ELECTROTACTONS: DESIGNING AND EVALUATING ELECTROTACTILE CUES

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Abstract

Electrotactile feedback is a novel haptic feedback modality that can be used to evoke a desired level of alertness and emotion or convey multidimensional information to the user. However, there is a lack of research investigating its basic design parameters and how they can be used to create effective tactile cues. This thesis investigates the effect of Electrotactile feedback on the subjective perception of specific sensations, such as urgency, annoyance, valence and arousal, to find the number of distinguishable levels in each sensation. These levels are then used for designing structured, abstract, electrotactile messages called *Electrotactons*. These have potential benefits over vibration-based cues due to the greater flexibility of the actuators. Experiments 1, 2 & 4 investigated the effects of manipulating the basic electrotactile parameters pulse width, amplitude and pulse frequency on perceived sensations. The results showed that all parameters have a significant effect on the perceived sensations, except for pulse frequency not having an effect on valence. Also, pulse frequencies of 30 PPS and above did not influence the perceived sensations. Experiment 3 investigated the use of pulse width, amplitude and pulse frequency to convey three types of information simultaneously encoded into an electrotactile cue. This was the first attempt to design *Electrotactons* using the basic parameters of electrotactile feedback. The results showed overall recognition rates of 38.19% for the complete *Electrotactons*. For the individual component parameters, pulse width had a recognition rate of 71.67%, amplitude 70.27%, and pulse frequency 66.36%. Experiment 5 investigated intensity and pulse frequency to determine how many distinguishable levels could be perceived. Results showed that both intensity and pulse frequency significantly affected perception, with four distinguishable levels of intensity and two of pulse frequency. Experiment 6 investigated the use of intensity and pulse frequency from in Experiment 5 to improve the design of *Electrotactons* on three body locations using two different size electrodes. The results showed overall recognition rates of up to 65.31% for the complete *Electrotactons*. For the individual component parameters, intensity had a recognition rate of 68.68%, and pulse frequency 94.41%. These results add significant new knowledge about the parameter space of electrotactile cue design and help designers select suitable properties to use when creating electrotactile cues.

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Declaration and Contributing Papers

The research presented in this thesis is entirely the author's own work. This thesis exploits only the parts of these papers that are directly attributed to the author:

Experiments 1 and 2 in Chapter 3 have been published at IEEE haptic symposium 2020:

Yosuef Alotaibi, John H. Williamson, and Stephen Brewster.: **Investigating Electrotactile Feedback on The Hand**. *In 2020 IEEE Haptics Symposium (HAPTICS), Vol. 2020-March. IEEE*, Crystal City, VA, USA, 637–642. DOI: 10.1109/HAPTICS45997.2020.ras.HAP20.13.8ee5dc37

Experiments 4 in Chapter 3 and Experiment 5 in Chapter 4 have been demonstrated, presented and published at CHI 2022:

Yosuef Alotaibi, John H. Williamson, and Stephen Brewster.: **First Steps Towards Designing Electrotactons: Investigating Intensity and Pulse Frequency as Parameters for Electrotactile Cues**. *In Proceedings of the 40th Annual ACM Conference on Human Factors in Computing Systems – CHI '22*, ACM Press, 2022. DOI: 10.1145/3491102.3501863

The use of Electrotactile feedback in cars was presented, discussed and published at BCS HCI 2020 :

Yosuef Alotaibi.: **The use of Electrotactile Feedback in Cars**. *In Proceedings the 32nd International BCS Human Computer Interaction Conference*, BCS HCI 2020. DOI: 10.14236/ewic/HCI20DC.12

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Chapter 1

Introduction

1.1 Motivation

Interacting with computing devices on a daily basis is becoming a major part of our life, such as laptops, phones and smartwatches, which present a large amount of information through visual and/or auditory feedback. However, when visual and auditory feedback is not available or inappropriate, such as when driving a car that requires full visual attention or being in a noisy environment that makes auditory feedback useless, it requires other modalities. Therefore, it is essential to create good feedback using alternative modalities that can overcome these obstacles. Through the sense of touch, tactile feedback can solve such obstacles for interacting and communicating with computer interfaces.

For many years, the sense of touch has been researched and used to deliver rich information to the skin through tactile displays. One area of use is aiding people with sensory impairments that require a sensory substitution system to interact with devices effectively, such as Braille, which helps blind or visually impaired people to read text by sensing raised dots representing the alphabet through the fingers [11]. In addition, more advanced tactile modalities have also been used and researched for many applications. Vibrotactile feedback was used in mobile phones to convey multidimensional information to the user [12]. Thermal feedback which was used to deliver navigational cues to drivers [13].

Another use is to design tactile feedback that conveys emotions and affective information. For example, designing vibrotactile cues with varying levels of urgency and annoyance for different events [14]. Another example is expanding the effective range of different tactile modalities by measuring the perceived valence and arousal [15]. However, these modalities have limitations. They can only generate a certain range of tactile experiences and in the case of vibrotactile can be masked by the vibration of the application's environment.

Moreover, the high cost and the size of the actuators for these modalities prevent them from being adopted in portable and wearable devices. To overcome these limitations, it is important to improve or implement good feedback for these interactions through which information can be presented.

Electrotactile feedback is an alternative tactile technology that can overcome the limitations of some of the other modalities, expanding the options for tactile display. It has many potential benefits as it provides a different tactile experience than vibrotactile in many ways. For instance, the actuators used for electrotactile displays are thin and small, flexible, light, durable, highly energy efficient, have no mechanical resonance, and are highly responsive, giving them advantages over the mechanical actuators used for vibrotactile displays [16–20], allowing them to be mounted in different ways on mobile phones, steering wheels, etc., offering new opportunities for haptics. Electrotactile feedback uses the flow of electrical current to stimulate the skin's receptors directly potentially evoking different kinds of sensations to the more common vibrotactile form. Controlling this electrical flow is achieved by manipulating parameters such as pulse width, amplitude and pulse frequency [21].

Studies have investigated the use of electrotactile feedback for many different tactile applications. For example, an electrotactile display has been used to present patterns to the palm of the hand and it showed a high recognition rate [22]. It can be added to haptic devices in VR to make the experience more realistic [23]. In addition, sensations that can be elicited by electrotactile feedback have been found, such as itchiness [6]. These studies show that people are very sensitive to electrotactile stimulation, making it suitable for delivering feedback and eliciting sensations. However, there is a lack of work investigating how to manipulate electrotactile to evoke a range of different sensations to elicit a particular response. In addition, there was no attempt to construct structured and abstract messages using electrotactile feedback that can be used to convey information to the user, similar to the vibration-based Tactons [24] more commonly seen in the literature.

This thesis investigates the subjective perception of electrotactile feedback in terms of functional aspects of alertness (urgency and annoyance) [14] and emotions (valence and arousal) [15, 25] to design cues with desired levels of sensations. This will evaluate the acceptability of using electrotactile as a tactile modality and provides insight into what electrotactile parameter can be used to influence subjective perception. Furthermore, the unique levels of perceived sensations will be then investigated to design and evaluate a novel type of electrotactile icons, called *Electrotactons* that uses electrotactile stimulation to create structured, abstract, tactile messages for user interfaces.

1.2 Thesis Statement

Electrotactile stimulation is a novel form of tactile feedback but has had little study in HCI. This research explores the parameters of electrotactile feedback to create a range of novel tactile cues and encode information in structured messages called *Electrotactons*. Results show that manipulating pulse width, amplitude and pulse frequency can create effective cues and that users can learn the mappings between the *Electrotactons* and their meanings.

1.3 Research Questions

1. **Research Question 1:**

   What parameters of electrotactile stimulation can be used to influence subjective perception?

2. **Research Question 2:**

   How can the parameters of electrotactile feedback be used to encode information in *Electrotactons*?

3. **Research Question 3:**

   What levels of performance can be achieved when these parameters are combined to create *Electrotactons* to present multidimensional information?

1.4 Thesis Outline

Chapter 2, *Literature Review*, presents an overview of tactile perception and the fundamentals of electrotactile stimulation in human-computer interaction. It discusses electrotactile parameters from psychophysical studies, showing how they can influence perception and convey information. It then reviews some of the research areas that use electrotactile feedback in different applications. Finally, this chapter discusses the creation of structured and abstract messages through different tactile modalities that informed the work of this thesis.

Chapter 3, *Investigating Basic Parameters of Electrotactile Stimulation*, presents four experiments. Experiments 1, 2 & 4 investigate how manipulating basic electrotactile parameters (pulse width, amplitude and pulse frequency) affects subjective perception, addressing Research Questions 1 & 2. Experiment 3 builds on the results of Experiments 1 & 2 and investigates the creation of three-dimensional structured and abstract messages called *Electrotactons* to convey information, contributing answers to Research Questions 2 & 3.

Chapter 4, *Investigating Complex Electrotactile Parameters*, presents two experiments. Experiment 5 investigates electrotactile parameters intensity and pulse frequency in a force-choice method to measure how many levels participants can discriminate to answer Research Question 2. Experiment 6 builds on the results of Experiment 5 to improve the design of *Electrotactons* and provide an answer to Research Question 3.

Chapter 5, *Conclusions*, presents a summary of the research done in this thesis and links the findings back to the research questions outlined in the introduction. This chapter discusses the main contributions of this thesis, outlines its limitations and proposes ideas for future work.

1.5 Overview of Experiments

Table 1.1 provides a brief summary of each experiment and links it to the research questions they contribute answers to.

Chapter	**Experiment**	**Research Questions**	**Context and Purpose**
Chapter 3	Experiment 1	1&2	Manipulating pulse width and pulse frequency and measure their effect on the subjective perception of different sensations
	Experiment 2	1&2	Manipulating amplitude and pulse frequency and measure their effect on the subjective perception of different sensations
	Experiment 3	2&3	Using the clear levels of different sensations to create 3D *Electrotactons* and measure their performance
	Experiment 4	1&2	Manipulating intensity (pulse width and amplitude) and measure their effect on the subjective perception of different sensations
Chapter 4	Experiment 5	2	Manipulating intensity (pulse width and amplitude) and measure how many levels participants can discriminate using a force-choice method
	Experiment 6	3	Using the distinguishable levels of intensity and pulse frequency to create 2D *Electrotactons* and measure their performance

Table 1.1: Summary of experiments presented in this thesis and research question the experiments contributed to answering

Chapter 2

Literature Review

2.1 Introduction

This chapter will set up the fundamentals of electrotactile feedback that enable the reader to understand how it interacts with the human skin before investigating its effect on subjective perception and using it to design *Electrotactons*. Section 2.2 provides an overview of the physiology of touch and the haptic system and discusses the concept of skin impedance, types of electrical currents and electrodes in terms of how they affect electrotactile stimulation. Section 2.3 discusses the parameters that play an essential role in controlling electrotactile stimulation to influence perception. Section 2.4 introduces the motivation for the first research question by identifying the limitations in the literature when it comes to investigating the subjective perception of urgency, annoyance, valence and arousal in electrotactile feedback. Moreover, it discusses the techniques and methodologies that have been used to measure the subjective perception of different sensations.

Section 2.5 looks at different use case scenarios that employ electrotactile feedback to convey information to the user such as sensory substitution and virtual reality to better situate the research done in this thesis. Section 2.6 introduces the motivation for the second and third research questions and discusses the literature on different tactile modalities that inspire investigating the use of electrotactile feedback to create structured and abstract cues to convey information. Finally, Section 2.7 provides an overview of different research areas such as pain management and muscle stimulation that use electrical stimulation technology.

