Vibro-Thermal Haptic Display for Socio-Emotional Communication Through Pattern Generations

by

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ABSTRACT

Touch plays a vital role in maintaining human relationships through social and emotional communications. This research proposes a multi-modal haptic display capable of generating vibrotactile and thermal haptic signals individually and simultaneously. The main objective for creating this device is to explore the importance of touch in social communication, which is absent in traditional communication modes like a phone call or a video call. By studying how humans interpret haptically generated messages, this research aims to create a new communication channel for humans. This novel device will be worn on the user's forearm, and has a broad scope of applications such as navigation, social interactions, notifications, health care, and education. The research methods include testing patterns in the vibro-thermal modality while noting its realizability and accuracy. Different patterns can be controlled and generated through an Android application connected to the proposed device via Bluetooth. Experimental results indicate that the patterns SINGLE TAP and HOLD/SQUEEZE were easily identifiable and more relatable to social interactions. In contrast, other patterns like UP-DOWN, DOWN-UP, LEFT-RIGHT, LEFT-RIGHT, LEFT-DIAGONAL, and RIGHT-DIAGONAL were less identifiable and less relatable to social interactions. Finally, design modifications are required if complex social patterns are needed to be displayed on the forearm.

DEDICATION

This work is dedicated to Shraddha Gharat, Shriniwas Gharat and Soham Gharat for giving me this opportunity and supporting me throughout my education. A special thanks to my friends and family, who have always been present for me during this process. Finally, a very special thanks to my classmate Nikita Joshi for making this opportunity possible in the first place.

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Chapter 1

INTRODUCTION

1.1 Motivation

Research in haptic displays was carried out in several modalities such as pressure [He *et al.* (2015)], vibrotactile [Israr *et al.* (2014)], clenching [Caswell *et al.* (2012)], thermal [Peiris *et al.* (2019)], skin stretching [Gupta *et al.* (2017)], dragging [Ion *et al.* (2015)] and air [Lee and Lee (2016)]. Haptic stimuli have been tested on various parts of the body like the hands [Balcer (2014)], lower back [Gooch and Watts (2010)], face [Yamen Saraiji *et al.* (2018)], thenar eminence [Singhal and Jones (2018)], wrist [Peiris *et al.* (2019)], back of the wrist [Halvey *et al.* (2012)], forearm [Tewell *et al.* (2017b)], chest [El Ali *et al.* (2020)], using a range of form factors from head-mounted displays [Chen *et al.* (2017)] to small thermo-electric wearables [Maeda and Kurahashi (2019)].

Previous studies in thermal haptics used Peltier units embedded into wearable devices to apply thermal stimuli on several parts of the body such as wrists [Peiris *et al.* (2019)], palms, fingers [Roumen *et al.* (2015)], arms [Tewell *et al.* (2017a)], ears [Nasser *et al.* (2019)], and the head [Peiris *et al.* (2017)]. Although researchers have explored the utility of thermal bracelets [Peiris *et al.* (2019)] for providing spatial-temporal feedback, it has not been researched from the perspective of conveying patterns. [Cang and Israr (2020)] explored socio-emotional sentiments through vibrotactile feedback but did not consider the thermal modality during their study.

This research plans to design, demonstrate and test a multi-modal haptic display using Eccentric Rotating Mass(ERM) vibrational motors and ceramic Peltier units on the forearm as a medium to transfer patterns and explore the various nuances it can portray during social interactions.

1.2 Contributions

The contributions of this thesis are as follows.

1. Design a novel multi-modal display which aims to enhance and enrich social communication during social and emotional interactions.

2. Develop a multi-modal haptic display that generates pre-defined and user-defined patterns.

3. Create an android application for remotely controlling this device from a distance.

4. Perform human subjects research and collect data to explore the role of touch during social interactions through a vibro-thermal haptic display.

5. Suggest future design directions for vibro-thermal displays.

Chapter 2

RELATED WORK

2.1 Thermal Haptics

Wilson et al. [Wilson *et al.* (2011)] conducted a series of comprehensive investigations on thermal feedback in Human-Computer Interaction (HCI), which provided essential insights on designing thermal feedback: 1) The hand is a very sensitive part of the body for thermal cues. 2) Thermal displays with a 1°C/s rate of change are suitable for most applications. 3) Clothes greatly hinder the perception of thermal feedback. 4) Based on the speed and the direction of temperature change, thermal icons can be designed for mobile phones. 5) Users strongly agree on the application of thermal feedback in social communication and rating-related representations [Wilson *et al.* (2015)], and 6) Thermal feedback can be applied for emotion representation [Wilson *et al.* (2016a)] and to widen the range of emotion representation in addition to other feedback modalities. Experiments using the ThermalBitDisplay [Niijima *et al.* (2020)] showed that when thermal feedback is provided using Peltier elements, perception varies depending on body site: three Peltier elements provided cold sensations when touched with a finger, but provided hot and painful sensations when touched with the lips.

Therminator [Günther *et al.* (2020)] was a localized on-body thermal display concept that was based on liquid flowing through a suitable network of tubes for the arm and the abdomen; instead of Peltier elements, electro-thermic elements with liquids were used, as liquids with different temperatures could flow through a network of deformable and thermally conductive tubes that can adapt to any shape, which enabled them to be used on any part of the body. Pilot studies with the Thermo-haptic Earable Display[Zhu *et al.* (2019)] made a significant observation that participants found it easier to locate a cold stimulus than a hot stimulus; the response time for cold percetual responses was 1.2 seconds faster.

The skin contains more cold receptors than hot receptors which indicates great sensitivity to cold stimuli than hot [Peiris *et al.* (2019)]. The Thermal Bracelet [Peiris *et al.* (2019)] used four Peltier modules; two diagonal Peltier modules were used for cooling, and the other two were used for heating [Nakatani *et al.*]. Through the thermal summation principle, the bracelet could be used to deliver fast thermal cues to users. TherModule [Maeda and Kurahashi (2019)] implemented thermal feedback in a wearable and modular system for interactions using a wireless platform. Ambient [Yamen Saraiji *et al.* (2018)] conveyed facial thermal feedback in applications of tele-existence and remote-operated systems. Machine learning was used to reduce the time delay between the user action and output in hand motion prediction for fast thermo-haptic feedback [Chernyshov *et al.* (2018)]. Heat-Nav [Tewell *et al.* (2017a)] demonstrated experimentally that continuous temperature changes could guide behavior and be used for mobile interactions in pedestrian navigation. Tewell *et al.* also developed a Thermal Array Display(TAD) consisting of three thermal electric coolers on the arm, which displayed patterns of warm, cool and neutral temperatures. Tewell et al.[Tewell *et al.* (2017a)] were the first to demonstrate that continuous thermal feedback can be effectively used without pausing between signals for re-adaptation of the skin. Similarly, The Heat is On [Tewell *et al.* (2017b)] used an array of three thermal simulators. Their proposed design increased the stimulated skin area, easing the perception of thermal signals for users. It showed better results than a single thermal electric cooler; they concluded that the TAD enabled more accurate discrimination with more minor temperature differences between thermal signals, reducing time for user identification of thermal state changes. During the research of a novel multimodal vibro-thermal display [Nakatani *et al.* (2016)] the researchers realized that heat exhaustion can adversely affect the performance of the device.

Hot under the Collar [Wilson *et al.* (2016a)] made the first attempt to map a range of thermal stimuli to dimensional models of emotions and suggested that the distribution of points better fitted a vector model than the circumplex, thereby making it difficult to convey the full range of emotions through thermal feedback alone, and were only suitable for conveying calm, positive emotions or excited, negative emotions. In their experiment, Hot and Tight [Song *et al.* (2015)], concluded that thermal cues performed poorly compared to squeezing actions and experienced thermal cues to be intrinsically hard to build with rapid changes, and varied depending on the body location. In the Heat of the Moment [Wilson *et al.* (2015)], four real-world interactions using thermal feedback were performed, and their associations with different information/data types were mapped. They also suggested several design guidelines: 1) Thermal feedback designs can be created with a good degree of reliability and depend on how different users interpret them. 2) Warmth (above 32°C) should be used to convey the physical or social presence of other people, while cool (below 30°C) should be used to convey the absence of people or usage. They also suggested applications like conveying risk-related cues or multiple levels of ambient feedback. ThermOn [Sato *et al.* (2013)] enabled users to feel dynamic hot-cold sensations on their body corresponding to the sound of music. Thermal stimuli worked more synergistically with sounds as such stimuli were more emotionally compatible with sounds.

Thermal Feedback Identification in a Mobile Environment [Wilson *et al.* (2013)] tested absolute identification of encoded, two-dimensional thermal icons while sitting or walking, and concluded that direction of change was a valuable thermal feedback parameter in mobile environments. Baby it's Cold Outside [Halvey *et al.* (2012)] investigated the impact of environmental factors for the use of thermal feedback in interactions; from this testing, they suggest that the ambient temperature affects stimuli detection rates and the effect is more fine-grained. They also expressed that even if thermal feedback is sensitive to ambiance, all the previous recommendations were valid. Lee and Lim [Lee and Lim (2012)] developed a structured way of thinking about the quality of heat (thermal expression, thermal expression unit, and the two levels of thermal expression composition) and identified the critical expression elements (temperature, duration, location, and temperature change rate). They also provided different design opportunities like testing thermal feedback with messengers' applications , secret conversations as a lightweight chatting tool, for greetings felt through the skin, refreshment purposes, and alarms.

Akiyama et al. [Akiyama *et al.* (2012)] studied human thermal threshold depending on the adapting skin temperature, and proposed a method that involves slightly raising and lowering the adapting temperature in neighboring skin regions using two adjacent Peltier devices to lower the thermal threshold and thus render the skin more sensitive to thermal stimuli. In Haptically Augmented Remote Speech Communication [Katja Suhonen *et al.* (2012)], touch input was mapped to the thermal output device; cold messages were for negative feelings, whereas warmth communicated positive feelings. Adding thermal stimuli during a conversation provided an opportunity for the participants to emphasize parts of the conversation. Emotional responses to thermal stimuli [Salminen *et al.* (2011)] tested dynamic and pre-adjusted stimuli.

They found that warm stimuli for both the cases were rated as more arousing and dominating than neutral or cold stimuli. Furthermore, the authors suggest that warm stimuli, especially pre-adjusted, can be used in mobile contexts to catch the user's attention during an ongoing task. Halvey et al. [Halvey *et al.* (2011)] performed experiments to explore the effect of clothing on the perception of thermal stimuli. This investigation suggested that lower thermal conductivity materials require more intense changes while high thermal conductivity materials result in more error. They also added that higher intensity changes were more comfortable with cloth than direct contact. Also, with materials, cooling was perceived as more intense and warming was more comfortable. Thermo-Message [Mynatt *et al.* (2010)] displayed several issues regarding thermal feedback and made a design recommendation that homeostatis can be critical while interpreting messages. Moreover, thermal stimuli were considered bipolar (hot and cold) while there are multiple perceptions present. The heat itself does not solely cause the memorization of thermal expression, but it tends to include the context of how the person experiences the heat. They suggested using a thermal expression for playful use, action, emotional messages, and specific predefined messages to partners. Thermal expressions have applications such as 1) unnoticed but casual communication, and 2) uniqueness in its emotional values. Thermal icons, if designed based on the responses of the skin, can be accurately identified with little training [Singhal and Jones (2018)]. Thermal Icons [Singhal and Jones (2018)] used a water-cooled heat sink, and Chernyshov et al. [Chernyshov *et al.* (2018)] designed a compact and efficient water cooling system that provided cold sensations using Peltier elements, as cold feedback is much more complicated. Since the excess of heat has to be transported away from the device and stored or disposed of, most modern thermal output systems use TECs: flat, rectangular, thermoelectric components that cool down and heat up on either side depending on how current is applied.

ThermoTouch [Kratz and Dunnigan (2016)] used a grid of thermal pixels instead of the use of Peltier elements for thermal output, and they also used liquid cooling and electro-resistive heating to output thermal feedback at arbitrary locations. Some limitations of the Peltier element-based approaches which were brought forward were: they have slow temperature switching speed, limited temperature range, low efficiency and cost. The approach used in Thermo-Touch [Kratz and Dunnigan (2016)] also had disadvantages: the setup was bulky, it required an external cooling system, and hence it was best for fixed or semi-movable scenarios where portability was not a crucial design goal.

