strange sound(like while he is sleeping), I quickly catch that. I think it's a signal of our existence. . . "

P2001 : "the vibrational actuator was quite comforting to some extent. It would have been weird if he was actually breathing on my body, but because it was just actuation it felt good. Especially with COVID, and knowing there is somebody who is breathing and who is connected it's nice."

Privacy and Intrusion Concerns

Many users mentioned that they would not be comfortable with sharing their breathing pattern with others unless other people share their breathing data as well. Users would feel much more comfortable sharing data with close friends than with acquaintances or strangers.

P15001 : "I can share it with my close friends and family, with whom I would be comfortable being vulnerable. I think it would also matter if they are doing the same. I don't want to be the only person sharing *my data and being vulnerable."*

P9002 : "For me, it feels like personal data, like a violation of privacy for that matter. I feel vulnerable when people can see my data. Feels like a breach of privacy, maybe it's not. Maybe just because it's very new that it feels that way. Once it becomes normal then I think it'll be fine. But just because it's not there yet, that change is what scares me. "

P5001 : "I mean any relationship has to be beyond wearable tech, that's only when it makes sense. What's the use of using crutches to develop a relationship? For professional purposes yes, but not for personal relations. Because you explore aspects of happiness and fights."

P13001: "I wouldn't wear it. For me, it is just too much tech on your body. I wouldn't prefer anything which overly analyses any senses of my body. It could be heartbeats or breathing, but I would not prefer that. "

Normalised sharing of physiological data

Users are open to using this type of a wearable device albeit in the future when wearing such a device is normalised.

P9001 : "On a personal front, I don't think I would like to wear it. But if it becomes normalized and you can see everyone's breathing data then it'll be easier to understand the vibe of the room as well. If people are excited or if they are in a sad mood. I could sense the mood before I start interacting with them, and then I can act accordingly. "

P6001 : It needs to be normalised first and I will need some kind of *training to interpret the data. Data just by itself is kind of useless until it is in a refined form or we can extract the results. Let's say if you tell someone that your blood pressure is 120/80, it is just numbers for that person. If you don't have the knowledge that 120/80 is normal then this refined form of data is useless for him. The refined form of data must also be interpreted in such a way that the meaning of it can be understood."*

Feeling conscious

Users mentioned that they would feel exposed as breathing data is very private and intimate.

P6001 : "For a healthy person it would be fine. But for an unhealthy person, not everyone would be okay with sharing their breathing data with everyone. Let's say if the data is drastically different from the normal person then someone can know that this person has asthma or some other health issue."

P11001 : "I wouldn't want that. Let's say I climb stairs and start breathing heavily. If a person is close to me they'll question why I'm breathing so hard. Even if physically it makes sense,I'm still embarrassed. So even if physically I can do heavy activity and I might do it well, I still wouldn't want someone to see how heavy my breathing is. "

12001 : "I would definitely want to know how other people are feeling but I would not want to show how I am feeling. Sometimes it's nice to be reserved. When you go into a room and you are super tense then I really wouldn't want the other person to know that."

P15001 : " I think I would be more mindful of my breathing if I knew that it is being showcased. I wouldn't like sharing my breathing data all the time though. It's sort of performative right, Like when we are *clicking pictures or videos, we take extra care of how we look. ”*

Possible Use case Scenarios

The users could think of various scenarios in which such a wearable device could be helpful.

P13002 : ”If this can turn into an application for security or lie detection or something like that. Or for old people who stay in nursing homes, this could help with their regular checkups or monitoring their health, then it’ll be interesting. ”

P8002 : ”I was thinking about a pregnancy scenario where the nurse tells the woman to calm down and breathe with her.... Another thing about the actuators, that instead of a visual actuator, an audio one can be helpful. Because in a medical or clinical setting the beep sounds are pretty normal. Like in a surgery, the audio is more common, not the vibrational one. In a surgery the doctor cannot wear this kind of thing on the hand. But the audio can help.

P12002 : ”It would be useful in Poker though! Haha”

6.4 Discussion

In this chapter, the research results are discussed and contextualized with the research questions (See section 3.1) and the idea that inspired this work: accentuating breathing patterns through visual and haptic modality to facilitate breathing synchronization in a colocated social interaction.

Challenges for showcasing real time breathing patterns

Breath sensing

A feasible way of sensing breathing over a prolonged periods of time that would not feel intrusive or uncomfortable. The placement of stretch sensor must be tight enough for it to detect the change in resistance and yet not too tight for it to be uncomfortable.