2.2 The Sense of Touch

In the area of human-computer interaction, researchers have employed the sense of touch as an interface for computer haptics. The sense of touch which is also called tactile/cutaneous system is part of the field of haptics. Based on the ISO standard, the field of haptics can be defined as sensing and movement of the skin, tendons, muscles and joints and it consists of two distinct sensory systems. The first is the tactile/cutaneous system that provides the sensation on the outer surface of the skin. The second is the kinesthetic system which provides the sensation of static and dynamic body movements in terms of afferent information originating in muscles, tendons and joints [26, 27]. This thesis focuses on the subjective perception of electrotactile and the design of *Electrotactons* by stimulating the cutaneous system. The following literature review, therefore, will focus on cutaneous electrotactile perception, skin and current interaction, skin impedance and electrodes.

2.2.1 The Cutaneous System

When it comes to sensing the surrounding environment, the human skin plays an essential role in sensing things that touch it or objects being handled by the hand so a person can interact with it, the cutaneous system is responsible for these interactions [27]. Furthermore, it can also sense skin deformation from vibration and pressure, as well as electrical current, thermal, and chemical stimulation. In this thesis, the focus is on the perception of electrotactile feedback that can be defined as stimulating the skin nerves using an electrical current producing haptic sensations [1].

As electrotactile feedback stimulates the skin nerves, it is important to understand the physiology of the skin and its different nerve endings that are responsible for tactile sensations. There are two types of skin on the human body: glabrous skin (hairless) and hairy skin, and each contain nerve receptors called mechanoreceptors (nerve endings) that are innervated by the A-β (a primary afferent nerve responsible for tactile input [28]). When the skin is stimulated, the electric membrane potential of both the mechanoreceptor and the nerve connected to it changes inducing an action potential that starts the transmission of an electrical signal towards the central nervous system [29]. There are four types of mechanoreceptors in both skin types located in and between two layers of the skin: the outer layer called the epidermis and the inner layer called the dermis [30]. Under the skin, another type of nerve receptors located in muscles and tendons called proprioceptors are responsible for sensing the position of the body parts [30] that electrotactile feedback can stimulate in cases that will be explained in Section 2.7.

In the glabrous skin, each one of these mechanoreceptors is responsible for sensing a specific skin deformation. The four types (from the outer layer of the skin to the inner) are the Merkel cells located at the tip of the deep epidermal that react to low-frequency vibration and are responsible for the perception of texture and form. Next comes the Meissner's corpuscles located at the epidermal-dermis junction that react to light touch and are responsible for controlling grip and detecting motion. Then Ruffini endings located more deeply within the dermis that reacts to shear deformation, therefore, detecting the direction of the motion very well. Finally, at the end are the Pacinian corpuscles located deep within both the dermis and the subcutaneous fat layer under the dermis that react to high-frequency vibration, therefore, able to perceive temporal patterns [30–32]. Figure 2.1 shows the structure of the glabrous skin and the locations of its mechanoreceptors across the skin layers. Selectively stimulating these mechanoreceptors is possible when using different frequency ranges in vibrotactile [1] Table 2.1, but when using electrotactile, when stimulating the Pacinian corpuscles, the shallow mechanoreceptors are inevitably co-activated [23].

The hairy skin has the same four mechanoreceptors as the glabrous skin but they are spread differently across the skin layers. The Ruffini endings are usually found around hair follicles, and Pacinian corpuscles are rare and usually found around the joints and tendons [30]. In addition, there is a fifth type of mechanoreceptor found only in the hairy skin, called C-fibres. It is a low threshold, slow conducting afferent that responds well to slow touches to the skin (affective touch) but not well to rapid skin deformation, like vibration [33, 34]. This thesis will look at the mechanoreceptors found in both skin types as it investigates electrotactile feedback on three different body locations.

Processing tactile stimuli in the glabrous skin is done through the four mechanoreceptors, whereas in the hairy skin is done through only three mechanoreceptors (Meissner's, Pacinian and Ruffini corpuscles). In addition, the innervation density in the glabrous skin is higher compared to the hairy skin. This makes the glabrous skin strongly sensitive to fine spatial details, like curvatures, corners and edges [9, 30]. This is important as this thesis investigates the subjective perception and recognition rate of electrotactile cues on the glabrous skin of the palm.

Depending on the adapting rate, which is a term used to describe the reactions of afferents to sustained indentations of the skin, the four mechanoreceptors are categorised into two classes: fast adapting (FA), which responds only at the onset and offset skin deformation, but not sustained deformation, and slow adapting (SA), which response to sustained deformation [35]. These classes are then divided into two groups based on the size of their receptive fields. Group I has small receptive fields, and group II has larger receptive fields [36]. When matching each mechanoreceptor with its category and group, we get that the Merkel cells are associated with SA I, Meissner's corpuscles are associated with FA I, Ruffini endings are associated with SA II and Pacinian corpuscles are associated with FA

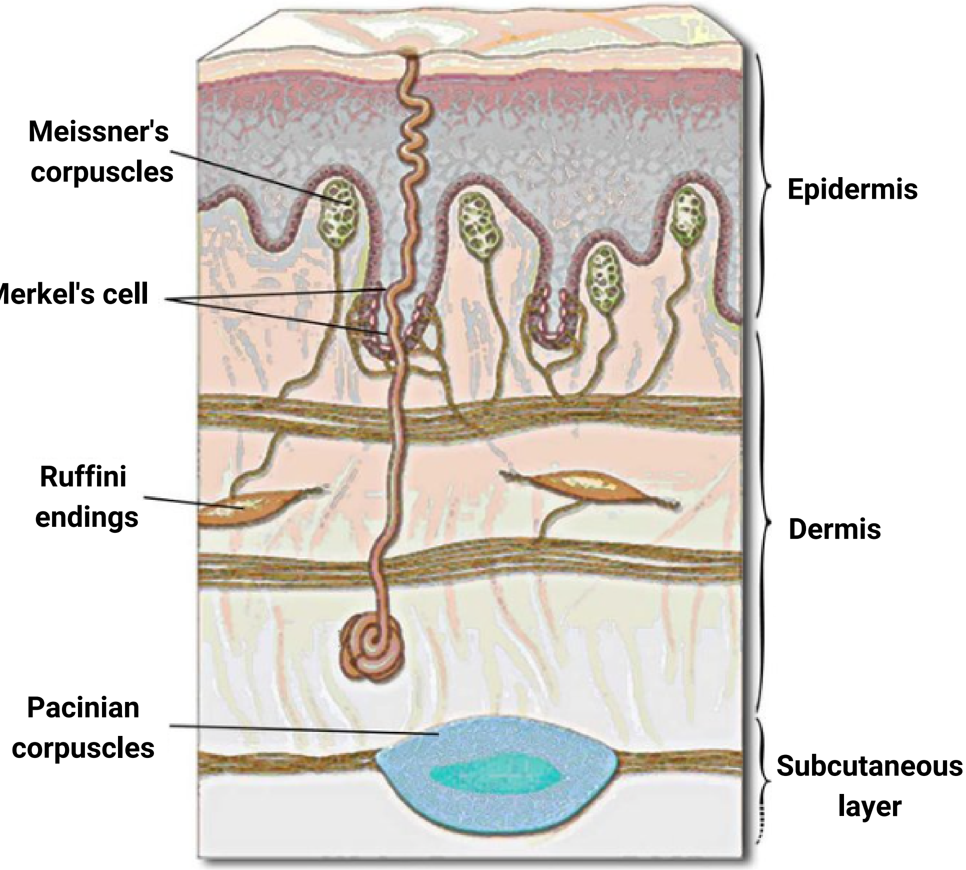

Figure 2.1: A cross-section of glabrous skin, showing the layers of the skin and its mechanoreceptors, edited from [2].

II. Table 2.1 shows the four types of mechanoreceptors, their types and respective sensory modalities.

Type	Meissner's Corpuscles	Merkel's Cells	Ruffini Endings	Pacinian Corpuscle
Class	FA I	SA I	SA II	FA II
Sensory Correlate	Stroking, fluttering, low-frequency vibration	Pressure, texture	Skin stretch	High vibration
Frequency range	10-200 Hz	0.4-100 Hz	7 Hz	40-800 Hz

Table 2.1: Properties of the mechanoreceptors in the glabrous skin and corresponding sensory modalities adapted from [1].

2.2.2 Skin Impedance and Electrical Current Interaction

Now that the structure of the skin and the mechanoreceptors relevant to the sense of touch have been explained, the next step is to understand how the electrical current generated by the stimulator interacts with the skin evoking electrotactile feedback. The skin needs to be a part of a closed electrical circuit so that the current can flow, generating an electrical field that stimulates the mechanoreceptors [21]. To create this circuit, two electrodes are placed on the skin where the current flows from the anode (the positive electrode) to the cathode (the negative electrode). Figure 2.2 shows the flow of the electrical current between the electrodes stimulating the mechanoreceptors.

To make the flow of the electrical current happen, it needs to surpass the skin's resistance. The outer layer of the epidermis is called the stratum corneum, which acts as a barrier to the flow of the electrical current and, therefore, is considered to be the main skin part causing resistance at the skin-electrode interface. The skin resistance towards the electrical current is called impedance; the higher its value, the more electrical current is required to surpass it. The impedance value depends on many factors such as body location, the distance between the two electrodes and if the condition of the skin under the electrodes is wet or sweaty, which reduces the impedance. Once the electrical current starts to flow between the electrodes, the conductance of the stratum corneum increases significantly [37] leading to electrotactile stimulation.

When the closed circuit is established, the flow of the electrical current contains anions (-) and cations (+) that will interact with the mechanoreceptors eliciting a tactile sensation. The mechanoreceptors are electrically excitable neurons transmitting information through electrical or chemical signals. The excitement of the neurons is achieved when the electrical gradient of its cell membrane is changed. When the inside (intracellular), which contains more anions and the outside (extracellular), which has more cations is exposed to an electrical field, the result will be an action potential to transmit information to the central nervous system [29].

2.2.3 Electrotactile Stimulation

Through electrical current, electrotactile feedback is delivered to the skin, which stimulates the mechanoreceptors. Square and sinusoidal waves are the two waveforms of the electrical current used for the stimulation. The square waves are more commonly used and are the standard for electrotactile feedback, as their shape is easy to manipulate [1]. In addition, they provide a quick depolarization of the nerve's axon to improve stimulation and prevent the cells from absorbing ions that might cause damage [38].