Salminen et al. [Salminen *et al.* (2013)] found that a 6°C change in temperature (especially when warm) was rated as unpleasant, arousing, and dominant. The findings that warm stimuli and cool stimuli are associated with positive or negative emotions respectively, was consistent with previous work that tested thermal stimuli in isolation [[Wilson *et al.* (2015)]; [Salminen *et al.* (2013)]; [Salminen *et al.* (2011)]]. However a 4°C increase was still rated as arousing and dominant but pleasant. A lower limit of about 15°C-17°C and an upper limit of 45°C-52°C was considered by researchers in order to avoid pain irritations associated with the thermoreceptors [Niijima *et al.* (2020)]. A minimum of 15s interval in between different trials was suggested. The primary reason for this was to avoid the thermal adaptation effect. Wilson et al. [Wilson *et al.* (2015)] used a temperature range of 22°C-38°C, a safe and comfortable zone of temperatures appropriate for thermal feedback with 2°C as the slightest difference between two stimuli. A significant discovery was that the extent of referral increases for warm sensations nearer the elbow or towards the body centre, and cold stimulation has greater referral distance near the hand or towards the periphery [Tewell *et al.* (2017b)].

Wilson et al. [Wilson *et al.* (2015)] highlighted that the role of emotions can vary depending on which scenarios thermal stimulation is used (e.g., happy memories, social closeness, etc.). Emotions are often stated to be connected to sensed variations in temperature [Salminen *et al.* (2011); Song *et al.* (2015)], where warm temperatures were found to be comfortable and pleasant and promoted social proximity, while colder temperatures were perceived as being uncomfortable to most. Temperature can also be mapped to emotions [Wilson *et al.* (2011)], providing another option for simple mapping: a hot stimulus could be used to encode a positive meaning, or priority of an event. “Warm” was associated with words such as “generosity”, “happiness”, “humor” and “sociability” [Wilson *et al.* (2016a)].

Summary: Thermal feedback was perceived with higher accuracy than vibrotactile feedback [Peiris *et al.* (2019)]; thermal feedback is silent and effective in noisy, bumpy environments, and potentially of use as a dedicated channel of communication or in enhancing tactile feedback in multi-sensory displays [Singhal and Jones (2018)]. People like to use haptic communication mainly with people close to them [Suhonen *et al.* (2012)]; also, participants preferred receiving haptic stimuli through their hands via a mobile phone or a wristband-like device. As warm temperatures were compared to social and emotional interactions, the research team decided to implement the proposed device with warm temperatures.

2.2 Vibrotactile Haptics

Vibrotactile feedback (VTF) is effective in many situations but not appropriate in noise-sensitive environments, such as libraries, and is also less effective in loud and bumpy environments, like trains. Feel Effects [Israr *et al.* (2014)] created a library of feel effects and interpreted it based on the duration and intensity of the tactons, tested on the back of the user. The walker's emotional states were tested using a planar vibrotactile display embedded into the footwear [Turchet *et al.* (2017)]. Salminen et al. [Salminen *et al.* (2008)] investigated emotional experiences and behavioral responses to haptic stimulations. The results also concluded that even simple haptic stimuli could contain emotional information. Yoo et al. [Yoo *et al.* (2015)] showed that parameters like the perceived intensity, carrier frequency, duration and envelope frequency have clear relationships to tactile icons' emotional responses. This research also provided some design guidelines for tactile icons that have desired emotional properties. Even though this research [Yoo *et al.* (2015)] explored a wide range of parameter values, there still exist unexplored regions in the valence-arousal space.

In VibroGlove [Krishna *et al.* (2010)], a total of six basic human emotions and the neutral expression was presented to enrich social communication for people with visual disabilities, and the results conveyed that haptic interfaces could be used for conveying basic facial expressions. A haptic belt worn around the waist was used to provide direction and distance of interaction partners to users during social interactions [McDaniel *et al.* (2008)]. This helped people with visual disabilities know a person's precise location in front of him or her during interactions, assisting with avoiding looking or speaking in the wrong direction. Tactile Brush [Israr and Poupyrev (2011)] produced two-dimensional tactile moving strokes with varying frequency, intensity, velocity, and direction of motion on the back of the user. Some exciting patterns were also generated using the tactile brush [Israr and Poupyrev (2011)], which had applications in gaming scenarios.

2.3 Multi-modal Haptics

Altered-touch [Murakami *et al.* (2017)] was a fingertip haptic display with integrated force, tactile, and thermal feedback in a miniature form factor with a peltier module that weighed around 50 grams. Thermal Icons [Wilson *et al.* (2012)] was the first study of intramodal thermal and vibrotactile presentation. They demonstrated that thermal and vibrotactile stimuli together do not appear to hinder interpretation of each other significantly, and so thermal changes may be useful in addition to tactons.

Yang et al. [Yang *et al.* (2007a)] proposed a haptic display providing pin-array tactile and thermal feedback, and was used as a testbed for psychophysical studies relating human touch sensation and perceived feeling of various combined stimuli. Yang et al. [Yang *et al.* (2007b)] also proposed a display consisting of four unbalanced masses and a Peltier unit. Their results concluded that multiple actuators have many advantages for simultaneously displaying the various combinations of amplitude and frequency. The perceived magnitude of vibrotactile stimuli was affected by temperature variation only for high frequency (>150) vibrotactile stimulus [Yang and Kwon (2008)]. With their research, Wilson et al. [Wilson *et al.* (2016b)] tried to expand the emotional expressivity of interfaces and provided examples of combining different modalities for affective emotional states. In thermal haptic displays, many times, there are issues with heat exhaustion which affects performance. To improve performance Nakatani et al. [Nakatani *et al.* (2016)] suggested the use of materials that quickly absorb heat in the displays. Yoo et al. [Yoo *et al.* (2017)] explored Vibrothermal cues' emotional responses through constant temperature thermal stimulus and concluded that thermal and vibrotactile parameters have clear and somewhat independent effects on emotional responses. Besides, positive emotions should include a high-frequency vibration and cool temperature, whereas negative or intense emotions should include a low-frequency vibration with a hot stimulus. Further validation is required on whether thermal stimulus tends to intensify the emotions elicited by vibrotactile stimuli.

Chapter 3

VIBRO-THERMAL HAPTIC DISPLAY

3.1 Testing of System Components

3.1.1 Vibrational Motors

Linear Resonant Actuator (LRA) Motor:

The Linear Resonant Actuator (LRA) Motor has a rated voltage of 2V RMS (root mean square) and operates on an alternating signal pulse with a single axis direction of vibration. An alternating signal is required so that the vibrating flex material inside the motor can return to its starting position. The only component that can fail inside the LRA Motor is the spring when it is operated in the non-fatigue zone. It has a longer lifespan of approximately 1000 hours. The LRA Motors are available in several for factors, but the coin/pancake form factor of about 8-10mm in diameter was tested for this prototype.

Eccentric Rotating Mass (ERM) Motor:

Eccentric Rotating Mass (ERM) Motor is one of the most commonly used vibrational motors and has applications in different industries with a dual-axis of vibration direction. It is ideal for battery power supplies as it can work with a dc power source. A lifespan of 100-600 hours is what makes it very cost-effective. It is slow to start and shut down (50-100ms). The ERM Motor has a rotating mass and comes in different form factors like coin/pancake, brushless (BLDC), encapsulated/enclosed, and PCB

Mounted ranging from 3.2mm to 45mm. For this prototype, an ERM Motors of 8mm diameter was tested.

Findings based on Theory and Specifications:

LRA Motors consume less power than ERM Motors and even operate at lower voltages. In LRA Motors, the signal amplitude and frequency can be controlled independently and is capable of producing richer experiences in haptics. The vibration in LRA Motors is more directed and provides a cleaner feeling than the ERM Motors. The ERM Motor is more cost-effective than LRA Motors and has a wide range of normalized vibration amplitudes (0.25 G- 150G) compared to the LRA Motor (0.75G-2G). The LRA Motor provides a vibration frequencies of 150-250Hz, while the ERM Motors provides vibration frequencies from 30 to 500Hz. It is not easy to produce complex and subtle waveforms using the ERM Motor as frequency and amplitude cannot be controlled independently.

Findings based on testing with micro-controller(Arduino UNO):

LRA Vibrational Motor:

The LRA Motor produces moderate vibrations when tested with an alternating signal through the Arduino microcontroller's digital pins. The amplitude of vibrations increased with an increase in voltage.

ERM Vibrational Motor:

The vibration amplitudes produced through the digital pins was very high. For practical applications, if many motors operate together, it can feel annoying as very high amplitudes of vibration are generated. When tested with 3.3 V and 5V, the amplitude increased proportionally to the voltage increase (frequency is directly proportional to the voltage, and the amplitude is directly proportional to the voltage's square). This type of motor can test an initial hypothesis for the project as these motors' intensity is highly realizable to the human skin.

3.1.2 *Peltier Units*

Ceramic Peltier Device:

The traditional Peltier device works through the Peltier effect; it is solid and cannot be bent. Most of the previous research in thermal haptic displays is based on this device for providing thermal feedback. The Peltier unit tested for this prototype is the CP20251 from CUI Devices [`https://www.digikey.com/en/products/detail/cui-devices/CP20251/1747356`]. This device was selected based on its voltage specifications and its response to input voltage. The CP20251 functions perfectly at 5V dc and generates warm temperatures needed for this prototype within a few seconds. As it operates at a lower voltage, it can be used on portable devices to generate thermal cues.

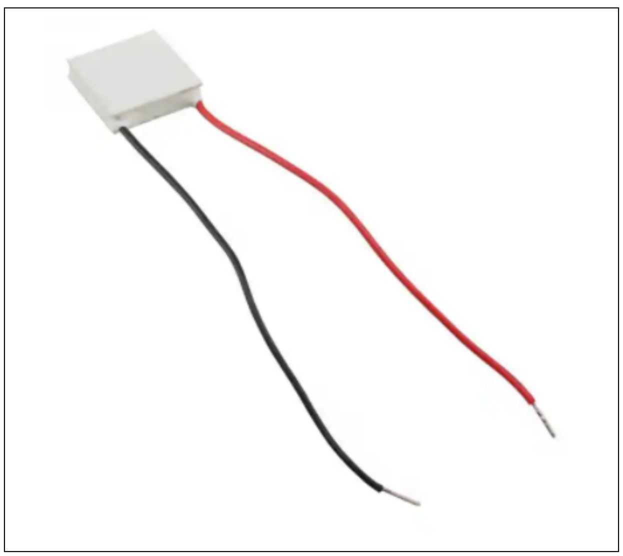


Figure 3.1: Ceramic Peltier Unit

Source: Digikey®

Flexible Thermo-electric Device (FTED):

The Flexible Thermo-electric Device (FTED) tested is flexible, light, thin, and responds immediately, unlike ceramic Peltier units [http://tegway.co/tegway/]. It can produce thermal cues similar to the traditional Peltier device. As it is in a suitable form factor, it can be easily embedded into wearable devices. The FTED does not contain any ceramic substrates and is entirely flexible, thus consuming less energy. This device consists of smaller elements in the form of rows and columns, where each element on the FTED cannot be controlled individually, but an array consisting of a few rows or columns can be controlled. The FTED is also available in custom form factors as per requirement.