Processing speed

Showcasing breathing patterns can be achieved by using micro controllers, although to process the breathing synchronization in real time and showcasing it on different actuators will need powerful processing speed. The lag in the system showcasing the occurrence of synchronization will make users feel that the system is not responsive.

User training

The breathing pattern change on visual modality is easy to decipher, but users will need to get acquainted with vibrotactile actuation of different breathing patterns. The breathing data needs to be quantifiable and actionable for users to engage with the wearable device. The device would be too cumbersome to wear for prolonged periods of time if used only for monitoring purposes.

Calibration

Every individual has a unique breathing pattern. Breathing pattern is a physiological signal that cannot be standardized as it can lead to hazardous consequences. The device will still need to be calibrated to showcase some standard form of long/short/normal breaths. The device will have to be calibrated depending on the needs of users i.e sportsman, asthma patient, mental health patient.

Limitations of the study

Processing Algorithm

In the wearable device that has been created the synchronised breathing pattern was not showcased back to the users due to the processing speed. Even if the facility was provided not all the participants reached and maintained a synchronized state in which they could actually see that they are synchronized. A faster and more efficient algorithm can be developed to match the real time breathing rate of synchronization.

Sample size

The study was conducted with a small sample size with different relationships in a narrow age bracket. Most of the users were students hence different relationship types such as mentor-student, doctor-patient, family members etc was not explored. Majority of the pairs were male-female pairs, with only a single pair being female-female. The future scope allows various exploration avenues to understand how people interact with each other in social settings.

Ethics

If there is a reason for technology detox then it should be a complete and total detox. If we reach a stage in which we need to rely on technology to understand other people's emotions, or the ones close to us, then the essence of human connection will be lost.

If we approach everything from a perspective to quantify and monetize even our most mundane physiological functions, then we will be living in a truly dystopian world. While formulating the research question, most of the question I came up with started with a *WHAT* and a *HOW*. That is how engineers and designers are trained to think. Thinking about the *WHY* made me realise the pitfalls and the benefits of the wearable for breathing synchronization. The need for such a wearable would not have generated if humans had less distractions which led them to ignore their colocated peers. But all technological developments come at a cost.

In today's day and age when there is an information overload from all information and communication technologies, which in turn is the cause of anxiety. The need to connect to others to relieve that anxiety thus becomes a *circular problem*. To give a solution which uses technology to add in more information to the users about their own breathing pattern which in turn can cause more anxiety. The need to create this device seems imminent, although using technology to combat a problem primarily created by technology seems futile. Due to the technological advancement in our hands, and the ability and inspiration to create more and more new things which will help us understand each other, it becomes easy to find the *HOW* of any question, but I don't think anybody wants to focus on the *WHY*. Asking *WHY* seems like looking at the power of current technological advancement in a cynical light.

The sole reason to use a breath synchronization device shows enough incentive and intention to connect with others. And if the intention and incentive is present, the use of such a device becomes redundant. But the cost of distractions and attention demand is too high. By empowering ourselves with technology we are simultaneously debilitating our ability to connect with each other using the sophisticated system that human evolution has equipped us with.

Breathing is an activity which is largely ignored by our brains. The reason why the human body has evolved to not notice the mundane processes such as heart rate and breathing is to make sure that we do have enough brain processing left to experience and work with the other stimuli that the world will throw at us. But if the mundane regular processes such as breathing are brought to the point where they are noticeable at all times, and not just our own but of the others as well, we will tend to lose our minds because it will just be another information to process.

Applications

As mentioned in the ethics paragraphs, the need and intention to synchronise with someone who has a close relationship with you gives you enough incentive to not use technology. Although there can be instances, when you do not possess any particular close relation with the person yet you do have an incentive to synchronise your breath with.

Therapy

For instance in the case of therapy. The application for this type of research can be further used to create devices which help therapists understand how the breathing patterns of their patients differ for which type of incident that they are narrating. Along with helping the therapists create and influence breathing patterns for the patients, this device can also help them remain calm and maintain that calmness.

Sports

Another application that can be used for this type of wearable is in sports. Where the breathing pattern to gain the maximum output from a player can be used in training when the coach will be able to view and manipulate the players breathing pattern to make sure that the optimum level of output is being achieved by the players.