The electrical current has two types of polarity: biphasic and monophasic. The biphasic

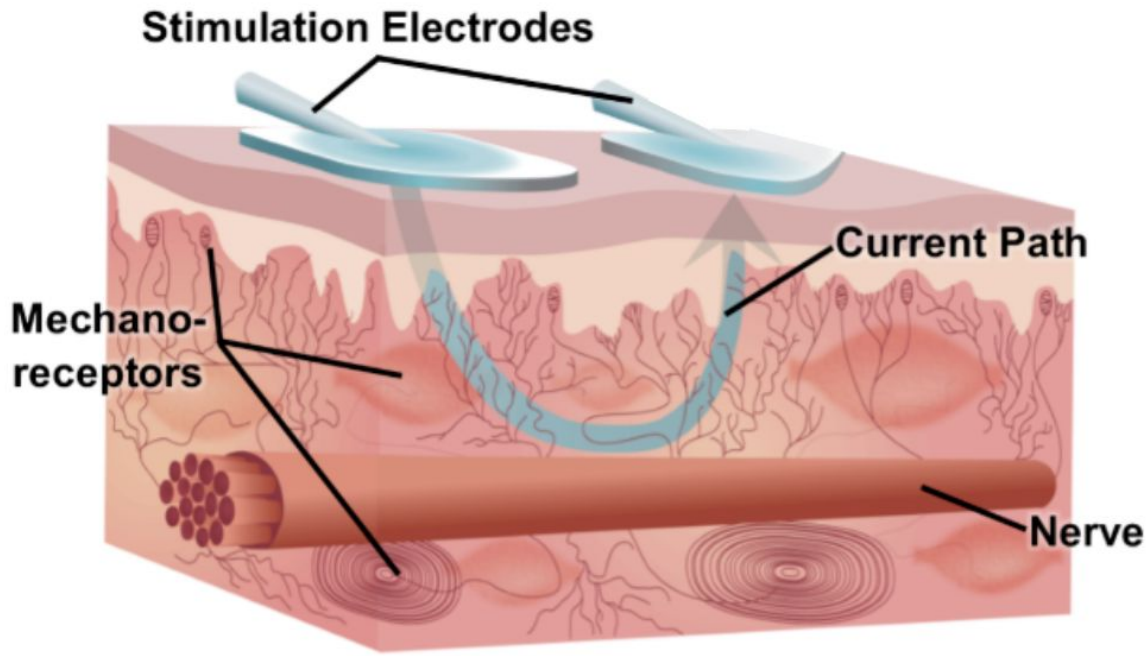

Figure 2.2: The electrical current flowing through the skin between two electrodes [3].

current has two phases. The first phase can be either a positive current (anodic) or a negative current (cathodic) injected into the skin, followed by the second phase of opposite polarity that is equal to the first to maintain current balance. The monophasic current has a single phase current that can be either positive or negative [39]. Figure 2.3 shows the configurations of both types of electrical current. This electrical current is generated by an electrical stimulator made specifically for tactile applications. In the literature, some researchers did construct the stimulator themselves based on their requirements as in Kajimoto *et al.* [16] and Pohl *et al.* [6], and others used off the shelf stimulators such as functional electrical stimulation (FES) used by Stewart *et al.* [40] and Malešević *et al.* [41].

Most of the applications of functional electrical stimulation (FES) use biphasic current, as having two phases of opposite charges helps to avoid the accumulation of charges at the cell membrane that might cause damage or at the electrodes that might deteriorate in prolonged use [42, 43]. This thesis uses a biphasic current in its experiments as it uses functional electrical stimulation (FES) to generate the current and as a safer option.

Both current types have been used in the literature to target a specific sensation or mechanoreceptor. For example, Isaković *et al.* [42] used biphasic current for the pur-

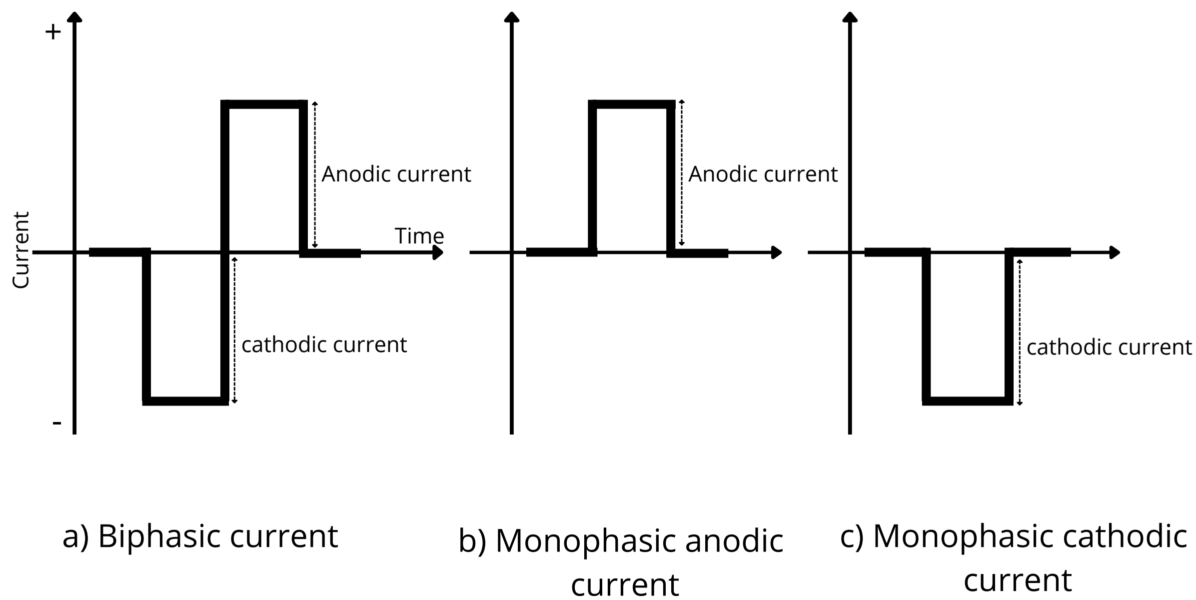

Figure 2.3: The different types of electrical current.

pose of validating their custom-designed multi-pad electrodes that stimulate the fingertips to explore the distribution of sensations in terms of identifying the location of a pad being activated. In their experiment, they placed a pad containing 8 electrodes on the tip of the index finger of 10 participants. After each stimulus, participants were asked which electrode was activated by selecting the location from a PC. The results showed that participants were able to identify the location of the stimulation with a degree of high accuracy when using a biphasic current.

In another study, Kajimoto *et al.* [44] developed an electrotactile display called "tactile primary colours" which elicited a wide range of sensations by stimulating the mechanoreceptors separately. They used two stimulation methods. In the first method, they used array electrodes. The other method used anodic and cathodic currents. Based on the orientation of the mechanoreceptor, a different method of stimulation was used. The FA I is vertical to the skin surface, while SA I and FA II are horizontal. Based on orientation, the anodic current is used to stimulate FA I, while the cathodic current is used for SAI and arrayed electrodes for FA II. They reported that with each stimulation method, participants felt different sensations such as pressure and vibration. The results showed the

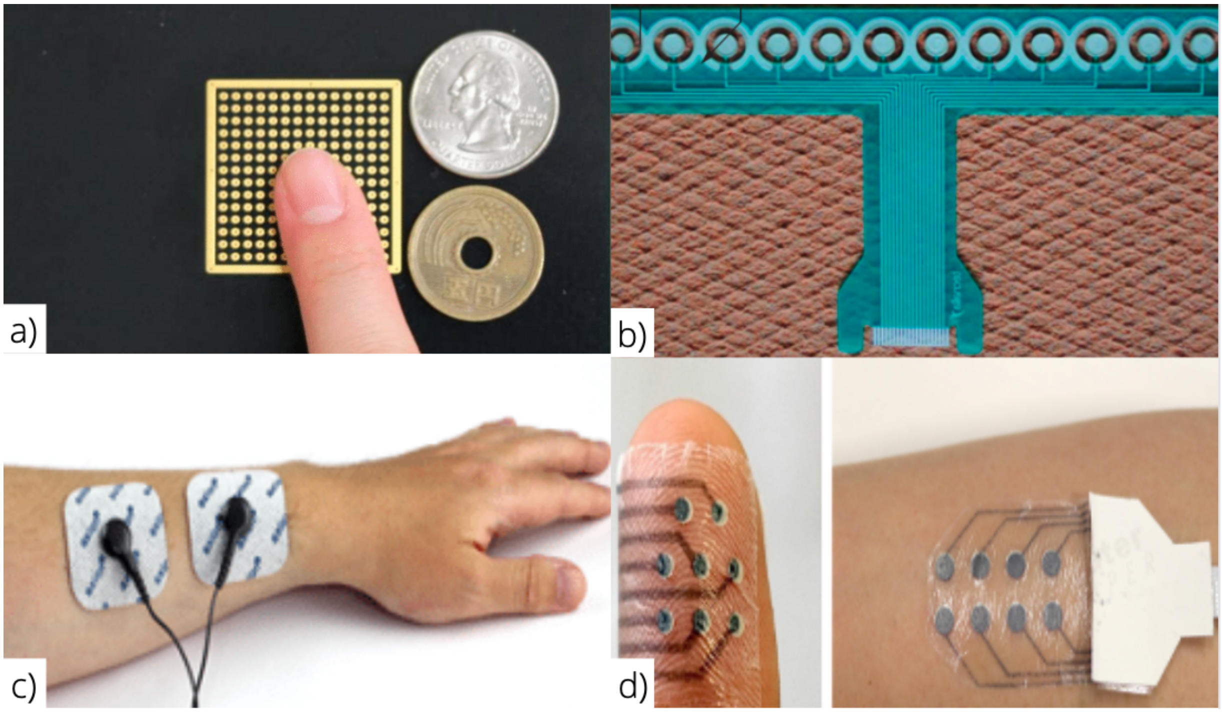

Figure 2.4: Different shapes and configurations of electrodes. a) A multi-electrodes electrotactile display [4]. b) A concentric configuration electrodes with a circle shape cathodes and concentric anodes [5]. c) Self-adhesive wet gel electrodes [6]. d) Two different configurations of electrodes film used for Tacttoo [7].

possibility of targeting a specific mechanoreceptor by using different current types.

2.2.4 Electrodes

The means by which electrical current can stimulate the mechanoreceptors is the electrode. Two electrodes are used to achieve the flow. One electrode would be a cathode (+), and the other would be an anode (-), depending on the type of current being used as explained in the previous section. The electrodes need to be in contact with the skin during the stimulation to form a close circuit. Otherwise, there will be no stimulation.

Surface electrodes are the most popular in electrotactile applications, as they are not invasive and attached to the skin, making it easy to stimulate the mechanoreceptors. They play a crucial role in the transmission of the electrical current from the stimulator to the skin; therefore, they are responsible for the quality of the stimulation. Size, shape, configuration, material and placement of electrodes directly impact the perception of electrotactile feedback and are determined based on the application's design. Figure 2.4 shows some examples of different electrodes.

Current density is one of the concepts mentioned in the literature when talking about the size of the electrodes. It is defined as the amount of current flow per unit area, so high current density means a high amount of current is in a particular area of the skin under the electrode [45]. However, there is an inverse relationship between the current density and the size of the electrodes. The smaller the electrodes, the higher the current density, which may lead to an uncomfortable sensation [46]. For example, when using two electrodes of different sizes with the same current amplitude, the smaller electrode will stimulate the mechanoreceptors more as it has a higher current density than the large electrode.

When designing electrotactile feedback, the electrodes need to be made of materials that offer a conductive surface. Common conductive materials include silver, gold, platinum and similar alloys [47]. One of the early electrodes used for electrical stimulation was metal plate electrodes covered by fabric tissue. The metal has to be made of biocompatible material, such as stainless steel or silver/silver chloride. The fabric is often made of an elastic polymer textile material that is conductive by getting wet with water or electrode gel. The problem with these electrodes was that the distribution of the electrical field under the electrodes was unequal, which may cause severe skin burns. Carbon rubber electrodes came after as a safer alternative by covering the metal plates with carbon rubber and not allowing direct contact between the skin and the metal. The resistance of the carbon rubber is higher than the metal, which helps prevent high current concentrations in small areas. Gel or water at the contact point is needed when using a higher current and recommended with low current [8].