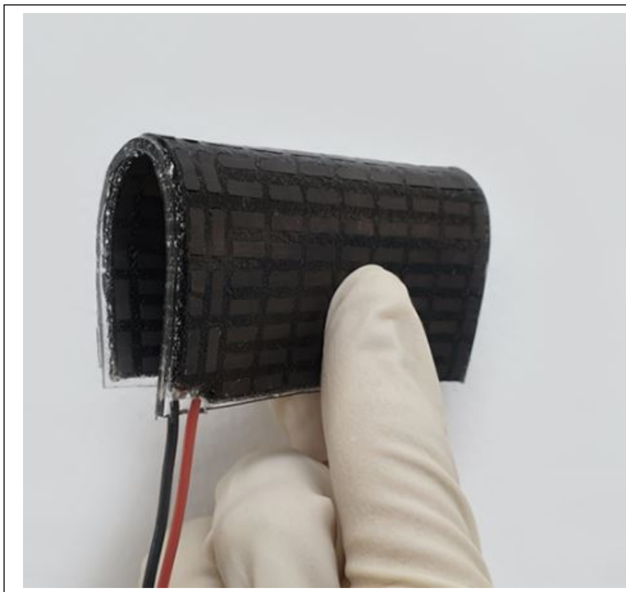


Figure 3.2: Flexible Thermo-electric Device

Source: TEGWAY™

Ceramic Micro-Peltier unit:

The Peltier unit's smaller form factor was also tested; the device used was CP0734-238 from CUI Devices [https://www.digikey.com/en/products/detail/cui-devices/CP0734-238/12822054]. The micro-Peltier unit is a smaller version of the traditional ceramic Peltier units, with a size of 3.4 * 3.4 * 2.38 mm. The specifications of this device allow a maximum voltage of 0.5V and a maximum current of 0.7A during its operation. This device can be used in later prototypes to create Peltier unit arrays in a very compact space.

Figure 3.3: Ceramic Micro-Peltier Unit

Source: Digikey®

Findings based on testing with micro-controller:

The FTED was tested using 5V from the Arduino UNO through a Metal-oxide semiconductor field-effect transistor (MOSFET) acting as a switch. The FTED was very fast, and it returned to its initial temperature instantly. As it is flexible, it was easy to test this device around the wrist or fingers.

The micro-Peltier unit was tested using a bench-top power supply as the micro-controller outputs were above the specifications. When the voltage was stepped down

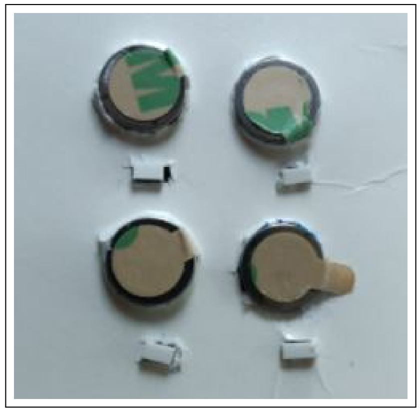


Figure 3.4: Micro-peltier & LRA Motor Matrix Testing

using an R-2R DAC (Digital to Analog converter), the current specifications did not meet the requirements to turn ON the micro-Peltier unit.

The ceramic Peltier unit was tested similarly to the FTED with 5V from the Arduino UNO and a MOSFET as a switch. The ceramic Peltier provided the discernable temperature within few seconds of operation. It took a few seconds to return to its normal temperature after the Peltier was disconnected from the input voltage.

3.2 Selection of Components

3.2.1 Selection of Vibrotactile Motor

The vibrotactile motors were selected from the LRA Motor and the ERM Motors. As this is an initial prototype to test the hypothesis of pattern generation and recognition during human communication, ERM Motors were are used as they are more realizable than the LRA Motors. For more enriched patterns and changes in the frequency of vibrations, LRA Motors are recommended for use. Further prototypes can be developed using LRA Motors to generate vibrations from various frequencies and amplitudes, thereby providing more enriched vibrations.

3.2.2 Selection of Peltier Unit

The traditional ceramic Peltier unit has a 40mm * 40mm size, which is quite big and cannot be arranged in a matrix form that can fit the wrist or the forearm. The FTED unit is flexible and can be easily fabricated into desired shapes, but the cost involved is too high and was not selected for the current prototype. According to the electrical specifications of this device, the micro-Peltier unit of size 3.4mm * 3.4mm * 2.38 mm is a Peltier unit available in a very small form factor; more hardware components were needed to generate and control the voltage required for the micro-Peltier unit. To create a prototype with fewer hardware components, micro-Peltier units were not selected for the current prototype. In this prototype, the ceramic Peltier units of size 20mm * 20mm * 5.1mm were used as they are smaller in size than the traditional Peltier and can be arranged in a matrix form to fit the size of a forearm.

3.3 System Design

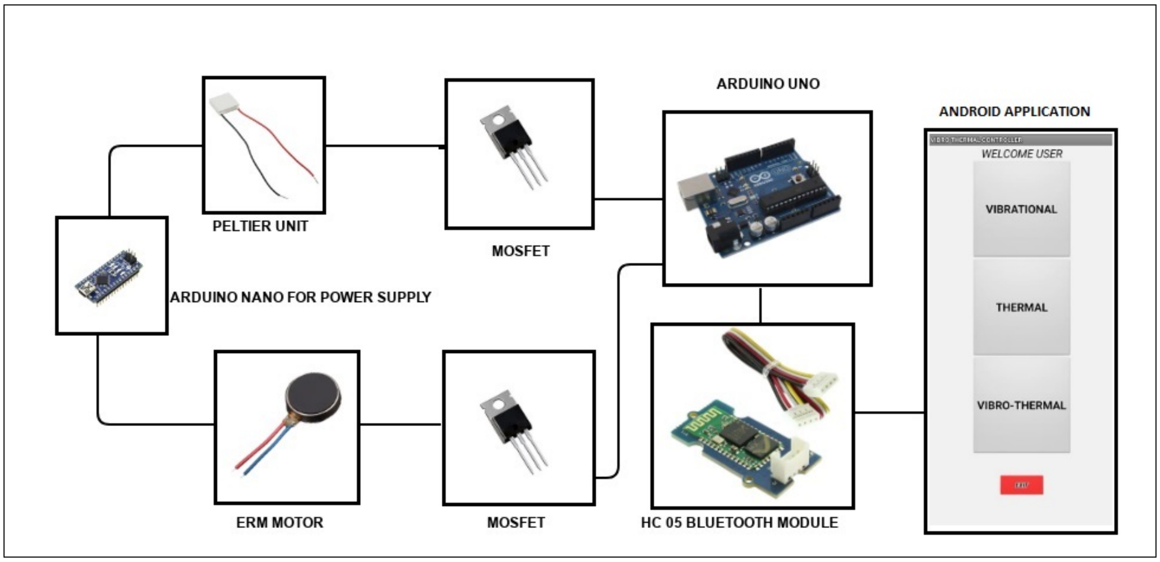


Figure 3.5: System Design

This Vibro-thermal haptic display consist of software and hardware components. The Figure 3.5 shows the various components. The Peltier units and vibrational motors are powered through an Arduino Nano. Temperture and vibrational changes in the Peltier unit and vibration motors, respectively are controlled through an Arduino UNO. A Bluetooth module is connected to the Arduino UNO which can receive data and provide it as an input to the Arduino UNO. The entire hardware present in this prototype is interfaced through an Android application. The Android application provides the user with an interface to control and generate different patterns through the Vibro-thermal device.

3.4 Hardware Design and Components

3.4.1 Vibro-thermal Display

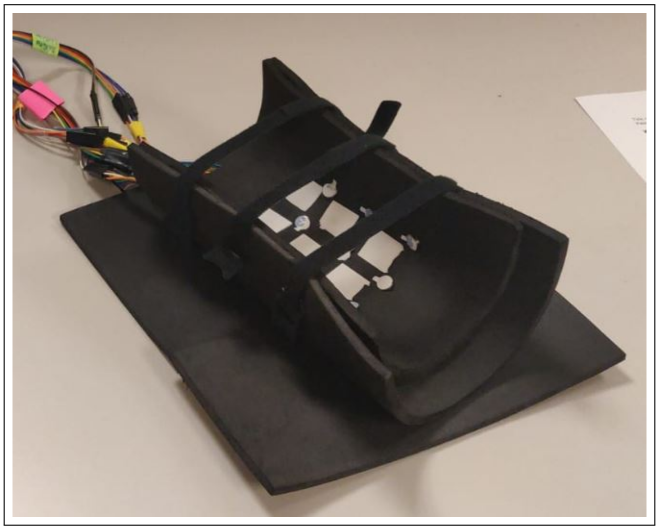


Figure 3.6: Vibro-thermal Display

Figure 3.7: Vibro-thermal Display on Forearm

The Figure 3.8 shows the arrangement of Peltier units and ERM vibration motors implemented in this prototype. The ceramic Peltiers and the ERM Motors are arranged in a 3*3 matrix pattern staggered to each other. The size in contact with

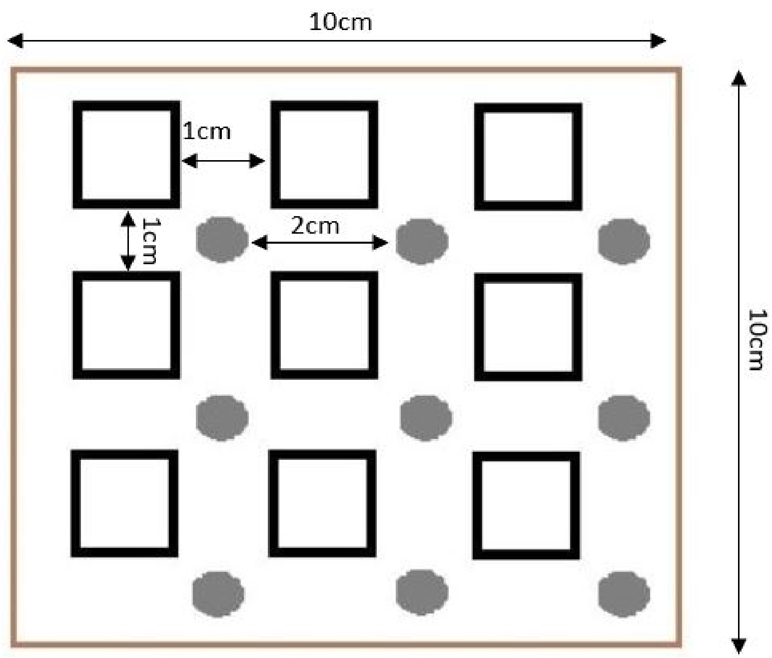


Figure 3.8: Vibro-thermal Display Design

the user's skin is within 10cm*10cm. The effective area of the Peltier unit and the vibrational motors are similar with small variations. This arrangement is beneficial when controlling the device in thermal and vibrotactile modalities individually or simultaneously.

The Peltier unit's two sides can become hot or cold depending on the direction of current; if the Red terminal of the Peltier is connected to 5V dc and the black terminal is connected to ground(GND), then the top side warms and vice versa. In this prototype, as only warm temperatures are tested, the +ve terminals of all the Peltiers is connected to 5V dc. The -ve terminals are connected to the drain terminal of the respective MOSFET's arranged in an array form. The gate of the MOSFET's is connected to the Arduino pins, which control the Peltier heating. The source terminal of the MOSFET's is connected to GND, which completes the entire circuit.

Similarly, the +ve terminals of the ERM Motors is connected to 5V, and the -ve terminals is connected to the drain of the MOSFET. The gate of the MOSFET is connected to the Arduino pins that control the vibrations of the ERM Motors. The source of the MOSFET is connected to the GND terminal completing the circuit.

An array of eighteen MOSFET control the nine Peltiers and nine ERM Motors. The MOSFETs are mounted on a breadboard for prototyping purposes. This circuit can be fabricated into a printed circuit board in upcoming prototypes. The Bluetooth module (HC-05) used in the prototype for interfacing the hardware and the software, is connected to Arduino UNO and utilizes the TX (transmitter) and RX (receiver) pins on the Arduino UNO. An Arduino Nano supplies power to all the Peltier units and the ERM Motors. This isolation of power supply avoids grounding issues when the Peltier units and ERM Motors draw current. The circuit schematic is given below which contains the electrical connections of the Vibro-thermal device.