Yoga and Meditation

Breathing synchronisation can also be used to teach yoga. Each and every asana is accompanied by a particular type of breathing exercise that has been done to achieve the maximum benefits of the particular asana. The yoga teachers can guide their students better while emphasising on how deep they should breath, when they should inhale/exhale and hold their breath for each position. Along with performative yoga, guided meditations can be conducted using this device for mindful breathing and to feel connected with peers.

Miscellenous

Other applications would be in scenarios where strangers are meeting for the first time, although they do have an incentive to connect. For instance dates, job interviews, or working together for any common goal (projects, collaborations, etc.). This will help them connect with each other faster. For eg: calming an interviewee before starting the interview, understanding if your date is into you and take a call if you should invest more of your time if they are not.

Chapter 7

Conclusions and recommendations

7.1 Conclusion

What is the effect of visual and vibrotactile modalities in facilitating breath synchronisation in a colocated social interaction?
The results show that to understand someone's breathing pattern, the visual modality is better and preferred by the participants, whereas to affect someone's breathing pattern or change one's own breathing pattern to synchronise with others, the vibrotactile modality is preferred. Considering the need for showcasing breathing data, the consensus is that there must be quantifiable and actionable way of understanding breathing data as the context with which breathing data is portrayed will largely affect if someone wants to synchronise or not.

How to design wearable on-body visual and vibrotactile displays that can accurately represent human breathing for facilitating breathing synchronisation?
This research showcases one way of facilitating breathing synchronization using visual and vibrotactile modalities. Further research can be made with better strategies in detecting breathing data in real time and showcasing the same with different modalities.

7.2 Recommendations

Although this was a modest attempt at understanding which modality leads to maximum breathing synchronisation between interacting partners; to further emphasise the breathing pattern of another person onto one's body to achieve maximum breathing synchronisation between interacting partners, different other modalities for haptic and visual feedback can be further experimented. Further research into haptic feedback such as using pressure, temperature, and movement can be used to explore which leads to an easier path to breathing synchronisation. Whereas for visual feedback, exploration in colour, brightness, and patterns can be experimented with. A more robust wearable device can be created to understand how the breathing pattern can be influenced. Once the preferred modality is understood which can actually influence a person subconsciously, a computer generated pattern, or synchronisation with a remote person can be created. Although the complexity in processing all the data when we are not even focusing on our own interoception may cause debilitating effects on the brain, it is definitely a good way to explore how we can use these types of devices to influence somebody positively. Further research can be performed in how the breath synchronisation can be used to manipulate emotions. I.e make someone calm or agitate them.

The most obvious future scope would be to use this wearable in remote conditions.

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Appendix A

Information about Experiment

CWI Centrum Wiskunde & Informatica   UNIVERSITY OF TWENTE.   TU Delft Delft University of Technology

Consent Form for "Wearable Visual and Vibrotactile Displays for Collocated Breathing Synchronisation"

Please tick the appropriate boxes	Yes	No
Taking part in the study		
I have read and understood the study information dated [__/07/2021], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
I understand that taking part in the study involves getting my breathing data collected, being photographed, and audio recorded for the exit interview. After the study, I consent to completing the relevant questionnaire and exit interview. The audio recordings of the interview will be transcribed into text and the recording would be destroyed. The text will be used to analyse breathing biofeedback. Any identifying information iof the participants in the video recordings would be blurred. The information will only be communicated between the research group. When the files involving people are used in a report, paper or presentation, the person would be blurred in advance.	☐	☐
Risks associated with participating in the study		
I understand that taking part in the study involves the following risks: Mild discomfort while experiencing visual and/or vibrotactile stimulus, Mild discomfort while using the stretch sensor.	☐	☐
I understand that all equipment is disinfected before use and I agree to follow required COVID guidelines	☐	☐
Use of the information in the study		
I understand that information I provide will be used to analyse breathing biofeedback. The information will only be communication between the research group. When the files involving people are used in a report, paper or presentation, the person would be blurred in advance.	☐	☐
I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team.	☐	☐
I agree that my information can be quoted in research outputs	☐	☐
I agree that my real name can be used for quotes	☐	☐
Future use and reuse of the information by others		
I give permission for the data(gender, age, general health, breathing biofeedback) that I provide to be archived in TU Delft repository so it can be used for future research and learning. I understand that the questionnaire and exit interview data provided by me will be anonymised.	☐	☐
I give the researchers permission to keep my contact information and to contact me for future research projects.	☐	☐