The latest material is the self-adhesive hydrogel electrode. A multi-layer configuration of hydrogel is used to make these electrodes, as shown in Figure 2.5. The electrode-skin interface hydrogel layer has an electrically conductive gel that has a low peel strength. On top of it, a second hydrogel layer connects the substrate layer, which is made of a low-resistive material similar to carbon rubber with the electrode-skin interface layer. The purpose of the second hydrogel layer is to provide a good adhesive to the substrate layer. The scrim layer is located between the two hydrogel layers that prevent slippage and can distribute the electrical current equally [8].

The shape and the configuration of the electrodes affect the sensation elicited. One of the most basic configurations is using two self-adhesive electrodes that can match the ergonomics of the body part they are attached to, as seen in Figure 2.4 (c). The spacing between the electrodes can dictate how deep the electrical current can travel inside the skin. Takahashi *et al.* [48] did a study investigating the effect of electrode spacing on the force sensation by stimulating the skin on the wrist. They had two conditions: wide spacing (16 mm) and narrow spacing (1 mm). After each trial, participants were asked to quantify the perceived force sensation by pulling a spring scale. Their results showed that the wide conditions generated a clearer force sensation indicating that the current stimulated the proprioceptors, which are located deeper under the mechanoreceptors.

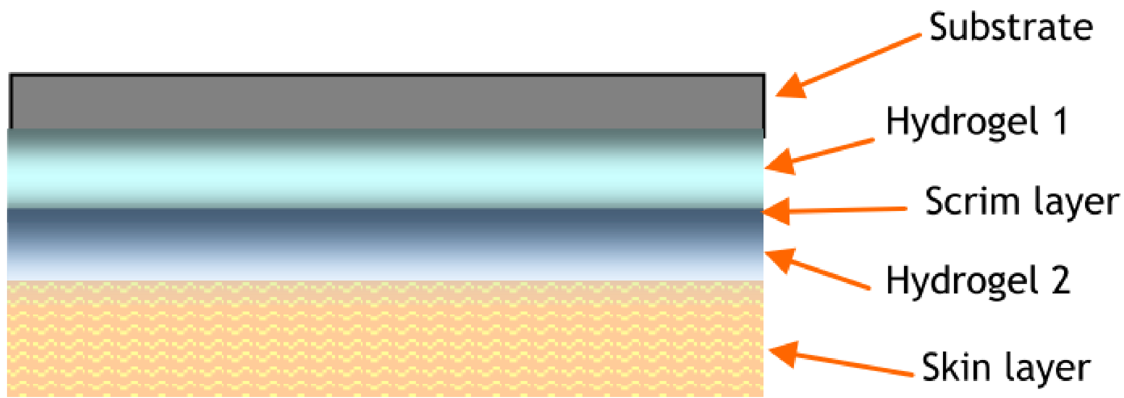

Figure 2.5: The multi-layer configuration of the Self-adhesive hydrogel electrodes, adapted from [8].

A multi-electrodes electrotactile display is another configuration used in applications that require a high electrode density, as seen in Figure 2.4(a). Kajimoto *et al.* [4] proposed an electrotactile display with 196 electrodes in total that can be used in touch screens. The diameter of each circular electrode was 2 mm, and the centre distance between the two electrodes was 3 mm. This high-resolution display allows patterns of different shapes to be presented. Their system can measure the position of the finger and present the stimulating pattern to the electrodes under the finger. Only one stimulating electrode can be activated at a time. Figure 2.4(d) shows a multi-electrodes film that can be applied to complex body geometries in a thin and conformal form factor [7]. Another configuration of electrodes as seen in Figure 2.4(b) is called concentric electrodes. It has an inner electrode and an outer ring electrode that minimize current leakage to the adjacent tissues for more precise stimulation [47].

2.2.5 Summary

The electrotactile stimulation used in all experiments in this thesis was generated using a functional electrical stimulation (FES) that produced a biphasic electrical current. The electrodes chosen were self-adhesive hydrogel electrodes. They are easily applied and can be securely attached to the skin. In addition, the current is distributed equally across the area of the electrode causing the mechanoreceptors under it to be stimulated equally and minimizing discomfort.

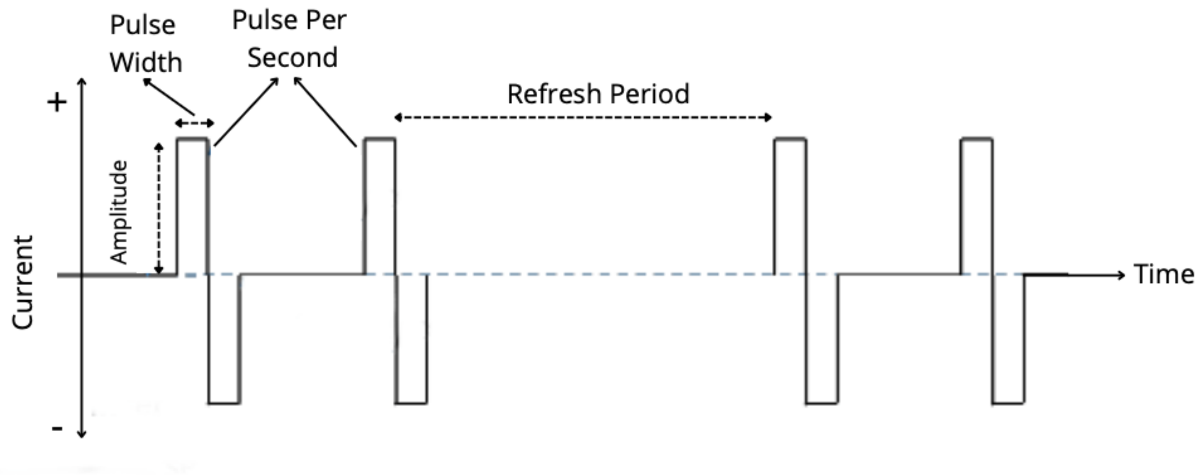

Figure 2.6: The structure of a biphasic electrotactile stimulus. The X axis is time, the Y axis is amplitude.

2.3 Perception of Electrotactile Parameters

To employ *Electrotactons* in HCI applications, it is necessary to understand the individual parameters of electrotactile feedback to elicit a specific sensation or encode information, and the capabilities and limitations of the human skin when perceiving these parameters. Figure 2.6 shows the structure of the electrotactile signal, and its basic parameters that can be manipulated, such as amplitude, pulse width and pulse frequency. By manipulating one of these parameters or combining them, different sensations can be evoked or used to encode information. When basic parameters are combined, it creates complex parameters. The combination of amplitude and pulse width creates the parameter intensity. The parameter rhythm is the combination of different intensities and durations. There are other parameters, such as body location, and type of electrical current, which were explained in the previous section. In this section, an overview of each of these parameters will be provided, and its relevance when using each of these parameters in *Electrotactons* interface design. In addition, looking at the different thresholds for each of the parameters that cause a change in perception.

2.3.1 Basic Parameters

Amplitude

The Y axis in Figure 2.6 is amplitude, and it refers to the magnitude of the electrotactile stimulus delivered to the skin measured in milliampere (mA) and contributes to the intensity of the stimulation [38, 49]. The electrotactile stimulus increases from 0 mA to a specific value for some time and returns to 0 mA. To elicit an effect while remaining comfortable, the amplitude must be high enough to be felt [50]. The range of amplitude used for electrotactile feedback varies depending on the person, the electrical stimulator and the size of the electrodes, making it difficult to decide the range without calibration.

Giron *et al.* [51] conducted an experiment to mimic tactile sensation using electrotactile feedback on the finger by varying only the amplitude. They used an amplitude range between 0 - 15 mA and made pulse width fixed at 200 μs and pulse frequency fixed at 10 PPS. Amplitude was increased by 0.5 mA every 5 seconds from 0 to 15 mA, and every time participants perceived a different sensation, they clicked a button. The results showed that changing the values of amplitude did evoke different sensations when the differences between the two stimuli were between 1 mA and 2.50 mA. This implies that the parameter amplitude could be used to encode information but it needs to be investigated as this thesis uses different hardware and body locations.

Pulse Width

Pulse width is the length of time that amplitude lasts before going back to its baseline value, determining the amount of charge delivered measured in microseconds (μs). Besides amplitude, pulse width also contributes to the intensity of the stimulation [38, 49]. The range used for electrotactile feedback varies for the same reasons as amplitude. Pulse width was investigated as a feedback variable by Dideriksen *et al.* [52]. They placed one electrode on the forearm in the middle and the other on the dorsal side. The pulse width was incremented in 50 μs steps while amplitude and frequency were fixed at 305 mA and 70 PPS. In the experiment, they asked participants to track a predefined target trajectory using a joystick that indicates the tracking error with electrotactile feedback. The correct rate of the tracking was 69%, indicating that it can be used as a parameter to encode information. This demonstrates that pulse width has the potential to be used in the design of *Electrotactons*.

Pulse Frequency

Pulse frequency is the number of electrotactile pulses in a second measured in pulses per second (PPS) Figure 2.7. The mechanoreceptors' perception of electrotactile pulse frequency has a lower threshold compared to vibrotactile. Saunders *et al.* [53] recommended that the optimal pulse frequency range for electrotactile stimulation is between 2-100 PPS. The use of electrotactile pulse frequency in the literature was associated with different senses: such as vibration and roughness, and the discriminability of its different levels was investigated.

Kajimoto *et al.* [17] constructed a mechanical and electrotactile stimulator to selectively stimulate Meissner corpuscles and Pacinian corpuscles. In the first step, they presented

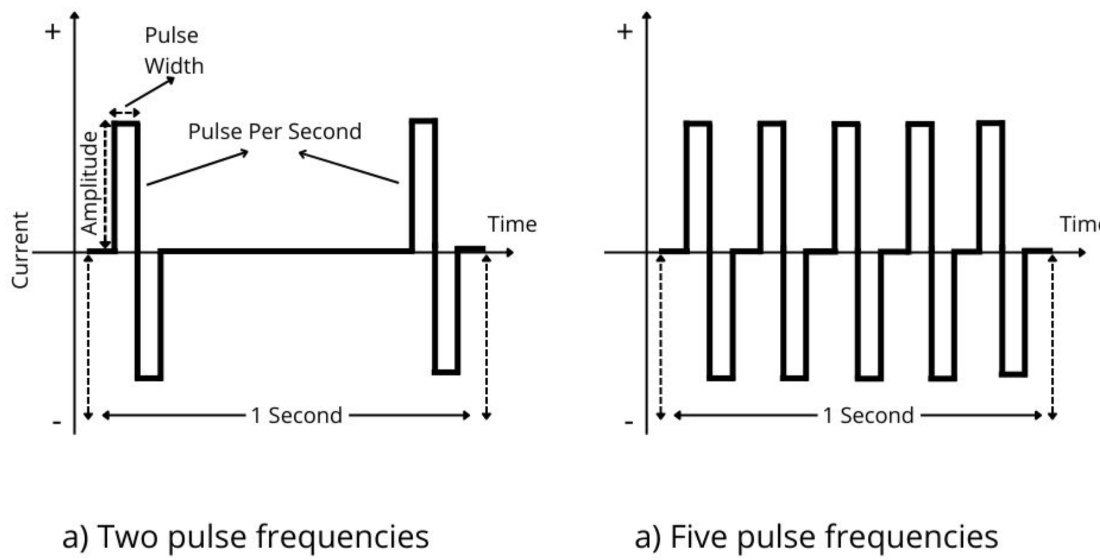

Figure 2.7: Two signals with the same amplitude and pulse width, but different pulse frequencies.

participants with two mechanical stimuli (standard and comparison) with an amplitude of 0.1 mA, and duration of 1s and asked participants which stimulus was higher. The standard frequencies were 15, 30, 60, and 120 PPS, and the comparison frequency started from either 0.5x or 2.0x the standard frequency. In the second step, they did the same with electrotactile stimuli; the amplitude was 2.4 mA, the pulse width was 0.2 ms and the same frequencies as the mechanical stimuli with the addition of 45 PPS. They assumed that the perception of electrical stimulation would be the same as the mechanical one. After comparing the results, the frequency discrimination threshold was the same for both modalities at 15 and 30 PPS, because Meissner corpuscles were activated in both electrotactile and mechanical stimulation. At high pulse frequencies, both Meissner and Pacinian corpuscles were activated by mechanical stimuli, making it possible to distinguish between different pulse frequencies. For the electrotactile stimuli, participants could not distinguish frequencies at 45 PPS and above. The reason was that only Meissner corpuscles were activated making it hard to distinguish them.