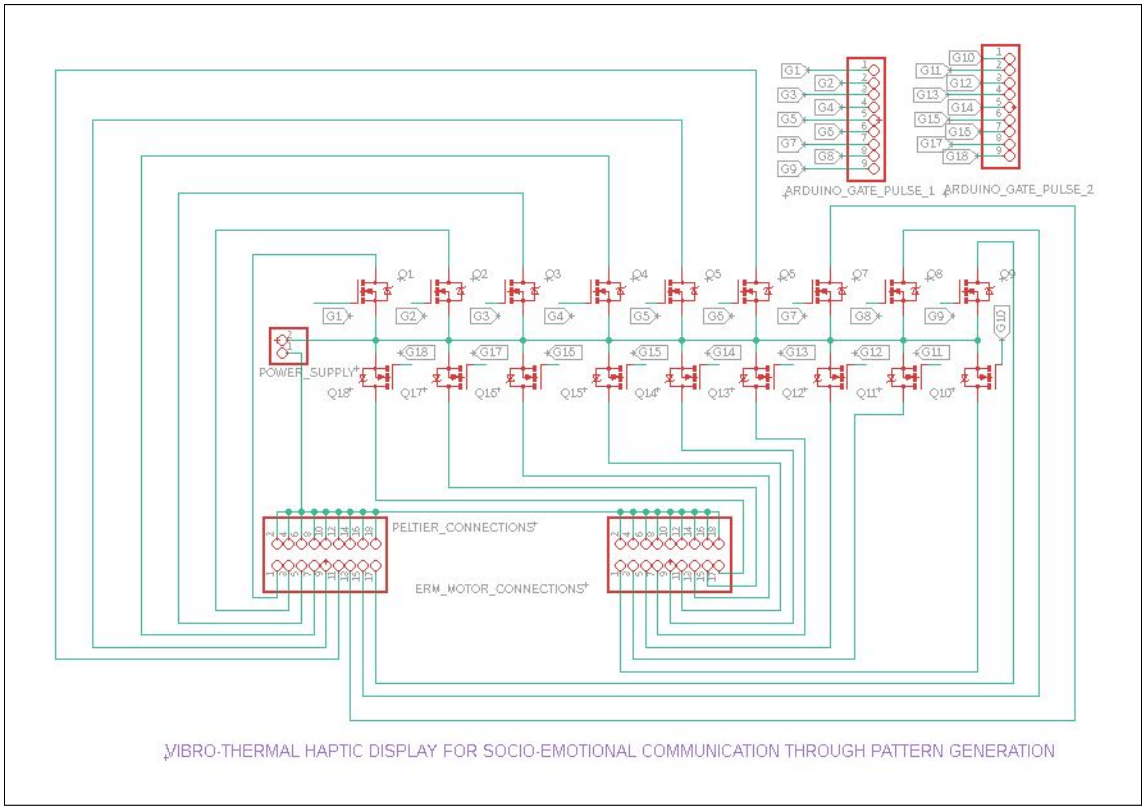


Figure 3.9: Circuit Schematic

3.5 Software Design and Components

3.5.1 Arduino Programming

The Arduino Uno microcontroller is used in this prototype to control the temperature changes of the ceramic Peltier units and the vibrations of the ERM Motors. According to the commands received from the android application, the output voltage of each pin of the Arduino Uno is precisely controlled through the Arduino code. A switch case condition is used to choose between the several cases available from the android application. The commands received from the android application can be viewed on the serial monitor in the Arduino IDE as the user controls different patterns.

3.5.2 Android Application Development

The Android Application was created to reduce the hardware component involved in controlling this device, developed using the MIT App inventor 2 [`https://appinventor.mit.edu/explore/ai2`]. The Android application consists of different screens depending on the type of modality the user wishes to control. The user can also select between the pre-defined patterns or create new patterns using the keypad provided. The Android application interacts with the hardware using the HC-05 Bluetooth module connected to the Arduino UNO.

Android Application Screens & Working:

1. Main Menu

When the application is launched, the initial screen welcomes the user and prompts the user to choose between different haptic modalities. Selecting any of the options will proceed the application to the requested modality control screen. The user can exit the application using the EXIT button at the bottom of this screen.

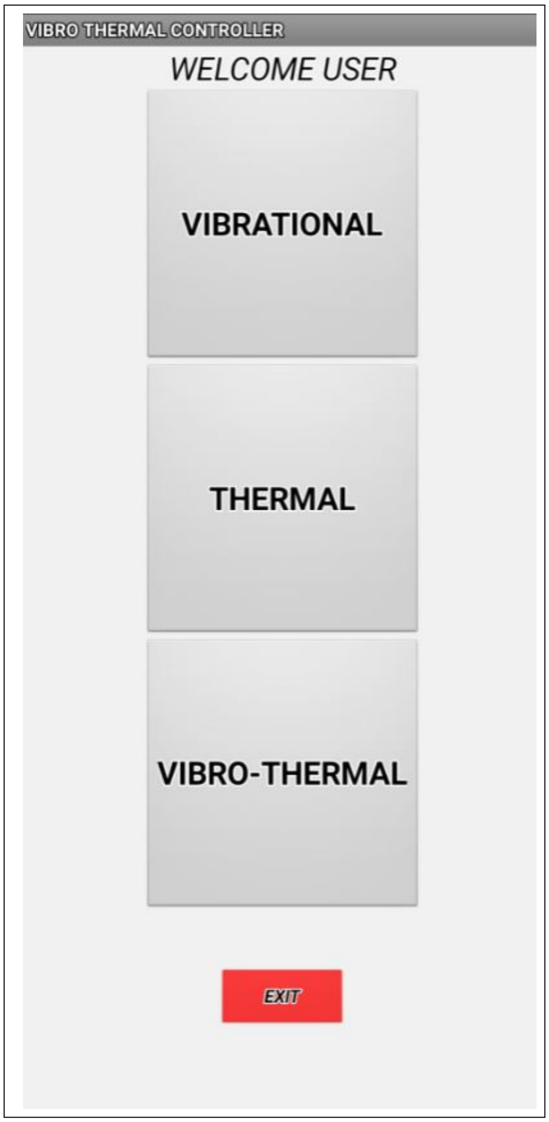
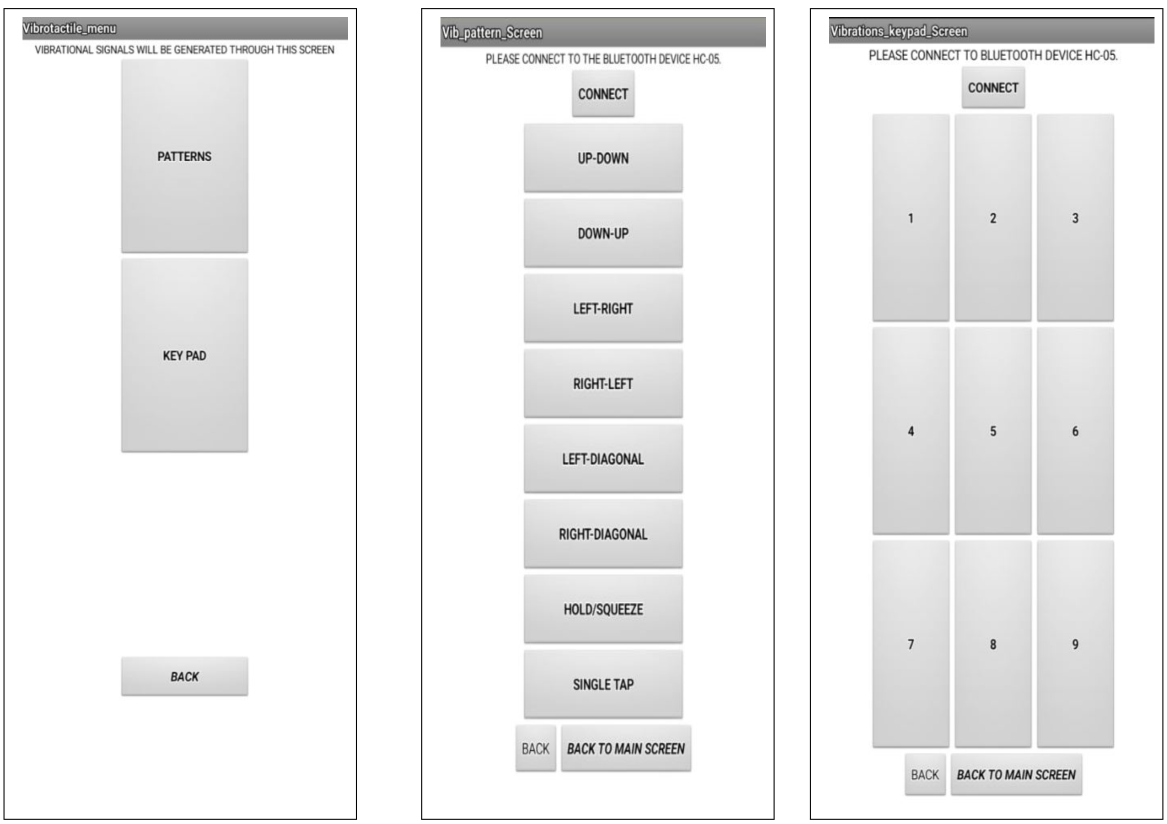


Figure 3.10: Main Screen

2. Vibrotactile Selection

On selecting the Vibrational option, the user will proceed to the vibrotactile control screen. The user then selects between pre-defined patterns or user-defined keypad; if pre-defined patterns are selected, the application proceeds to the screen with different pattern options for the user to choose. Before selecting any of the patterns, the user needs to connect the mobile device to the Vibro-thermal display through Bluetooth (HC-05). If the user selects the user-defined keypad option, the application proceeds to a screen with different numbers to select from, which coincides with the Vibro-thermal display positions. Before selecting any of the options, the user needs to connect with the Bluetooth device (HC-05) through the connect button.



(a) Vibrotactile Menu (b) Vibrotactile Pattern Selection (c) Vibrotactile Keypad

Figure 3.11: Vibrotactile Multiple Screens

3. Thermal Selection

On selecting the Thermal option, the user will proceed to the thermal control screen. The user then selects between pre-defined patterns or user-defined keypad; if pre-defined patterns are selected, the application proceeds to the screen with different pattern options for the user to choose. Before selecting any of the patterns, the user needs to connect the mobile device to the Vibro-thermal display through Bluetooth (HC-05). If the user selects the user-defined keypad option, the application proceeds to a screen with different numbers to select from, which coincides with the Vibro-thermal display positions. Before selecting any of the options, the user needs to connect with the Bluetooth device (HC-05) through the connect button.

(a) Thermal Menu (b) Thermal Pattern Selection (c) Thermal keypad

Figure 3.12: Thermal Multiple Screens

4.Vibro-Thermal Selection

On selecting the Vibro-Thermal option, the user will proceed to the Vibro-thermal control screen. The user then selects between pre-defined patterns or user-defined keypad; if pre-defined patterns are selected, the application proceeds to the screen with different pattern options for the user to choose. Before selecting any of the patterns, the user needs to connect the mobile device to the Vibro-thermal display through Bluetooth (HC-05). If the user selects the user-defined keypad option, the application proceeds to a screen with different numbers to select from, which coincides with the Vibro-thermal display position. Before selecting any of the options, the user needs to connect with the Bluetooth device (HC-05) through the connect button.

(a) Vibro-Thermal Menu (b) Vibro-Thermal Pattern Selection (c) Vibro-Thermal keypad

Figure 3.13: Vibro-thermal Multiple Screens

3.6 Implementation

With this vibro-thermal display several patterns can be displayed. As the size of the matrix increases, more shapes can be demonstarted. Given below is an illustration of some patterns.The Figure 3.14 shows the different patterns tested with this device on human subjects. The main aim for testing these patterns was to collect information about the various nuances that change in direction of Vibro-thermal cues can produce and their relatabilty to social interactions.