________________ Name of participant   ________________ Signature   ________ Date

Figure A.1: Consent Form

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Information Sheet for "Wearable Visual and Vibrotactile Displays for Collocated Breathing Synchronisation "

Purpose of the study
The purpose of this study is to evaluate the effects of visual and vibrotactile modalities on breathing synchronisation between a pair of friends/companions in a collocated setting. We will investigate the relation between the modalities and change in breathing pattern of the participants. The findings will be used for a thesis project exploring the use of different modalities to facilitate breathing synchronisation. The project is under the supervision of experts from TU Delft, Centrum Wiskunde & Informatica and University of Twente. The study will be conducted in the form of a controlled experiment.

Benefits and Risks of Participating
Your participation will contribute to the knowledge regarding breathing biofeedback, specifically effect of visual and vibrotactile modality on breathing synchronization between a dyad.The knowledge will support future breathing synchronisation designs and research.

In this study you might feel slight discomfort while experiencing the visual and/or vibrotactile stimulus. You might also feel slight discomfort while using the stretch sensor. To minimize the discomfort, we strongly suggest you follow the instructions of the researcher as we need you to be comfortable to provide us with a normal breathing feedback.

Since the participation is during the COVID period, the study will take place only when you, your friend and the researcher are in healthy states. Each component used in the study will be disinfected before being used. You need to wear a face mask during the participation and wash hands/use sanitizer before the participation. In addition you need to follow the rules and regualtions of the local government.

Data Usage
During the study, your basic data (gender, age, general health) will be collected. Breathing biofeedback will be collected with the help of sensors. The data will be used for analysis by the student researcher. Only the research group can get access to your data.

Text regarding your gender, age, general health, along with video and biofeedback data will be stored in a local hard drive and TU Delft storage. Only the research team is authorised to this data. The raw data will be kept for atleast 3 years after the graduation of the primary researcher. Some pictures, text, videos might be used in report, paper, presentation or portfolio purposes in which case your figure would be blurred in advance(if you choose to do so)

Procedure for withdrawal from the study
You are free to withdraw from the study at any point. If you wish to withdraw your participation from the study, you can email the student researcher anytime before the end of the study.

In case you want to see the result of your experiment, you can refer to the student researcher for access.

Contact Details
Shalvi Palande - Student Researcher
s.r.palande@student.utwente.nl

Prof. Dr. Ir. Jansen K.M.B - Professor, Faculty of IDE
k.m.b.jansen@tudelft.nl

Figure A.2: Information Sheet

Appendix B

Questionnaires

CWI
Centrum Wiskunde & Informatica

UNIVERSITY OF TWENTE.