An electrotactile augmentation technique for roughness modulation of real materials using pulse frequency was proposed and evaluated by Yoshimoto *et al.* [54]. They confirmed that the perceived roughness at the finger pad can be altered using electrotactile augmentation by controlling pulse frequency. In their experiment, they investigated how to modulate the perceived roughness of wood, Velcro, leather and tracing paper using 6 levels of pulse frequencies (0, 20, 40, 60, 80, and 100 PPS). The electrical stimulation was applied to the participant's fingertips when they explored the materials. Their results showed that pulse frequency had a significant effect on perceived roughness in the presence of real materials. This study gave an insight into how to evaluate the discriminability of different levels of pulse frequency when electrotactile feedback is used alone, as it would be when mounted to a mobile phone, for example.

2.3.2 Intensity

Both amplitude and pulse width govern the amount of electrical charge applied to the stimulated area. When one of them increases, the level of perceived intensity would increase [6]. Finding the balance between amplitude and pulse width is key for using intensity as a parameter for designing electrotactile feedback stimuli. To understand how the intensity level of electrotactile stimulation affected perception, Kaczmarek *et al.* [55] conducted two experiments using a 7x7 49-point fingertip electrotactile display. In the first, they used eight equally spaced intensity levels ranging from just below the sensation threshold to just below the discomfort threshold to present four patterns. The task was to identify the shape of the pattern presented. The results showed that the recognition rate of the pattern increased as the intensity level increased. The second experiment was the same as the first, except the stimulation range was from no stimulation to sensation threshold, and the results were the same, with increasing intensity leading to an increase in recognition rate. These results indicate that intensity is a valid parameter candidate for creating *Electrotactons* but further research is needed to understand the range of sensations that can be produced and how many discriminable levels there are for a useful cue design.

2.3.3 Combinations of Different Parameters

Manipulating more than one parameter in electrotactile feedback can be used to deliver the same information or each parameter can be manipulated independently to encode a different dimension of information or sensation. This would expand the design space of electrotactile feedback effectiveness and efficiency. Okpara *et al.* [56] investigated the perceptual effect of manipulating electrotactile intensity and pulse frequency in a single cue. The electrodes were placed on the middle finger of the left hand. Four levels of both intensity and pulse frequency were tested. The study consisted of two sessions and each had three phases. The first was a calibration phase where minimum intensity I_s and maximum intensity I_m were recorded. In addition, ten intensity measurements (five at 10 PPS and five at 100 PPS) and the average calculated I_s at 10 PPS and the average I_m at 100 PPS were also recorded. The frequencies used were 10, 15, 35, and 100 PPS. In the second phase, participants were given 120 pairs of stimuli and were asked to rate each pair as "same" or "different". The third phase was the same as the second, but the order of the pairs was reversed. They found a strong relationship between the stimulus and perception. The higher one of the parameters, the greater the sensitivity to the other parameter variations.

In another similar study investigating the combination of intensity and pulse frequency, Kaczmarek *et al.* [57] investigated its effect on perception and how to make a predictable and reliable presentation of specific sensations. They manipulated both intensity and pulse frequency to see how many perceptual dimensions electrotactile feedback can produce. They used four levels of intensity that were selected between the sensation threshold and discomfort threshold that achieve approximately uniform differences in the perceived change of sensation intensity, and four levels of pulse frequency 10 PPS, 51 PPS, 35 PPS, and 100 PPS making 16 conditions. Participants were presented with 120 pairs of stimuli and judged the dissimilarity between the first (A) and second (B) presented on their fingertips. The pairs were presented in A-B and B-A formats. Results showed that participants had a high rate of discriminating between the stimuli, making it reliable for encoding information into these parameters. In addition, they found that with higher intensity levels, a greater range of pulse frequencies can be perceived. The methodology of this study will influence the way this thesis investigates intensity.

2.3.4 Calibration

In the majority of studies that involve electrotactile feedback, the calibration phase is essential to set up the detection and discomfort thresholds for each participant. The reason for this is skin impedance. As mentioned in Section 2.2.2, the impedance of the skin depends on its condition, which influences the perception of the electrotactile feedback. People differ in their skin condition, as what might be perceived as a low intense stimulus for one participant could be perceived as a high-intensity stimulus for another.

Not including a calibration phase when designing electrotactile feedback may cause discomfort, skin irritation, and absence of sensation [58]. Researchers used different methods of calibration to set up the appropriate electrotactile stimulation thresholds. The method of limits has been used, where the experimenter would increase the intensity of the stimulus until the participant indicates the detection or discomfort threshold. In addition, the method of adjustment was also used, which is the same as the method of limits, except that the participant would be in control of increasing the intensity of the stimuli [59].

Štrbac *et al.* [5] used the method of limits to determine the detection threshold for their experiment. They set the pulse width to be fixed at 200 μs, while increasing the amplitude by 0.1 mA steps until the participant indicated that they felt the stimulation. The other amplitude value was above the detection threshold to obtain a pleasant, but distinct sensation, as they only needed two intensity values for the experiment. The method of adjustments was used by Kaczmarek *et al.* [60]. They asked their participants to tweak a knob clockwise or counterclockwise to obtain detection and discomfort thresholds.

Other methods were also proposed and implemented in an attempt to optimize and automate the calibration of electrotactile stimulation. Pohl *et al.* [6] created thirty stimuli randomly from a parameter space (2–5 ms pulse width, 0–150 steps of the amplitude and 30–80 pulse frequency) for each participant and asked them to rate them by no movement, slight movement or strong movement. Then used the collected data to find a plane in the parameter space that tells which parameters resulted in movement from those that did not. Real-time pulse width modulation was proposed by Kajimoto [16] to monitor the skin impedance to stabilize electrotactile stimulation. When the skin is in contact with the electrotactile display, a feedback loop of approximately 1.45 μs was used to measure the impedance. Based on the impedance, the pulse width is calculated to be used for the stimulation.

2.3.5 Spatial location

Spatial location refers to the user's body location to be stimulated by electrotactile feedback. Given their size, the electrotactile electrodes can be placed on any body location and they are only bounded by the design of the application. Spacial location can be used as a parameter in two ways; first, encoding information into the location. Second, encoding information in the pattern in which the electrodes are activated. In addition, as discussed in Section 2.2.1, depending on body location, glabrous or hairy skin, tactile sensitivity varies. The choice of a body location when designing electrotactile feedback needs to be considered carefully. In the literature, the fingertips are commonly used as it is innervation dense, making them highly sensitive with good spatial acuity [9], making them ideal for an application that requires the user's touch, but impractical for wearable devices. Choosing a different body location like the forearm frees the hands, but the spatial acuity will be lower as the innervation density is low. Figure 2.8 shows the innervation density of different skin regions over the whole body.

When choosing two points of stimulation on the body in a way that they are perceived as different locations is called the two-point limen. The direction of the effect on the two-point limen in electrotactile stimulation can vary depending on the specific parameters of the stimulation, such as the frequency, amplitude, and duration of the pulses. In general,

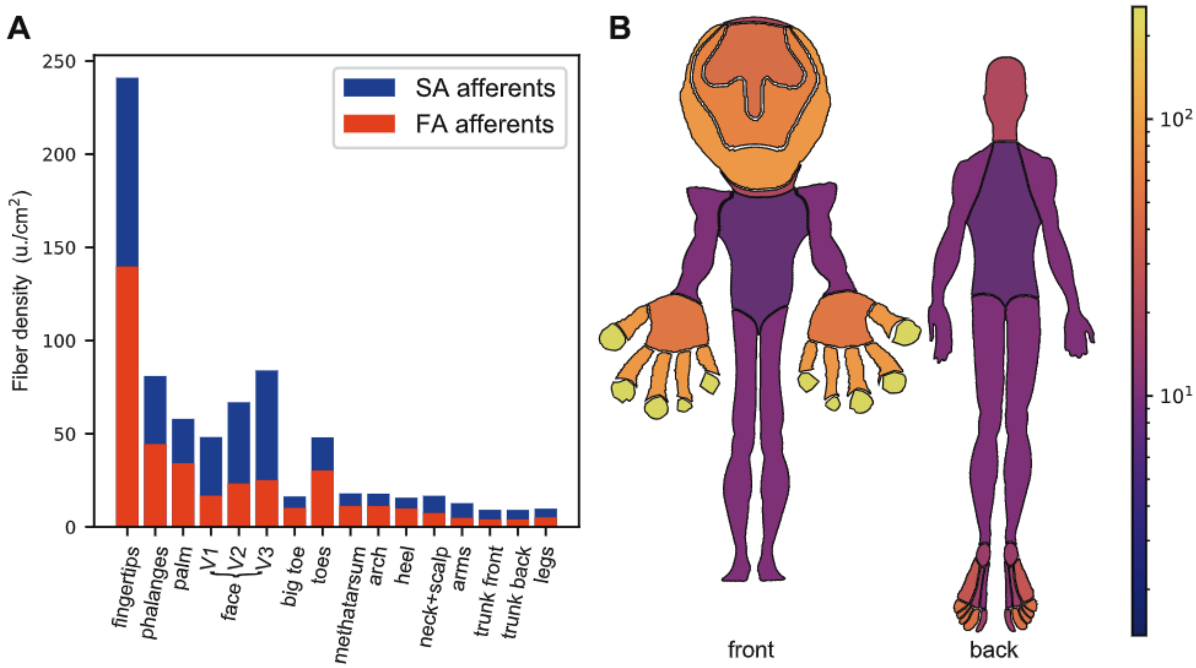

Figure 2.8: Whole body tactile innervation densities. a) A graph showing the total innervation density for the SA and FA afferents for different skin regions. b) Illustration of the whole body peripheral innervation density for both SA and FA. The colour and scaling of each body area indicate its innervation density (units/cm^2), adapted from [9].

the two-point limen in electrotactile stimulation can be affected by the spatial resolution of the electrodes and the size of the receptive fields of the skin [61]. The two-point limen for electrotactile feedback on the skin of the back was found to be 5 mm, which is slightly smaller than vibrotactile, as electrotactile does not have mechanical resonance [62]. This distance varies across the body based on innervation. The lower the innervation density, the greater the distance between two electrotactile stimuli need to be further apart to be discriminated [9]. Solomonow *et al.* [63] conducted an experiment to investigate how the manipulation of pulse frequency and pulse width affect the perception of the two-point limen using two stainless steel concentric electrodes on the palm. They would slowly bring the two electrodes closer to each other during the stimulation until the participant reported a single stimulus. This was repeated for pulse frequencies 5 PPS to 100 PPS with a pulse width of 10 μs and 100 μs. The results showed the two-point limen depends on both parameters, and that they are independent of each other.