Vibro-thermal display patterns:

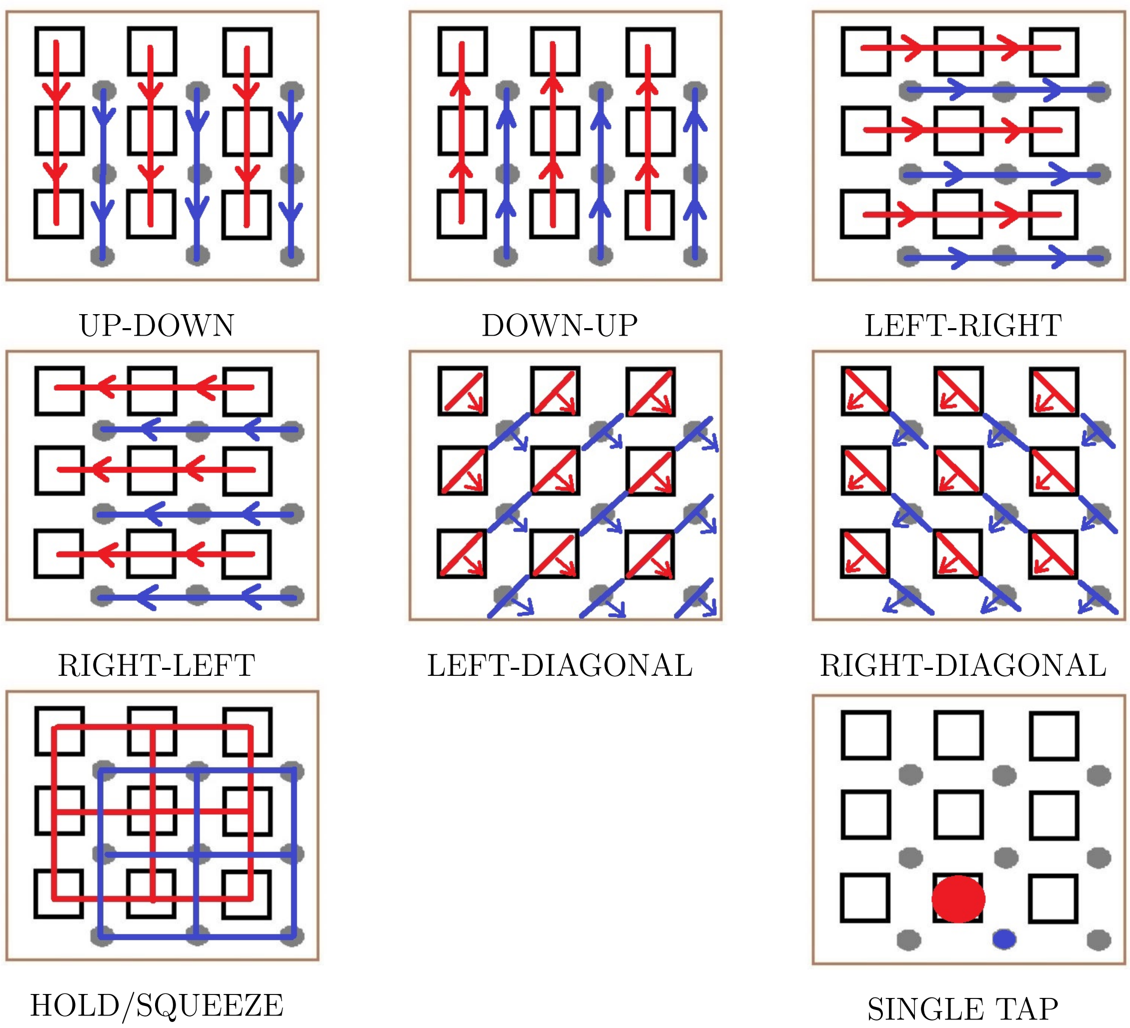


Figure 3.14: Different Patterns Using Vibro-thermal Modality

Chapter 4

SYSTEM OBJECTIVES, FUNCTIONALITY & APPLICATIONS

4.1 Objectives

- The final prototype consists of fewer hardware components.
- The system should operate with portable power supplies like battery banks and USB ports.
- The prototype should be compact in size and fit different users.
- The Android Application aims to be user-friendly, and the procedure to control various patterns in different modalities should be easy.
- To create a novel device based on the sense of touch for enriched communication in social and emotional interactions.

4.2 Expected Outcomes

- Humans are able to discern Vibro-thermally generated patterns on the forearm.
- Vibro-thermal modality is more accurate than thermal and vibrotactile cues individually.
- Specific patterns can enrich social or emotional interactions during communication.
- This system can be incorporated into traditional modes like voice calling or video calling to enhance the communication through the sense of touch.

4.3 Functionality (Pre-defined Patterns)

Pre-defined patterns can be generated through the Vibro-thermal device by controlling it through the android application. Eight pre-defined patterns were tested through this device which consists of change in directions of Vibro-thermal cues. The patterns tested were UP-DOWN, DOWN-UP, LEFT-RIGHT, RIGHT-LEFT, LEFT-DIAGONAL, RIGHT-DIAGONAL, HOLD/SQUEEZE, and SINGLE TAP, can be referred to in Figure 3.14

Figure 4.1: Pre-defined Pattern Screen

The HOLD/SQUEEZE pattern was created by actuating all the Peltier units and Vibration motors together. The SINGLE TAP is performed with just one set of Peltier unit and Vibration motor actuated, which simulates a human tap on the forearm.

4.4 Functionality (User generated Patterns)

The users can draw desired patterns in any of the thermal, vibrotactile and vibro-thermal modalities using the main menu followed by the keypad provided in the Android application. The user can input the sequence of numbers in the shape of the desired pattern, and the device will perform the patterns accordingly. Some examples of user defined shapes include a diagonal line, straight line, cross pattern, + shape.

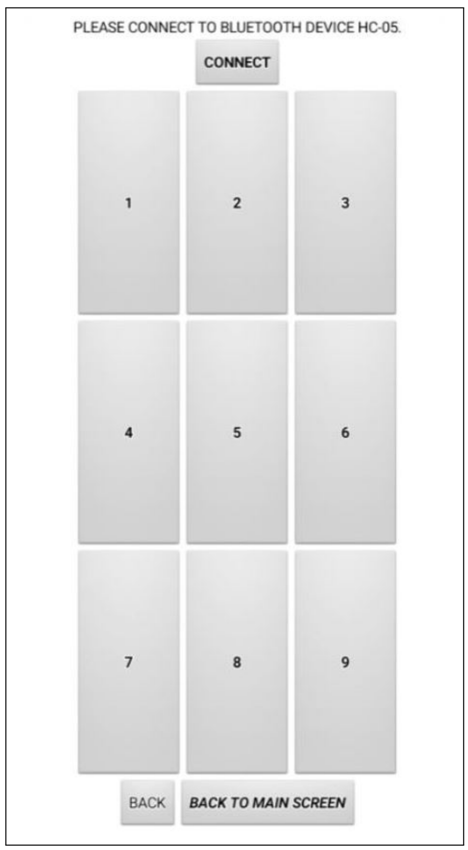


Figure 4.2: User Defined Keypad

4.5 Applications

Haptic displays have a wide scope of applications ranging from various areas such as notification [Wilson *et al.* (2017)], social aspects [Lee and Lim (2012)], navigation [Tewell *et al.* (2017a)], artifact properties (e.g., ratings of service), game controllers [Löchtefeld *et al.* (2017)]. This Vibro-thermal device can be used in following applications:

•Long-Distance communication: Individuals in close relationships can use this device for communicating socially/emotionally and with patterns close to their relationship. This device will add the sense of touch in social or emotional communications.

•Healthcare: Touch plays a very important role in recovering the health of a person. If certain members of a family cannot travel to meet each other, this device will play a prime role in their communication involving touch sensations, thereby improving the condition of the patient.

•Remote learning: Students can use touch as a source to remember certain concepts discussed in their classes. During a science lab session the students can see an experiment being performed remotely and feel the vibrations and/or thermal changes through this device.

•Notifications: This novel device can be used to provide notification in any of the thermal, vibrational or Vibro-thermal modalities. Thermal notifications will act as silent notifications and be useful in environments containing high noise or in silence zones like the library.

•Light-weight interaction platform: The Android application used to control and generate different patterns can have an add-on messaging feature on which two users can engage in and communicate through the sense of touch. This will act as a platform to interact socially within the user's network.

•Navigation: This device can be used in navigation, as the destination comes closer, the intensity of thermal and vibrational cues increase. Implementation using thermal modality can provide secrecy in certain scenarios. Well-designed patterns can provide information about the direction of the destination and its proximity from the user.

•Non-verbal means of communication: This device can be used in places where verbal communication is nearly impossible. In places like heavy machine industry, underwater scenarios and noise restricted environments, this Vibro-thermal display can be implemented as a mode of communication between people in this environment.

•Assistive technology for individuals who are blind or visually impaired: In remote scenarios, a person who is blind or a person who is visually impaired has very less resources for remote interactions with others. This device can provide an enhanced sense of social touch to enrich remote interactions.

Chapter 5

EXPERIMENTS

5.1 Procedure

The procedure for testing the Vibro-thermal haptic display with human subjects is given below:

Informational Phase:

Human subjects were briefed about this research and its potential benefits.

Familiarization Phase:

Participants were provided with the eight pre-defined Vibro-thermal patterns on their forearm and given the name of each pattern for familiarization.

Training Phase:

The research team randomly presented each pattern, and asked participants to identify the name of each pattern. If the pattern was misidentified, participant were corrected; if participants correctly identified the pattern, it was confirmed with them and the process continued until all patterns were played once. To move onto the testing phase, subjects must have 75% accuracy in the training phase (6 out of 8 patterns); otherwise, the training phase was repeated but not more than three times.

Testing Phase:

Participants were randomly presented with 8x3=24 Vibro-thermal patterns in no fixed order and the subjects guessed the patterns. No correction/confirmation was provided to participants after each pattern. The research team noted the responses of the participants for data analysis.

Post-Experiment Survey:

A post-experiment survey was completed by participants, which consisted of responding to Likert-scale questions inquiring about the patterns and their relatability to social touch cues involved in social interactions.

5.2 Implementation

The procedure was performed at room temperature and while the subjects were sitting. Ten subjects of age 25-40 participated in this study with participation being entirely voluntary. Participants placed the ventral part of their forearm on the device; one participant tested this device on their left hand while others tested it on their right hand. A gap of 15-20 seconds was given between each patterns to avoid thermal adaptation to the skin [Jones and Ho (2008)]. Each pattern was presented to the user remotely through the Android application. The entire testing process took less than an hour, and participants were allowed to take a break between different phases if needed.

5.3 Results and Discussion

5.3.1 Results

Table 5.1 displays the confusion matrix of the eight patterns tested with the Vibrothermal device. It can be observed that the pattern SINGLE TAP has the highest accuracy when it comes to identification by the subjects. Also, HOLD/SQUEEZE and RIGHT-DIAGONAL patterns have same accuracy of 96.67%. The patterns RIGHT-LEFT, LEFT-DIAGONAL and LEFT-RIGHT were fairly accurate with accuracies 93.33%, 86.67% and 80% respectively. The patterns DOWN-UP and UP-DOWN had the lowest accuracies with 66.67% and 63.33%, respectively. It can also be noted that the pattern UP-DOWN was more often confused with LEFT-RIGHT and DOWN-UP whereas less often confused with the RIGHT-LEFT pattern. The DOWN-UP pattern was more frequently confused with RIGHT-LEFT, LEFT-RIGHT and less frequently confused with the UP-DOWN pattern. The LEFT-RIGHT pattern was muddled with the DOWN-UP and RIGHT-LEFT patterns. The participants had a little confusion of about 6.67% with the RIGHT-LEFT pattern which is quite less as compared to the previous patterns. In addition, the LEFT-DIAGONAL was confused with the LEFT-RIGHT and RIGHT-DIAGONAL patterns. The RIGHT-DIAGONAL and HOLD/SQUEEZE had an identification accuracy of 96.67%, with around 3.34% being confused with the LEFT-DIAGONAL and SINGLE TAP patterns. The SINGLE TAP pattern was the most accurate, with 100% accuracy.