TU Delft
Delft University of Technology

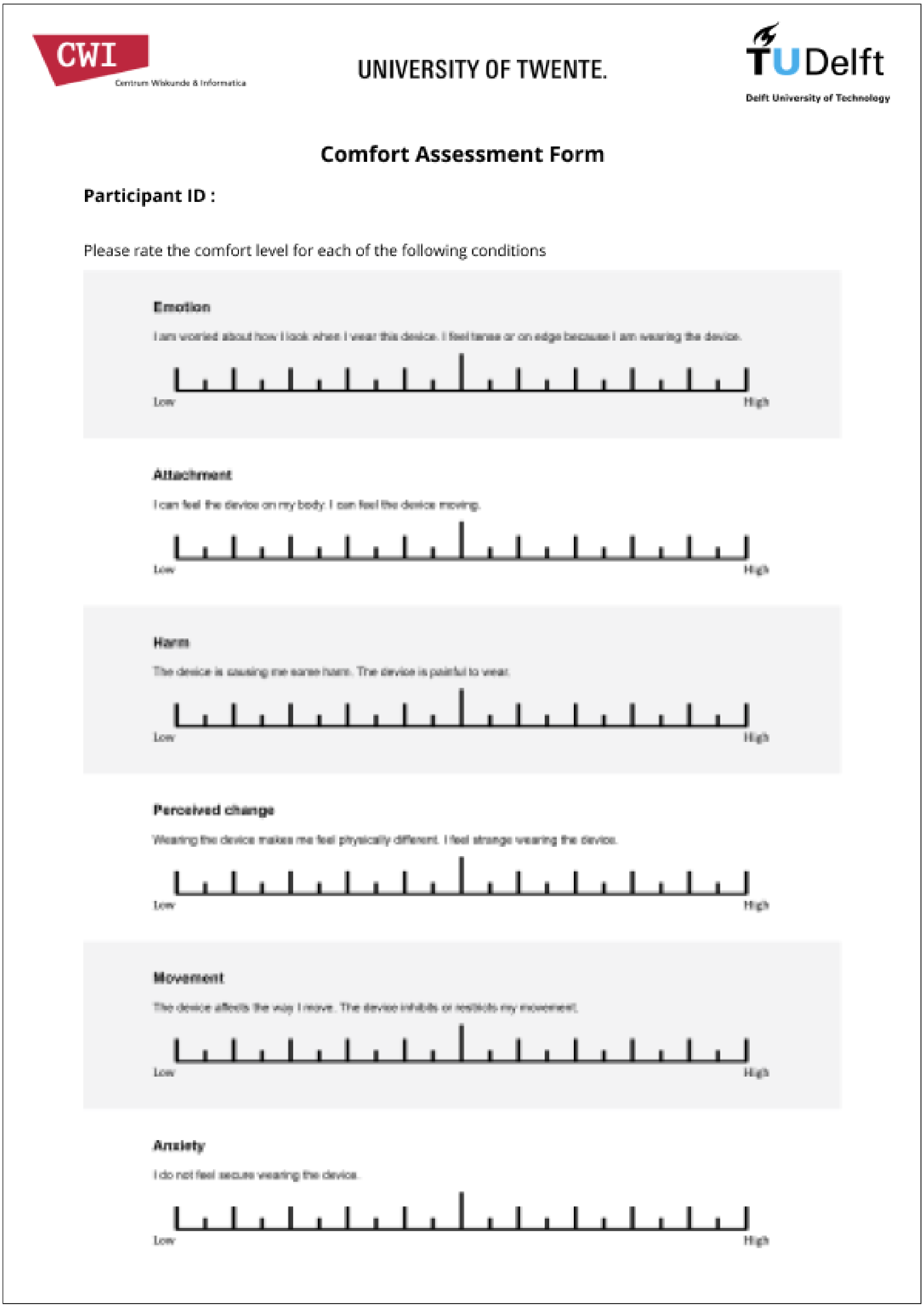
Network Minds Questionnaire

Participant ID : **Condition ID :**

Please rate the extent to which you agree/disagree with the following

Perception of Self	Perception of Other
1. I paid close attention to my partner's breath pattern **Disagree** **Agree**	My partner paid close attention to my breath pattern **Disagree** **Agree**
2. I was easily distracted from my partner's breath pattern when other things were going on. **Disagree** **Agree**	My partner was easily distracted from my breath pattern when other things were going on. **Disagree** **Agree**
3. I tended to ignore my partner's breath pattern **Disagree** **Agree**	My partner tended to ignore my breath pattern. **Disagree** **Agree**
4. I was able to influence my partner's breath pattern **Disagree** **Agree**	My partner was able to influence my breath pattern **Disagree** **Agree**
5. My breath pattern was often dependent on my partner's breath pattern. **Disagree** **Agree**	My partner's breath pattern was often dependent on my breath pattern **Disagree** **Agree**

Figure B.1: Networked Minds Questionnaire


CWI
Centrum Wiskunde & Informatica
UNIVERSITY OF TWENTE.
TUDelft
Delft University of Technology

Comfort Assessment Form

Participant ID :

Please rate the comfort level for each of the following conditions

Emotion

I am worried about how I look when I wear this device. I feel tense or on edge because I am wearing the device.

Low High

Attachment

I can feel the device on my body. I can feel the device moving.

Low High

Harm

The device is causing me some harm. The device is painful to wear.

Low High

Perceived change

Wearing the device makes me feel physically different. I feel strange wearing the device.

Low High

Movement

The device affects the way I move. The device inhibits or restricts my movement.

Low High

Anxiety

I do not feel secure wearing the device.

Low High

Figure B.2: Comfort Assessment Form

Appendix C

Analysis Reports

C.1 Interview Transcripts

FinalInterviews.pdf

C.2 All CCF Plots

CCFPlots.pdf

C.3 Synchronization Plots

All Baseline Plots

BaselinePlots.pdf

All Visual Plots

VisualPlots.pdf

All Vibrotactile Plots

VibrotactilePlots.pdf

All VisualVibro Plots

VisualVibroPlots.pdf

All InSync Plots

InSyncPlots.pdf