2.3.6 Duration

The term duration here refers to the length of the electrotactile stimulation. It is the time from the onset to the termination of the stimulus, and it can be expressed in seconds (s) and milliseconds (ms). When designing electrotactile cues, it is important to choose the appropriate duration that serves the main task of the application. It needs to be long enough to be detected by the user but not too long to make conveying information too slow. Geldard *et al.* [64] picked the appropriate stimulus duration to be between 0.1 and 2 seconds. They stated that a stimulus less than 0.1 seconds is likely to be perceived as a nudge or a poke, and longer than 2 seconds result in a slow perception of information.

When it comes to electrotactile stimulation, the perception fluctuates with time as physiological changes affect skin conductivity that may cause a lack of detection or discomfort [65]. In addition, the intensity of the electrotactile stimulation plays a role in the duration of the stimulus. The higher the intensity, the shorter the duration users can tolerate the stimulus. The duration time for electrotactile stimulation in the literature varies from 0.4 seconds [66] to 3 seconds [67] depending on the application, the electrical stimulator, the size of the electrodes, the conductivity of the skin and the intensity of the electrical current.

2.3.7 Rhythm

The use of rhythm as a parameter to encode information has been used in different tactile modalities. For example, in vibrotactile, it is the combination of vibration bursts, different intensities and gaps of different durations inspired by musical rhythms. The number of vibration bursts that can be perceived in a given time needs to be considered when designing rhythms. Kosonen *et al.* [68] conducted an experiment investigating the perception of rhythms through three different modalities such as; audio, vibrotactile and visual. They presented three lengths of rhythms: 4, 5 and 6 beats using one of the modalities and asked the participant to reproduce the rhythms as accurately as possible by clicking the mouse button. They reported that the audio modality performed the best with 92.1% accuracy, followed by vibrotactile 86% then visual 82.5%. From the subjective data, several participants stated that the tactile modality was as good as audio when presenting the rhythms. These results indicate that tactile modality may use rhythm as a parameter to convey information.

Using rhythm as a parameter in vibrotactile to convey information was investigated by Brown *et al.* [69]. They used rhythm and roughness as parameters to encode a message's type and importance. Three different rhythms were used to represent three types of messages: voice call, text message and multimedia message. To make sure each rhythm felt different, they used a different number of notes (short and long) for each rhythm. Three distinct levels were used for roughness to present high, medium and low importance. The results showed that rhythm was recognized with 93% accuracy, while roughness had 80%. These results make rhythm a strong candidate to be used as a parameter in vibrotactile displays. There was no literature using rhythm as a parameter in electrotactile feedback. Given the promising results from different tactile modalities that used rhythm, it can be assumed that rhythm would work for electrotactile as other modalities.

2.3.8 Summary

This section reviewed the basic and complex parameters of electrotactile feedback that could be used to create *Electrotactons*. Each of the basic (amplitude, pulse width and pulse frequency) and complex (intensity, spatial location and rhythm) parameters showed the potential to convey one piece of information. Calibration is important in setting up the detection and discomfort thresholds in electrotactile feedback as different people have different skin conductivity. In addition, different hardware has different configurations that dictate what parameters could be manipulated and what ranges of each can be used. This thesis will use the method of limits to set up the detection and discomfort thresholds for all its experiments as it is the most time efficient.

2.4 Subjective Perception

When designing tactile feedback, measuring subjective perception of different sensations is a great tool for the initial evaluation of the user's reaction to the tactile modality. In addition, interface designers can use these measurements to create cues that elicit a particular response from the user, delivering more than a simple cue. Researchers used the sense of alertness, emotion or a combination of both to gain insights into the design space of their tactile feedback. However, there is a lack of research exploring the subjective perception of electrotactile feedback. For that, this thesis investigates the effect of electrotactile cues on the functional aspect of alertness (urgency and annoyance) and emotion (valence and arousal) to expand the design space of *Electrotactons*.

2.4.1 Functional Aspects of Alertness

Creating tactile feedback with the desired sense of urgency and annoyance is crucial in applications that require a high sense of alertness and reaction [14]. In a driving scenario, for example, a warning signal of imminent danger that can threaten the well-being of the passengers should require a more immediate reaction than a warning signal of a low fuel level. Therefore, varying the level of perceived urgency of the feedback should match the situation's urgency so the user would react accordingly. In the meantime, it is important not to increase the level of urgency to the point where it can annoy the user and make the cue less effective and even be disabling [70]. In order to assess how salient different levels of urgency are, this thesis will measure the subjective perception of annoyance.

Many studies have investigated how manipulating the parameters of a tactile modality can have an effect on perceived urgency/importance [71,72]. For example, cues that have higher intensities or pulse frequencies can be perceived as more urgent than other cues. Cao *et al.* [72] manipulated the pitch for audio-tactile and the intensity (amplitude) for vibrotactile to investigate the perception of four different levels of urgency. The main task was to identify the level of urgency of the delivered cue while maintaining a moving square on the screen in a distracting environment (conversation, radio and noise). Their results showed that participants identified the level of urgency with a 99.2% accuracy rate and that the higher the urgency, the quicker the response. This demonstrated that designing a cue with a desired level of urgency can be successful.

In another study, Politis *et al.* [14] investigated the perception of three urgency levels using audio, visual and vibrotactile modalities and their combinations. They presented the stimuli to the participants three times in two different contexts. The first was in front of a blank screen, and the second was while looking at a driving simulator. After receiving each stimulus, participants were asked to rate the urgency and the annoyance of the stimulus on a scale of 0 to 100. The results showed that the perceived urgency of the stimuli matched their designed urgency. In addition, they observed that the more urgent the stimuli were, the more annoying they became, but they did not top urgency. Therefore, they recommended using the perceived annoyance of the stimulus as an indicator of the appropriateness of the urgency level.

2.4.2 Emotions

Conveying emotions through different means of tactile feedback gives interface designers the ability to expand their design space with a new and improved experience. Through the sense of touch, novel emotional interaction can be achieved. Researchers looked into the capability of different tactile modalities to convey affective information, including vibrotactile [15, 25], thermal feedback [73] and force feedback. They measured the emotion/affect of the tactile cues using the common valence and arousal scales from Russell's circumplex model [10] to avoid the ambiguous definitions of discrete emotional labels. This model has two dimensions, where the x-axis represents valence, and the y-axis represents arousal, and that creates a plot with four quadrants: pleasant, excited (top-right), pleasant, calm (lower-right), unpleasant, calm (lower-left) and unpleasant, excited (top-left), see Figure 2.9. Valence is the emotional pleasantness of a cue in which a higher valence means a more pleasant feeling, and a lower valence means a less pleasant feeling. Arousal is the emotional activation in which higher arousal means more intense, and lower arousal means calmer emotions.

Most tactile research looking into conveying emotions has used vibrotactile feedback. It was found that manipulating vibrotactile parameters such as intensity and frequency can influence the perceived valence and arousal simultaneously [74, 75]. Yoo *et al.* [76] sys-

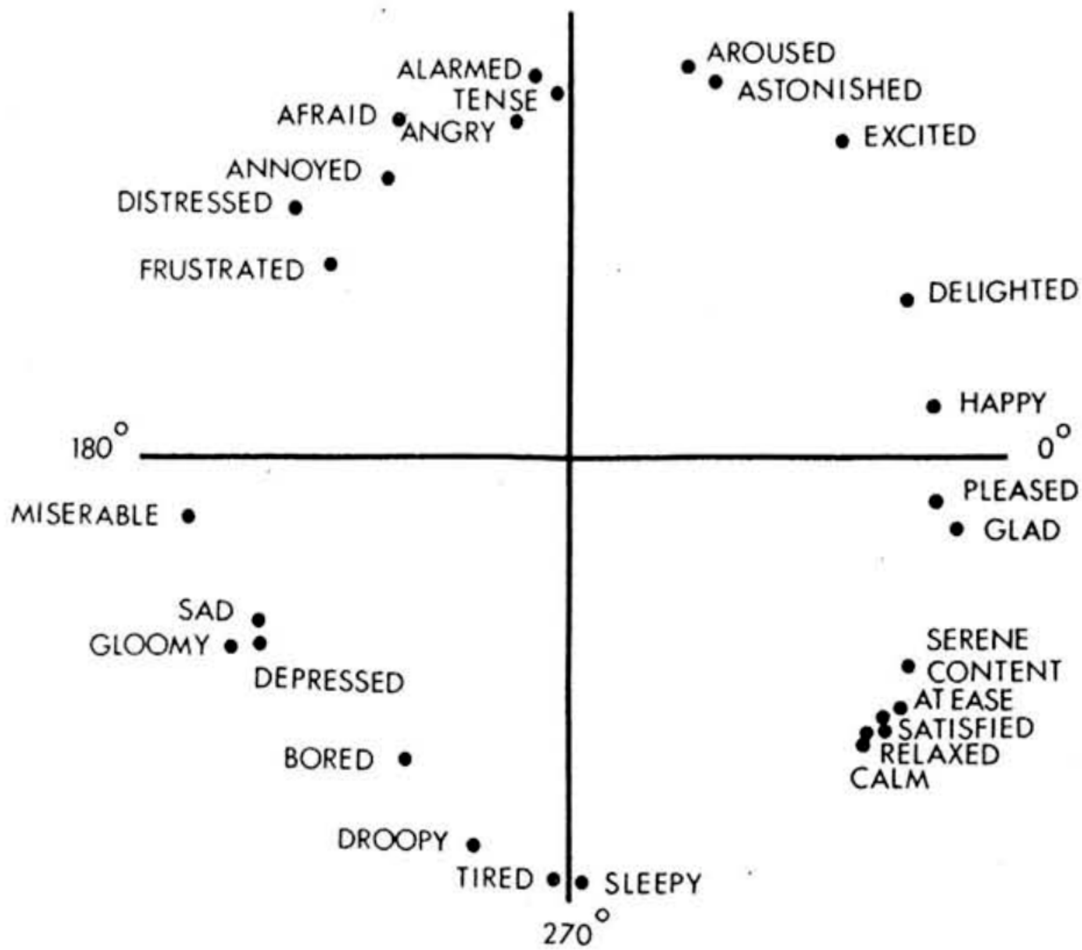

Figure 2.9: The Russell's Circumplex Model. It shows the mapping of emotions, where the y-axis represents arousal/excitement, and the x-axis represents valence/pleasantness, adapted from [10].

tematically analysed the rating of valence and arousal for a range of tactile icons created by manipulating amplitude, frequency, duration and envelope frequency. After receiving each stimulus, participants rated valence and arousal on a scale from -100 (unpleasant/not exciting) to 100 (pleasant/ exciting). They found that most tactile icons are perceived as highly arousing, but the valence rage was narrow on the unpleasant side.

Wilson *et al.* [15] conducted a study to expand the effective range of thermal, vibrotactile and visual feedback modalities. They first presented vibrotactile stimuli to the participants, then a combination of two modalities, and then a combination of all three modalities. The response for each stimulus was measured using a 7-point Likert scale for valence and arousal. Results showed that vibrotactile had a wider range of perceived arousal, whereas the combination of thermal and visual had a wider range of perceived valence. However, the presentation of all the modalities in a single stimulus did not yield a wider range compared to two modality combinations as it was hard to process it by the participants and caused confusion.