The participants' responses were noted on how closely the patterns simulated social touch experienced during social interactions with a 5-point Likert scale. The patterns SINGLE TAP and HOLD/SQUEEZE had a mean of 4.90 and 4.70 respectively which shows that all participants Strongly Agreed on these patterns being part of Social Interactions. The diagonals' patterns i.e. the LEFT-DIAGONAL and

PATTERNS	UP-DOWN	DOWN-UP	LEFT-RIGHT	RIGHT-LEFT	LEFT-DIAGONAL	RIGHT-DIAGONAL	HOLD/ SQUEEZE	SINGLE TAP
UP-DOWN	63.33%	13.33%	16.67%	6.67%	0%	0%	0%	0%
DOWN - UP	6.67%	66.67%	10%	16.67%	0%	0%	0%	0%
LEFT-RIGHT	3.33%	10%	80%	6.67%	0%	0%	0%	0%
RIGHT-LEFT	6.67%	0%	0%	93.33%	0%	0%	0%	0%
LEFT-DIAGONAL	0%	0%	6.67%	0%	86.67%	6.66%	0%	0%
RIGHT-DIAGONAL	0%	0%	0%	0%	3.34%	96.67%	0%	0%
HOLD/ SQUEEZE	0%	0%	0%	0%	0%	0%	96.67%	3.34%
SINGLE TAP	0%	0%	0%	0%	0%	0%	0%	100%

Table 5.1: Pattern Identification Confusion Matrix

Descriptive Statistics

	N	Minimum	Maximum	Mean	Std. Deviation
UPDOWN	10	2	5	3.60	.843
DOWNUP	10	2	5	3.50	.850
LEFTRIGHT	10	2	5	3.80	.789
RIGHTLEFT	10	2	5	3.70	.823
LEFTDIAGONAL	10	1	5	4.10	1.449
RIGHTDIAGONAL	10	1	5	4.10	1.449
HOLD_SQUEEZE	10	2	5	4.70	.949
SINGLE TAP	10	4	5	4.90	.316
Valid N (listwise)	10				

Figure 5.1: Likert Scale Analysis of Social Interactions

RIGHT-DIAGONAL patterns had a mean value of 4.10 each and a standard deviation of about 1.5, which reveals that these patterns were relatable to social interactions by most of the participants, but it varied person to person. The patterns LEFT-RIGHT, RIGHT-LEFT, UP-DOWN and DOWN-UP, had a mean relatable accuracy of 3.80, 3.70, 3.60, and 3.50, respectively. From these values, it appears that the above pat-

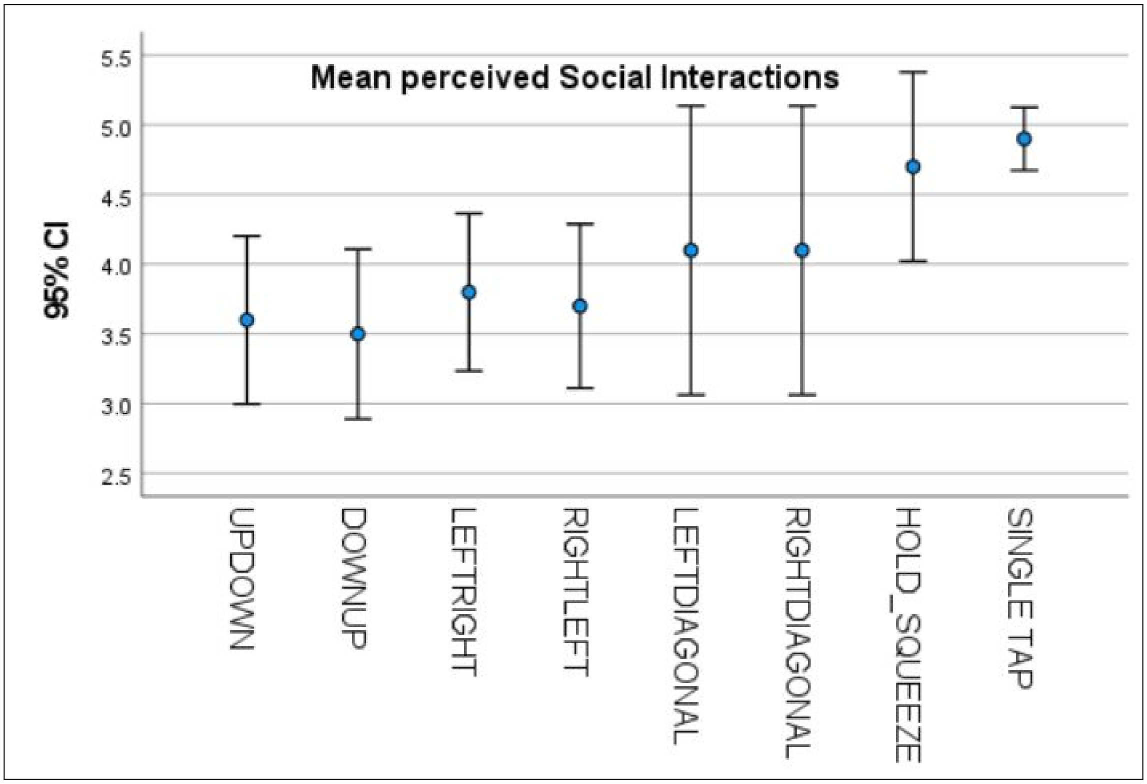


Figure 5.2: Mean Perceived Social Interactions

terns were less likely relatable to any social interactions by the participants amongst all patterns. Also, it was challenging to identify these patterns on the forearm.

5.3.2 Discussion

This research aimed to explore the response of different Vibro-thermal patterns and their relevance to different social interactions on the user's forearm. To explore this, an experiment with subjects was carried with the Vibro-thermal haptic device placed on the ventral portion of the forearm. As the results indicate, the SINGLE TAP was the most recognized pattern followed by HOLD/SQUEEZE and RIGHT-DIAGONAL. The other patterns were less accurate in identification as compared to these patterns. Most of the subjects felt that it was easy for them to recognize the Vibro-thermal patterns with little training. Some participants responded that while a few patterns like the HOLD/SQUEEZE, SINGLE TAP, RIGHT-DIAGONALS, and LEFT-DIAGONAL were easy to identify, patterns such as UP-DOWN, DOWN- UP, LEFT-RIGHT, and RIGHT-LEFT, were confusing and required more concentration. Some modifications were needed for generating complex social patterns through this device. A participant commented that they felt numbness in their forearm after consistent use of this device for 20 minutes, and it became difficult to localize the Vibro-thermal patterns after using this device for some time. The recognition also depended on the user's hand size as the area covered and the precise locations of the patterns generated were different. A participant stated that

> "It was easier to tell if the heat was on the Left or Right, but whether the heat was on the Top or Bottom was hard."

Patterns like SINGLE TAP and HOLD/SQUEEZE were intuitive and very efficient in displaying social interaction cues. The other patterns were quite confusing when it came to social interactions. Some participants pointed out that the patterns LEFT-RIGHT, RIGHT-LEFT, UP-DOWN, and DOWN-UP felt more like they were bumping into things and not like social interactions experienced earlier. Two of the participants could relate most of these patterns with the social interactions from their past. A participant stated that the warmth generated from this device was more than the warmth involved in social interactions; also, the vibrations could be spread out for intuition and better social touch experience.

Most of the participants agreed that this device could be used for social interactions; a person who is blind or a person who is visually impaired could use it to feel social interactions more intuitively. This device would also be beneficial for rehabilitation purposes. A subject discussed that this device in its current prototype would be difficult for social interactions; however, the current prototype will add some value if used during playing games within the family or similar social interactions. A subject responded that this device could be used in places where vocal communication is impossible, like underwater scenarios, and commented that the participant would like to use it for communicating with his diving partners underwater. A participant was interested in using this device during social interactions if substantial modifications were made to the vibrations and thermal patterns. Some of the participants were unsure if they would use this device for communicating socially but were interested in using it for lesser cognitive loads like a feedback device or for being informed discreteely. A subject quoted that

> " I would use it if it were a little easier to recognize."

A participant was also interested in using this device for secure social discussions and message transfers in noisy areas. A participant quoted that

> " Maybe if I were in a VR chatroom, it would be nice to do a tap to get someone's attention or hold/squeeze to do a hug ."

During the experiment's training phase, all participants obtained 75% accuracy i.e. 6 out of 8 patterns identified correctly, in just one attempt. This shows that with little training it is possible to familiarize and identify vibro-thermal patterns on the forearm.

Chapter 6

CONCLUSION & FUTURE WORK

6.1 Conclusion

The thesis aims to understand the response to different patterns generated through a Vibro-thermal display and its relevance to social interactions. It can be concluded from Table 5.1 that the confusion matrix for hot stimulus is quite spread out, which agrees with the previous conclusion made during the study of the Thermal-bracelet [Peiris *et al.* (2019)]. Warm temperatures can be used in application related to social or physical presence as earlier mentioned in The heat of the moment [Wilson *et al.* (2015)]. The patterns like SINGLE TAP and HOLD/SQUEEZE were very relatable to social interactions whereas the other patterns like the UP-DOWN, DOWN-UP, LEFT-RIGHT and RIGHT-LEFT were less relatable to social interactions experienced by the users. The identification of Vibro-thermal patterns on the top and bottom part of the forearm's ventral side was difficult to the users. It was easier to detect Vibro-thermal patterns on the periphery of the forearm than the center of the forearm. Vibro-thermal patterns drawn along the diagonals on the forearm were discernable to human skin but their relatability to social interactions varies from person to person. If Peltier units are used for generating warm temperatures then a heat sink can be eliminated from the design but this need further investigation.

6.2 Future Work

- A smaller size flexible wearable device that has less hardware and is portable.
- Create a pattern generation interface which can enable the user to draw patterns directly on a canvas and interpret them on the device.
- Collect more data from a variety of subjects under different working and environmental conditions.
- The FTED and vibrational motor can be sandwiched together to form a standalone Vibro-thermal unit. As this unit can be easily scalable, it can serve to form an array of arrangements needed.
- To test this device with an ongoing phone call or video conversation.

Future recommendations:

- The Linear Resonant Actuator (LRA) vibrational motor is recommended if complex patterns need to be generated, as the amplitude and frequency can be controlled.
- The Peltier units take some time for temperature change which should be considered while designing Vibro-thermal patterns.
- The forearm is an ideal place to test patterns involving social or emotional interactions.
- The positioning of Vibro-thermal patterns should not change with size of the users forearm.

Future design concept:

In future designs, the metal body of the motor can be used as a heat sink under ideal conditions, which can be a way to manage the excess heat/cold away from the user. Overlapping the Peltier units with the vibrotactile motors will reduce the area in contact with the user's skin. Implementing similar designs with a flexible Peltier unit and flexible vibrational motor can create a unique device with extensive applications.

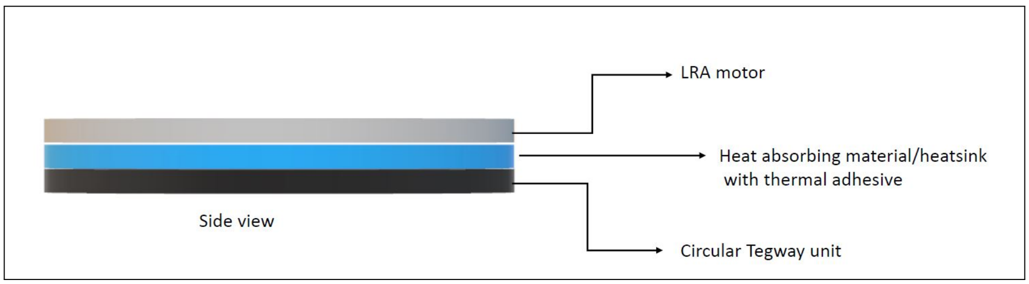


Figure 6.1: Future Work Design Concept

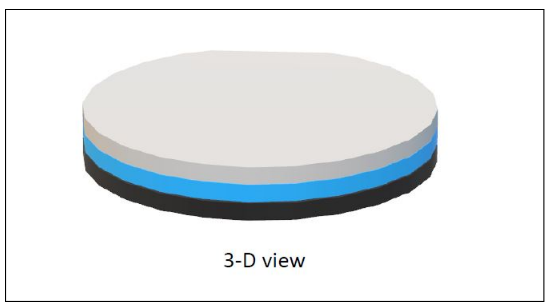


Figure 6.2: Future Work Design 3d View

Vibrotactile patterns to be tested in the future:

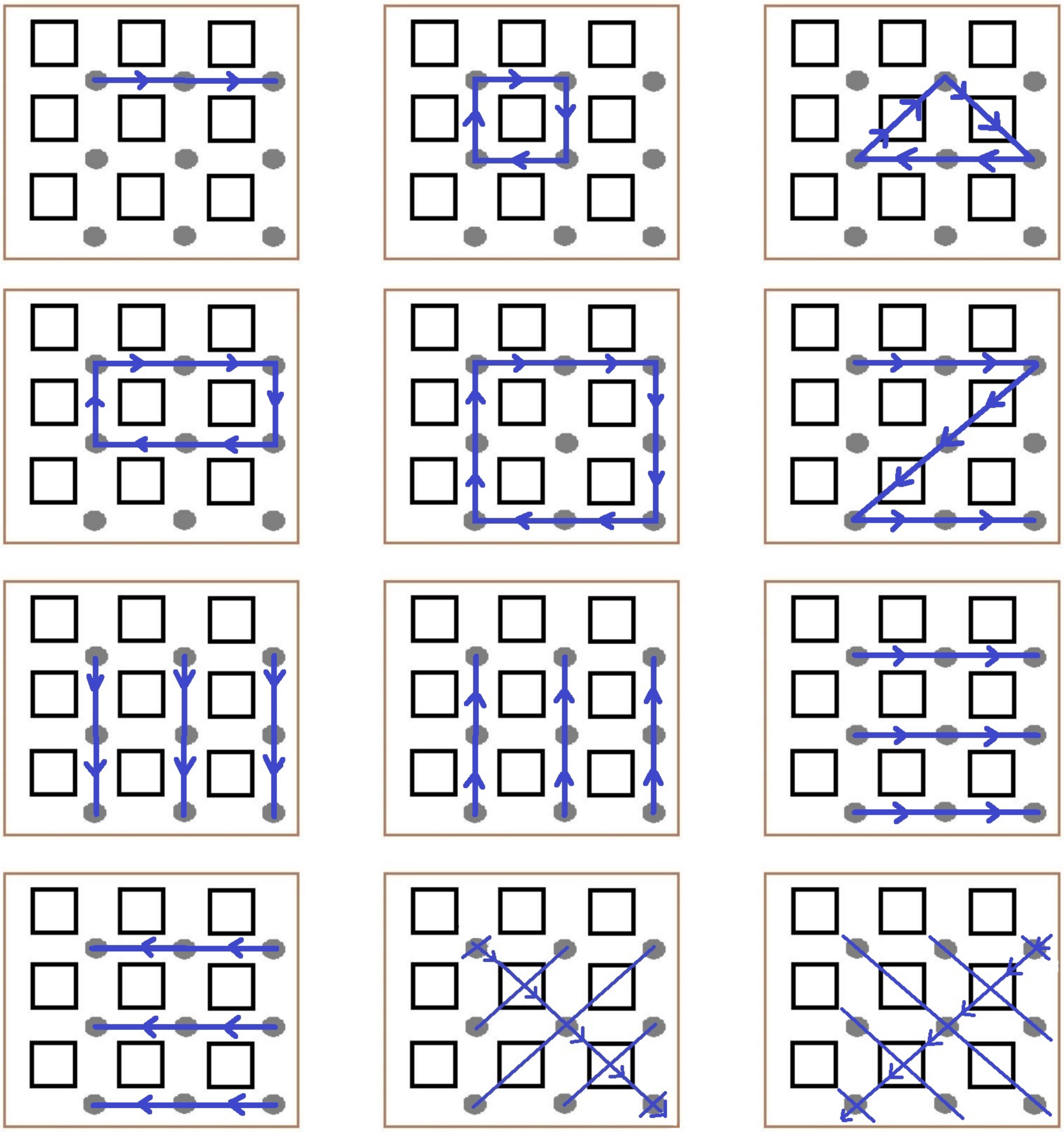


Figure 6.3: Different Patterns Using Vibrotactile Modality

Thermal patterns to be tested in the future:

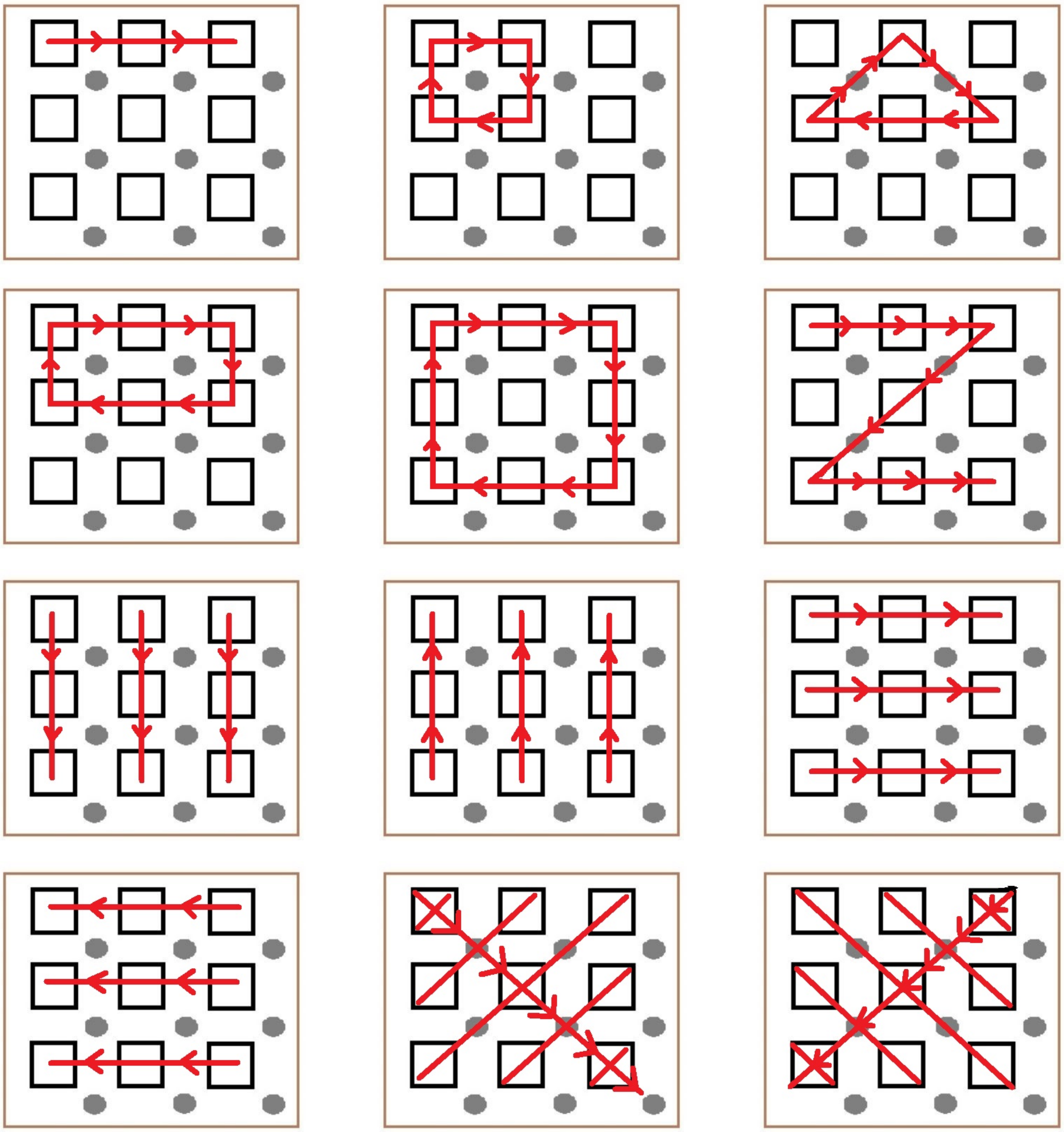


Figure 6.4: Different Patterns Using Thermal Modality

Akiyama, S., K. Sato, Y. Makino and T. Maeno, "Presentation of thermal sensation through preliminary adjustment of adapting skin temperature", in "Haptics Symposium 2012, HAPTICS 2012 - Proceedings", pp. 355–358 (2012).

Balcer, C. A., "VISUAL CUES EFFECTS ON TEMPERATURE PERCEPTION", URL https://commons.nmu.edu/theses (2014).

Cang, X. L. and A. Israr, "Communicating Socio-Emotional Sentiment Through Haptic Messages", IEEE Haptics Symposium, HAPTICS (2020).

Caswell, N. A., R. T. Yardley, M. N. Montandon and W. R. Provancher, "Design of a forearm-mounted directional skin stretch device", Haptics Symposium 2012, HAPTICS 2012 - Proceedings pp. 365–370 (2012).

Chen, Z., W. Peng, R. Peiris and K. Minamizawa, "ThermoReality: Thermally enriched head mounted displays for virtual reality", ACM SIGGRAPH 2017 Posters, SIGGRAPH 2017 **1**, 1–2 (2017).

Chernyshov, G., K. Ragozin, C. Caremel and K. Kunze, "Hand motion prediction for just-in-time thermo-haptic feedback", in "Proceedings of the ACM Symposium on Virtual Reality Software and Technology, VRST", (Association for Computing Machinery, 2018).

El Ali, A., X. Yang, S. Ananthanarayan, T. Röggla, J. Jansen, J. Hartcher-O'Brien, K. Jansen and P. Cesar, "ThermalWear: Exploring Wearable On-chest Thermal Displays to Augment Voice Messages with Affect", pp. 1–14 (Association for Computing Machinery (ACM), 2020).

Gooch, D. and L. Watts, "Communicating social presence through thermal hugs", Sissi2010 pp. 11–20, URL http://tobias.hesselmann.it/wp-content/uploads/2010/11/Proceedings-SISSI-2010.pdf{#}page=11 (2010).

Günther, S., F. Müller, D. Schön, O. Elmoghazy, M. Mühlhäuser and M. Schmitz, "Therminator: Understanding the Interdependency of Visual and On-Body Thermal Feedback in Virtual Reality", pp. 1–14 (Association for Computing Machinery (ACM), 2020).

Gupta, A., A. A. R. Irudayaraj and R. Balakrishnan, "HapticClench: Investigating squeeze sensations using memory alloys", UIST 2017 - Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology pp. 109–117 (2017).

Halvey, M., G. Wilson, S. Brewster and S. Hughes, ""baby it's cold outside": The influence of ambient temperature and humidity on thermal feedback", in "Proceedings of the SIGCHI Conference on Human Factors in Computing Systems", CHI '12, p. 715–724 (Association for Computing Machinery, New York, NY, USA, 2012), URL https://doi.org/10.1145/2207676.2207779.

Halvey, M., G. Wilson and S. A. B. S. A. H. Yolanda Vazquez-Alvarez, "The Effect of Clothing on Thermal Feedback Perception", (ACM, 2011).

He, L., C. Xu, D. Xu and R. Brill, "Pneuhaptic: Delivering haptic cues with a pneumatic armband", ISWC 2015 - Proceedings of the 2015 ACM International Symposium on Wearable Computers pp. 47–48 (2015).

Ion, A., E. J. Wang and P. Baudisch, "Skin drag displays: Dragging a physical tactor across the user's skin produces a stronger tactile stimulus than vibrotactile", in "Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems", CHI '15, p. 2501–2504 (Association for Computing Machinery, New York, NY, USA, 2015), URL `https://doi-org.ezproxy1.lib.asu.edu/10.1145/2702123.2702459`.

Israr, A. and I. Poupyrev, "Tactile Brush: Drawing on skin with a tactile grid display", Conference on Human Factors in Computing Systems - Proceedings pp. 2019–2028 (2011).

Israr, A., S. Zhao, K. Schwalje, R. Klatzky and J. Lehman, "Feel effects: Enriching storytelling with haptic feedback", ACM Transactions on Applied Perception **11**, 3, 1–17 (2014).

Jones, L. A. and H. Ho, "Warm or cool, large or small? the challenge of thermal displays", IEEE Transactions on Haptics **1**, 1, 53–70 (2008).

Katja Suhonen, S. M., J. Rantala, K. Väänänen-Vainio-Mattila, R. Raisamo, Lantz and Vuokko, "Haptically Augmented Remote Speech Communication: A Study of User Practices and Experiences", p. 834 (2012).

Kratz, S. and T. Dunnigan, "ThermoTouch: Design of a high dynamic temperature range thermal haptic display", in "Conference on Human Factors in Computing Systems - Proceedings", vol. 07-12-May-, pp. 1577–1582 (Association for Computing Machinery, 2016).