Evoking real-world sensation using vibrotactile stimulation was done by Macdonald *et al.* [25]. They investigated the affective properties of novel emotional resonant stimuli using a set of eight stimuli representing real-world sensations. After each stimulus, they asked participants to choose what sensation each stimulus reminded them of from a list, then rated the perceived valence and arousal on a 7-point Likert scale. Their results showed that when participants had a prior connection with the sensation presented, they rated it more pleasant. In addition, the range of emotional responses indicated that the stimuli were fairly pleasant and slightly alerting.

2.4.3 Alertness and Emotions

The combination of both alertness and emotions was used to understand the effect of tactile feedback on subjective responses to expand the design space, allowing interface designers to create cues that can evoke a wide range of sensations. McKeown *et al.* [70] measured the perceived urgency and valence to investigate speech, environmental sounds, auditory icons and abstract synthetic warnings as candidates for within-vehicle interfaces. They presented participants with nine driving events with varying situational urgency through each audio modality and asked them to rate the perceived urgency and valence on a 7-point Likert scale before and after they learned the stimulus-event relationship. They found that auditory icons, environmental, and abstract sounds that were mapped into highly urgent events were rated as unpleasant. In addition, speech did not affect both measures.

To evaluate their new type of haptic display that used a small swarm of robots to apply haptic patterns to any part of the body, Kim *et al.* [77] conducted a study to obtain user perception in terms of urgency and emotion. They created stimuli of varying frequency, amplitude, force and number of robots. After they presented the stimuli to the participants, they used a 7-point scale of SAM to measure valence and arousal. In addition, a 7-point semantic differential was used to measure urgency. The results showed that the number of robots and amplitude had the most significant effect on perception. An increase in both will increase the rating of urgency and arousal while lowering valence. They advised carefully controlling these parameters to elicit the desired perception.

2.4.4 Perception in Electrotactile feedback

In electrotactile feedback, researchers have measured the subjective rating of sensations such as warmth, cold, pain and itch. Saito *et al.* [78] conducted a study to investigate if electrotactile stimulation could be used to create a temperature sensation on a head-mounted display. They placed an electrotactile display with 192 electrodes on the forehead and applied anodic (positive current) and cathodic (negative current) stimulations, as changing the polarity of the current can induce pressure and vibration sensation [23]. In each trial, they randomly applied one type of stimulation to one of the electrodes and then asked participants to rate the intensity of cold, warm, pressure and vibration sensations on a 10-point Likert scale. Results showed that cold sensations were easier to generate than warm ones, but the quality was not as good as it was for pressure and vibration sensations.

Djozic *et al.* [79] investigated the effect of changing pulse frequency and pulse width on sensations on the left forearm. When manipulating one or more of these parameters, it was possible to create multiple sensations, but the problem was that the perceived sensation was not linear to the change of the parameters. The goal was to calculate Just Noticeable Differences (JND) between different parameters. The combination of three frequencies (10 PPS, 50 PPS and 100 PPS), and three pulse widths (1/4, 1/2 and 3/4 pulse width range calibrated for each participant) were tested.

Before conducting the experiment, there was a calibration stage to determine the sensation (ST) and the pain thresholds (PT) of the pulse width. They found no interaction between ST and pulse frequency, but there was an interaction between PT and pulse frequency. As pulse frequency increased, the JND decreased despite which pulse width was used. This suggests that pulse frequency has a more significant effect on the perceived sensation. The results also showed that as pulse width increased, JND increased. They concluded that stimulation was felt the best when the values of pulse width were low (10.96μs - 128 μs), and the value of pulse frequency was high (100 PPS).

In another study, Pohl *et al.* [6] created an itching sensation through the use of electrotactile feedback and explored how changing the parameters of the stimuli resulted in different sensations. They designed their own electrical stimulator because most functional electric stimulation devices did not have the level of flexibility to control the parameters. They restricted the pulse frequency to around 50 PPS, amplitude to be under 1 mA, and pulse width to 2-5 ms to ensure minimal discomfort. The study had two parts: short and long stimuli phases. The electrodes were placed on the hairy skin of the left forearm, just below the wrist. In the first part, participants were presented with 40 stimuli for 4s. They were asked to choose any number of words from a 21-term list (Figure 2.10) describing how it felt without asking about the itch sensation. Part of this list was used in the qualitative part of the experiments in this thesis. In the second part, participants were presented with 50 stimuli. For each stimulus, a dialogue box popped on the screen every 4s asking to rate how itchy and pulsating it was. They also asked participants to rate their comfort level, how natural the stimulus felt, and their sensation location.

The results for the first phase showed that the most used word was vibration. The words

Prickling	Gentle	Pulling	Vibrating	Pulsating	Itching
Irritating	Strong	Stinging	Soothing	Twitching	Hurting
Localized	Diffuse	Calming	Forceful	Energizing	Jabbing
Squeezing	Faint	Tickling			

Figure 2.10: The list of 21-terms used by Pohl *et al.* that was adapted for the qualitative part in the experiments of this thesis, adapted from [6]

that were used to describe the lower-intensity stimuli were gentle and faint, and the higher intensity was strong and forceful. The results for the second phase showed that when the level of itch was high, it resulted in discomfort. For the location of the itch sensation, some participants reported that some sensations could be felt away from the location of the electrodes. For the itch sensation, when averaging across participants, the itch pulse frequency was 60 PPS, 3.8 ms pulse width and 0.2 mA amplitude, but there was a wide variation between participants.

In a study into the quality of electrotactile stimulation, Graczyk *et al.* [80] investigated tactile perception by changing the pulse frequency in two studies. In the first, they delivered an electrotactile stimulus using 10 levels of pulse frequency (1, 2, 5, 10, 20, 50, 100, 200, 500 and 1000 PPS) and three levels of pulse width from detection threshold to maximum comfort level measured individually for each participant (Low, Mid and High). Six amputee participants took part in this study. Participants were asked to rate perceived frequency in each trial by moving a slider along a horizontal bar from low to high. Results showed that as pulse frequency increased up to 50 PPS, the perceived frequency increased without pulse width impacting perception. Conversely, perceived frequency flattened or decreased at higher pulse frequencies and became dependent on pulse width.

In the second experiment, they delivered two stimuli sequentially. The first one was a standard stimulus using three pulse frequency levels (20, 50 and 100 PPS) and three levels of pulse width (Low, Mid and High). The second stimulus was the comparison, and its pulse frequency and pulse width varied from trial to trial (25-175% of the standard). They asked participants to indicate which stimulus was higher in perceived frequency. Results showed that participants could discriminate between stimuli when the pulse frequency was set at 20 or 50 PPS, but the discrimination performance was poor at 100 PPS.

2.4.5 Summary

The research presented in this section motivated Research Question 1 and showed how manipulating the parameters of different tactile modalities such as pitch in audio-tactile, amplitude, duration, frequency in vibrotactile and pulse width, and pulse frequency in electrotactile can affect the perception of alertness and emotions. To measure perception in these studies, most used a 7-point Likert scale as a psychometric measure. The experiments in this thesis that evaluated individual parameters of electrotactile feedback in terms of perceived sensations were influenced by the experimental designs and methods used in these studies. The aim was to see how many distinguishable levels of each sensation these parameters can generate that can be used in the design of *Electrotactons*.

2.5 Electrotactile Display

The design of structured and abstract electrotactile messages called *Electrotactons* is the objective of this research. This section will provide an overview of some of the research in the area of electrotactile feedback to better situate the work of this research in context. Electrotactile display can be defined as an interface that delivers a small amount of electrical current to the skin to evoke a sensation that can be used to present information to the user [1]. The small and thin features of the electrotactile actuators allow them to be used in applications aiding people with sensory impairments and in virtual/augmented realities.

2.5.1 Electrotactile Display For Sensory Substitution

Electrotactile feedback has been used extensively in the research area of sensory substitution to aid people who suffer from visual or hearing impairments. Sensory substitution is the conversion of sensory stimuli into stimuli that can be received by another sensory modality [81]. For example, Bach-Rita *et al.* [82] used vibrotactile to convey information to blind people. In a study, Kajimoto *et al.* [22] developed a tactile vision substitution system for people with visual impairments called HamsaTouch that used an electrotactile display on the palm to present images. The system was attached to a smartphone and users held the phone sideways with their palm on top of the attachment while pointing to a screen that displayed a shape. A display of 512 phototransistors captured the image on the screen and converted it to a tactile image of 512 electrodes facing the palm. Participants were blindfolded, seated in front of a monitor, and holding the device with their dominant hand. Four patterns were displayed on the screen: a cross-shape, circle, horizontal bar and vertical bar, which users had to identify. The results showed that the recognition rates for the horizontal and vertical bars were 90%, the circle 65% and the cross-shape 35%.

This suggests that electrotactile stimulation on the skin of the palm can be used to create uniquely identified electrotactile cues for handheld devices. However, their electrotactile array would not be possible to use in many standard interaction scenarios.

One other use of electrotactile feedback in the field of sensory substitution is providing sensory information to people who use prostheses. Franceschi *et al.* [83] developed an electrotactile feedback system in an e-skin that translated touches to electrical signals, processed them, and then provided tactile information to the user. In their study, they placed the e-skin that contains 32 small rounded electrodes on the volar side of the participant's forearm. They used the methods of limits to calibrate each one of the electrodes to make sure that participants can feel the stimulation. During the study, the examiner would touch the e-skin in three patterns; single lines, geometrical shapes and letters. The task for the participants was to report the perceived shape verbally. Their results showed that the recognition rate for the single lines was 86%, geometrical shapes 73% and letters 72%. This indicates that electrotactile feedback can be used to create cues with rich, multidimensional information that can be interpreted.

2.5.2 Electrotactile Display In Virtual Reality

Virtual reality (VR) and augmented reality (AR) are some of the areas in that electrotactile feedback has been utilized to enhance the user experience. The main purpose of using electrotactile feedback in such areas is to provide rich tactile sensations when interacting with virtual objects or change the perception of real objects to make the experience more immersive. In contrast with other tactile modalities, electrotactile feedback uses small and thin electrodes, making it easy to implement in wearable devices. Hummel *et al.* [84] conducted a study using an electrotactile device designed specifically for immersive VR experience that is used for training. The aim of this study was to see if integrating electrotactile with VR can improve grasping, increases task completion and lowers the workload in an on-orbit service scenario. They designed their own electrical simulator to fit their requirements of the device needing to be small. They placed a small tactor that contains eight electrodes on each finger and asked their participant to complete three tasks: pressing a button, operating a lever switch and a combination of both with the addition of pulling a module out of its slot. These tasks were presented in two conditions: ET (visual and electrotactile) and NO (visual only). The results showed that the time for completing all tasks is less when using ET compared with NO. When measuring the workload with and without the electrotactile, the results showed that for all tasks, the load was higher without the electrotactile. They reported that the mental workload was significantly lower for the electrotactile compared to without it. Also, there was an increase in task completion with electrotactile feedback.