Krishna, S., S. Bala, T. McDaniel, S. McGuire and S. Panchanathan, "VibroGlove: An assistive technology aid for conveying facial expressions", Conference on Human Factors in Computing Systems - Proceedings pp. 3637–3642 (2010).

Lee, J. and G. Lee, "Designing a non-contact wearable tactile display using airflows", UIST 2016 - Proceedings of the 29th Annual Symposium on User Interface Software and Technology pp. 183–194 (2016).

Lee, W. and Y.-K. Lim, "Explorative research on the heat as an expression medium: Focused on interpersonal communication", Personal Ubiquitous Comput. **16**, 8, 1039–1049, URL `https://doi-org.ezproxy1.lib.asu.edu/10.1007/s00779-011-0424-y` (2012).

Löchtefeld, M., T. Lappalainen, J. Väyrynen, A. Colley and J. Häkkilä, "Comparing thermal and haptic feedback mechanisms for game controllers", in "Conference on Human Factors in Computing Systems - Proceedings", vol. Part F1276, pp. 1829–1836 (Association for Computing Machinery, 2017).

Maeda, T. and T. Kurahashi, “Thermodule:wearable and modular thermal feedback system based on a wireless platform”, in “ACM International Conference Proceeding Series”, (Association for Computing Machinery, 2019).

McDaniel, T., S. Krishna, V. Balasubramanian, D. Colbry and S. Panchanathan, “Using a haptic belt to convey non-verbal communication cues during social interactions to individuals who are blind”, HAVE 2008 - IEEE International Workshop on Haptic Audio Visual Environments and Games Proceedings , October, 13–18 (2008).

Murakami, T., T. Person, C. L. Fernando and K. Minamizawa, “Altered touch: Miniature haptic display with force, thermal and tactile feedback for augmented haptics”, in “ACM SIGGRAPH 2017 Posters, SIGGRAPH 2017”, (Association for Computing Machinery, Inc, 2017).

Mynatt, E., ACM Digital Library. and ACM Special Interest Group on Computer-Human Interaction., “Thermo-Message: Exploring the Potential of Heat as a Modality of Peripheral Expression Abstract”, p. 2174 (ACM, 2010).

Nakatani, M., K. Sato, K. Sato, Y. Kawana, D. Takai, K. Minamizawa and S. Tachi, “A novel multimodal tactile module that can provide vibro-thermal feedback”, Tech. rep. (2016).

Nasser, A., K. Zhu and S. Wiseman, “Thermo-haptic earable display for the hearing and visually impaired”, in “ASSETS 2019 - 21st International ACM SIGACCESS Conference on Computers and Accessibility”, pp. 630–632 (Association for Computing Machinery, Inc, 2019).

Niijima, A., T. Takeda, T. Mukouchi and T. Satou, “ThermalBitDisplay: Haptic display providing thermal feedback perceived differently depending on body parts”, in “Conference on Human Factors in Computing Systems - Proceedings”, (Association for Computing Machinery, 2020).

Peiris, R. L., Y. L. Feng, L. Chan and K. Minamizawa, “Thermalbracelet: Exploring thermal haptic feedback around the wrist”, in “Conference on Human Factors in Computing Systems - Proceedings”, (Association for Computing Machinery, 2019).

Peiris, R. L., W. Peng, Z. Chen, L. Chan and K. Minamizawa, “ThermoVR: Exploring Integrated Thermal Haptic Feedback with Head Mounted Displays”, pp. 5452–5456 (2017).

Roumen, T., S. T. Perrault and S. Zhao, “NotiRing: A Comparative Study of Notification Channels for Wearable Interactive Rings”, pp. 2497–2500 (2015).

Salminen, K., V. Surakka, J. Lylykangas, J. Raisamo, R. Saarinen, R. Raisamo, J. Rantala and G. Evreinov, “Emotional and behavioral responses to haptic stimulation”, Conference on Human Factors in Computing Systems - Proceedings pp. 1555–1562 (2008).

Salminen, K., V. Surakka, J. Raisamo, J. Lylykangas, R. R. Johannes Pystynen, K. Mäkelä and T. Ahmaniemi, "Emotional responses to thermal stimuli.", (ACM, 2011).

Salminen, K., V. Surakka, J. Raisamo, J. Lylykangas, R. Raisamo, K. Mäkelä and T. Ahmaniemi, "Cold or Hot? How Thermal Stimuli Are Related to Human Emotional System?", Tech. rep. (2013).

Sato, S. A. K., Y. Makino and T. Maeno, "ThermOn – Thermo-musical Interface for an Enhanced Emotional Experience", p. 150 (2013).

Singhal, A. and L. A. Jones, "Creating Thermal Icons - A Model-Based Approach", ACM Transactions on Applied Perception **15**, 2 (2018).

Song, S., G. Noh, J. Yoo, I. Oakley, J. Cho and A. Bianchi, "Hot & tight: Exploring thermo and squeeze cues recognition on wrist wearables", in "ISWC 2015 - Proceedings of the 2015 ACM International Symposium on Wearable Computers", pp. 39–42 (Association for Computing Machinery, Inc, 2015).

Suhonen, K., S. Müller, J. Rantala, K. Väänänen-Vainio-Mattila, R. Raisamo and V. Lantz, "Haptically augmented remote speech communication: A study of user practices and experiences", in "Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design", NordiCHI '12, p. 361–369 (Association for Computing Machinery, New York, NY, USA, 2012), URL `https://doi-org.ezproxy1.lib.asu.edu/10.1145/2399016.2399073`.

Tewell, J., J. Bird and G. R. Buchanan, "Heat-Nav: Using temperature changes as navigational cues", in "Conference on Human Factors in Computing Systems - Proceedings", vol. 2017-May, pp. 1131–1135 (Association for Computing Machinery, 2017a).

Tewell, J., J. Bird and G. R. Buchanan, "The heat is on: A temperature display for conveying affective feedback", in "Conference on Human Factors in Computing Systems - Proceedings", vol. 2017-May, pp. 1756–1767 (Association for Computing Machinery, 2017b).

Turchet, L., D. Zanotto, S. Minto, A. Roda and S. K. Agrawal, "Emotion Rendering in Plantar Vibro-Tactile Simulations of Imagined Walking Styles", IEEE Transactions on Affective Computing **8**, 3, 340–354 (2017).

Wilson, G., S. Brewster, M. Halvey and S. Hughes, "Thermal icons: Evaluating structured thermal feedback for mobile interaction", in "Proceedings of the 14th International Conference on Human-Computer Interaction with Mobile Devices and Services", MobileHCI '12, p. 309–312 (Association for Computing Machinery, New York, NY, USA, 2012), URL `https://doi-org.ezproxy1.lib.asu.edu/10.1145/2371574.2371621`.

Wilson, G., S. Brewster, M. Halvey and S. Hughes, "Thermal Feedback Identification in a Mobile Environment", Tech. rep. (2013).

Wilson, G., G. Davidson and S. Brewster, "In the heat of the moment: Subjective interpretations of thermal feedback during interaction", in "Conference on Human Factors in Computing Systems - Proceedings", vol. 2015-April, pp. 2063–2072 (Association for Computing Machinery, 2015).

Wilson, G., D. Dobrev and S. A. Brewster, "Hot under the collar: Mapping thermal feedback to dimensional models of emotion", in "Conference on Human Factors in Computing Systems - Proceedings", pp. 4838–4849 (Association for Computing Machinery, 2016a).

Wilson, G., E. Freeman and S. A. Brewster, "Multimodal affective feedback: Combining thermal, vibrotactile, audio and visual signals", in "ICMI 2016 - Proceedings of the 18th ACM International Conference on Multimodal Interaction", pp. 400–401 (Association for Computing Machinery, Inc, 2016b).

Wilson, G., M. Halvey, S. A. Brewster and S. A. Hughes, "Some like it hot: Thermal feedback for mobile devices", in "Proceedings of the SIGCHI Conference on Human Factors in Computing Systems", CHI '11, p. 2555–2564 (Association for Computing Machinery, New York, NY, USA, 2011), URL `https://doi-org.ezproxy1.lib.asu.edu/10.1145/1978942.1979316`.

Wilson, G., H. Maxwell and M. Just, "Everything's cool: Extending security warnings with thermal feedback.", pp. 2232–2239 (2017).

Yamen Saraiji, M. H., R. L. Peiris, L. Shen, K. Minamizawa and S. Tachi, "Ambient: Facial thermal feedback in remotely operated applications", in "Conference on Human Factors in Computing Systems - Proceedings", vol. 2018-April (Association for Computing Machinery, 2018).

Yang, G. H. and D. S. Kwon, "Effect of temperature in perceiving tactile stimulus using a thermo-tactile display", 2008 International Conference on Control, Automation and Systems, ICCAS 2008 pp. 266–271 (2008).

Yang, G. H., K. U. Kyung, M. A. Srinivasan and D. S. Kwon, "Development of quantitative tactile display device to provide both pin-array-type tactile feedback and thermal feedback", Proc. - Second Jt. EuroHaptics Conf. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst. World Haptics 2007 pp. 578–579 (2007a).

Yang, G. H., T. H. Yang, S. C. Kim, D. S. Kwon and S. C. Kang, "Compact tactile display for fingertips with multiple vibrotactile actuator and thermoelectric module", Proceedings - IEEE International Conference on Robotics and Automation , April, 491–496 (2007b).

Yoo, Y., H. Lee, H. Choi and S. Choi, "Emotional responses of vibrotactile-thermal stimuli: Effects of constant-temperature thermal stimuli", in "2017 Seventh International Conference on Affective Computing and Intelligent Interaction (ACII)", pp. 273–278 (2017).

Yoo, Y., T. Yoo, J. Kong and S. Choi, "Emotional responses of tactile icons: Effects of amplitude, frequency, duration, and envelope", IEEE World Haptics Conference, WHC 2015 pp. 235–240 (2015).

Zhu, K., S. Perrault, T. Chen, S. Cai and R. Lalintha Peiris, “A sense of ice and fire: Exploring thermal feedback with multiple thermoelectric-cooling elements on a smart ring”, International Journal of Human Computer Studies **130**, 234–247 (2019).

APPENDIX A

UNIVERSITY APPROVAL FOR HUMAN TESTING

ASU Knowledge Enterprise Development

APPROVAL: EXPEDITED REVIEW

Troy McDaniel
IAFSE-PS: Polytechnic Engineering Programs (EGR)
480/727-1063
Troy.McDaniel@asu.edu

Dear Troy McDaniel:

On 3/25/2021 the ASU IRB reviewed the following protocol:

Type of Review:	Initial Study
Title:	Vibrational and Thermal haptic display for Social-Emotional Communication through Pattern Generation
Investigator:	Troy McDaniel
IRB ID:	STUDY00013698
Category of review:	
Funding:	Name: Graduate College (GRAD)
Grant Title:	
Grant ID:	
Documents Reviewed:	• GPSA_GRSP_Grant_Letter.pdf, Category: Sponsor Attachment; • Protocol Vibro_thermal_haptic_display, Category: IRB Protocol; • Questionnaire_vibro_thermal_haptic_display.pdf, Category: Measures (Survey questions/Interview questions /interview guides/focus group questions); • Recruitement Script_vibro_thermal_haptic_display.pdf, Category: Recruitment Materials; • Shubham Gharat_MORE_Letter.pdf, Category: Sponsor Attachment; • Supporting document 03-22-2021.pdf, Category: Other; • Vibro_thermal_haptic_display-Consent-Social-Behavioral-Long_updated.pdf, Category: Consent Form;

The IRB approved the protocol from 3/25/2021 to 3/24/2022 inclusive. Three weeks before 3/24/2022 you are to submit a completed Continuing Review application and required attachments to request continuing approval or closure.

If continuing review approval is not granted before the expiration date of 3/24/2022 approval of this protocol expires on that date. When consent is appropriate, you must use final, watermarked versions available under the "Documents" tab in ERA-IRB.

In conducting this protocol you are required to follow the requirements listed in the INVESTIGATOR MANUAL (HRP-103).

Sincerely,

IRB Administrator

cc: Shubham Gharat
Shubham Gharat
Skylynn Young
Yatiraj Shetty
Troy McDaniel