Tactile augmented reality is changing the tactile feeling of real objects by applying tactile stimulation on the skin [85] and it's one of AR's applications. Tactto is a feel-through very thin temporary tattoo that uses electrotactile feedback to augment tactile sensations developed and studied by Withana *et al.* [7]. It can be applied to any body part to evoke a tactile sensation or augment the perception of a real object. For example, a smooth surface can be turned to be rough by applying electrical stimulation to the skin touching it. In another study, Yem *et al.* [19] developed a finger glove for AR named FinGAR. They wanted to stimulate the four types of mechanoreceptors individually to achieve high-fidelity tactile sensation. Electrotactile stimulation is used to elicit pressure sensation and low-frequency vibration, whereas mechanical stimulation is used to elicit skin deformation and high-frequency vibration.

2.5.3 Summary

The literature in the section presented some of the HCI applications that utilized electrotactile feedback. The ability to make the electrotactile actuators in a very small form makes it feasible to design a tactile interface that can reach body parts that usually wouldn't be possible with traditional tactile modalities. This makes electrotactile feedback the perfect candidate for sensory substitution devices where comfort and small factors are a requirement as the user is expected to wear it for an extended period of time. In addition, electrotactile feedback can make VR and AR more immersive by evoking or augmenting the tactile perception of virtual or real objects.

2.6 Designing Electrotactons

The previous sections gave an overview of the related work done in the field of electrotactile feedback and showed that it had been used for a range of different applications. Conveying information or evoking sensations was shown to be within the capabilities of electrotactile feedback that make it suitable for designing a type of haptic icon. The word icon here can be defined as using an image, picture or symbol to represent a concept [86]. The equivalent of icons in the audio-tactile domain are represented in Earcons [87, 88] and Auditory Icons [89]. Representing an icon through the sense of touch is called a haptic icon that encompasses all types of tactile or force feedback used in the icon narrative. It is defined as structured, abstract, tactile messages that can be used to communicate information non-visually. One of the sub-types of haptic icons that uses vibrotactile to convey tactile messages is called Tactons [90]. There has been much work within HCI on vibrotactile Tactons (for example, [91–95]) using mechanical actuators for stimulation. Brown *et al.* [69] did some of the earliest work in the area, investigating basic parameters, including the number of discriminable levels in each, to give designers information on how to use them successfully.

This thesis aims to investigate the use of electrotactile haptics to design a new haptic icon sub-type called *Electrotactons* (electrotactile tactons), which are designed using the structured, abstract approach to encode information. This section will look at the design strategies used to create Earcons and Tactons that influenced the design of *Electrotactons*.

2.6.1 Earcons

The design principles used to design Tactons were adapted from the design of Earcons, so it is important to understand the origin of the design principles as it passed to the design of *Electrotactons*. The creation of Earcons was done by Blattner *et al.* [88], and they introduced two design principles: representational Earcons and abstract Earcons. Representational Earcons are natural, everyday sounds used to encode information or represent items in computer interfaces. In contrast, abstract Earcons are single pitches or groups of pitches as building blocks for Earcons. As the name indicates, in abstract Earcons, the mapping between the data and the sounds is abstract. In most of the literature in recent years, the term Earcons refers to the abstract Earcons.

In his thesis, Brewster [96] improved the design of Earcons by using musical instrument timbres instead of using simple pitches. He defined Earcons as “abstract, synthetic tones that can be used in structured combinations to create auditory messages” and provided guidelines for designing them using timbre, register, rhythm and intensity. When using musical timbres, it is important to select timbres that are subjectively easy to distinguish from each other. He reported that register (overall pitch level of an Earcon) would be a poor choice in an absolute identifications scenario and that the difference between levels must be large if register must be used. The guideline for rhythm was to use a different number of notes in each rhythm. This will make it easy to discriminate between different rhythms. In addition, he was making them as short as possible, so they do not degrade the interaction with the interface. Finally, for intensity, he recommended not to use it as a parameter for designing Earcons. The reason was that when using high-intensity sounds, users reported annoyance. These guidelines provided by Brewster [96] was adapted by Brown [12] for the creation of the equivalent of Earcons in the tactile domain, Tacons.

2.6.2 Tactons

In the thesis of Brown [12], she applied the design principles used in the design of Earcons to create a specific kind of vibrotactile feedback called Tactons. She defined Tactons as “structured vibrotactile messages for presenting multidimensional information non-visually”. In addition, she investigated which vibrotactile parameters can be manipulated to convey information. As Tactons and *Electrotactons* utilise the same sense, the sense of touch, this thesis will adopt some of the design principles and methodologies used for designing Tactons when it is applicable. She provided design recommendations for individual parameters such as vibrotactile roughness and intensity and for Tactons such as two-dimensional Tactons and three-dimensional Tactons. These recommendations were used in this thesis to evaluate individual parameters of electrotactile feedback and to design the multidimensional *Electrotactons*.

In one of Brown's studies investigating the perception of vibrotactile roughness, she evaluated five vibrotactile levels created by amplitude modulation. The aim was to determine whether participants could distinguish between these levels so that roughness could be used as a parameter for Tacton design. The levels of modulation were sine, 20Hz, 30Hz, 40Hz and 50Hz. The study consisted of 50 tasks and used a forced-choice design. Participants were presented with two stimuli in a row in each task and asked which stimulus felt rougher. Their results showed significant differences between all pairs, except between 20Hz and 30Hz. In addition, they reported finding three levels which can be differentiated in terms of roughness, namely sine, 40Hz and 50Hz. This study motivated Research Question 2 and its methodology was adapted to investigate the perception of electrotactile roughness in Experiment 5 Section 4.2.

Brown *et al.* [71] also investigated the use of vibrotactile Tactons to encode three dimensions of information using three different vibrotactile parameters (rhythm, roughness and spatial location) to create more complex messages. They represented an upcoming appointment using three pieces of information encoded in the parameters: type of appointment (Meeting, Lecture or Tutorial) encoded into rhythm, importance of the appointment (Low, Medium or High) encoded in roughness, and time remaining until the appointment (30 min, 15 min or 5 min) encoded in the location of the actuator on the participant's forearm. For example, a Low Importance Meeting in 5 min would be encoded in the Meeting rhythm; a "smooth" vibration played on the wrist. They found that participants had difficulty distinguishing between the three levels of roughness, causing a low recognition rate of 47.8%. They performed a second study reducing roughness to two levels. Results showed that this increased the average overall recognition rate significantly to 80.56%. This study influenced the design of the multidimensional *Electrotactons* in Experiment 3 (Section 3.6) and Experiment 6 (Section 4.4).

The research summarised in this section has shown the process of evaluating individual parameters of vibrotactile feedback to be used in Tactons by looking at how many distinguishable levels it can produce motivating Research Questions 2 & 3 of this thesis. Moreover, it has summarised the use of individual parameters such as rhythm, roughness and spatial location for the creation of Tactons.

2.6.3 Electrotactons

Electrotactons are the electrotactile equivalent of Tactons, and both use the sense of touch for providing feedback. From the research on Tactons, it can be assumed that there is great potential for electrotactile stimulation for the creation of good haptic sensations for interaction design. Furthermore, there was a lack of knowledge in the literature on how to use basic parameters to construct structured and abstract electrotactile messages. For that, the aim of the research in this thesis is to gain an understanding of the basic parameters such as amplitude, pulse width and pulse frequency and complex parameters such as intensity and rhythm. The number of distinguishable levels each parameter produces will measure the suitability of the parameter to be used in the design of *Electrotactons*.

The literature review about the perception of electrotactile feedback in Section 2.3 indicated that the individual parameters such as amplitude, pulse width and pulse frequency are promising for encoding information in electrotactile messages making it suitable to be used in the design of *Electrotactons*. In addition, this review also indicated that intensity, spacial location and rhythm may also be used as parameters. As this thesis is the first investigation into the use of electrotactile to create structured and abstract messages, it was necessary to measure the subjective rating of each of the individual parameters to see how users react to this novel technology as an evaluation and identify how many distinguishable levels usable for the design of *Electrotactons*.

2.6.4 Applications of Electrotactons

The literature review in Section 2.2 and Section 2.3 showed a range of different applications that can make use of electrotactile feedback. The premise of the design of *Electrotactons* is to be abstract instead of mapping the cues to a particular meaning, making the same *Electrotactons* usable for different applications. Therefore, this thesis focused on how to design *Electrotactons* rather than implementing them in specific applications. However, given the advantages of the electrotactile actuators, *Electrotactons* can be considered in applications that utilize any tactile modality.

Electrotactons can be used in applications where attention-grabbing alerts and notifications are desired. Tactile feedback represented by electrotactile can be better than auditory or visual feedback in attention-grabbing because it provides a physical sensation that can be more immediately noticeable and difficult to ignore. When a device or interface provides tactile feedback, the user can feel a physical response that can be more engaging and memorable than a purely auditory or visual response. Furthermore, *Electrotactons* can convey more complex information compared to traditional tactile feedback, which can only be used for simpler alerts. For example, in an in-car steering wheel haptic system that uses vibrotactile to deliver alerts of varying levels of urgency or indicate the importance of a call, text or an upcoming appointment, the car's vibration will vibrate the steering wheel when driving over a rough road and mask the vibrotactile cues by stimulating the mechanoreceptors responsible for perceiving vibration. Whereas *Electrotactons* can potentially be used to deliver the same quality alerts and notifications without it being masked by the car's vibration as it uses electrical current to stimulate the mechanoreceptors compared to using mechanical stimulation in vibrotactile. Another example would be loud environments like a crowded stadium or an arena, organizers can use *Electrotactons* to alert staff members to different events and warnings dealing with crowd control that require an immediate reaction.

Another advantage of *Electrotactons* is that they do not produce residual sounds as vibrotactile does, making them very useful for private communication through which a set of pre-defined messages can be delivered without disturbing people around the user. This would apply to any handheld device, such as a mobile phone or computer mouse.

2.6.5 Summary

This section showed an overview of the approach used to design Earcons and Tactons and design principles to choose their suitable parameters, which influenced the design of *Electrotactons* in terms of how they can be structured and encode information through the manipulation of their parameters. The parameters that have the potential to be used in the creation *Electrotactons* are amplitude, pulse width and pulse frequency as basic parameters, and intensity and rhythm as complex parameters. This thesis is the first attempt to construct structured and abstract electrotactile icons called *Electrotactons* that adapted the design approach used in the creation of their vibrotactile equivalent, Tactons. The creation and evaluation of *Electrotactons* were done through empirical studies presented in this thesis utilizing what was learned about electrotactile perception in Section 2.3 and the design approach of Tactons.

2.7 Electrical Stimulation Technologies

In Section 2.2.3 and Section 2.3, the mechanism of stimulating the mechanoreceptors with an electrical current through the manipulation of its parameters to elicit a tactile sensation were explained. When stimulating the Pacinian corpuscles, which are the deepest mechanoreceptors in the shallow skin layer, the mechanoreceptors before it will be co-activated [23]. When this electrical current passes the shallow layer of the skin, especially beyond the subcutaneous layer due to high values of pulse width, amplitude and pulse frequency (Figure 2.1), it goes into a different domain. At this point, the current can be used in the domain of neuroscience through transcutaneous electrical nerve stimulation (TENS), or when the current reaches deeper into the muscles, it can be used in the electrical muscle stimulation (EMS) domain. This section provides an overview of these domains that are outside of the scope of this thesis but employs the same technology.

2.7.1 Transcutaneous Electrical Nerve Stimulation (TENS)

Transcutaneous electrical nerve stimulation (TENS) is defined as the use of electrical current to target the primary afferent nerve A-β to relieve pain with minimum side effects as there is no potential for overdose [97]. As the effects of the TENS are fast in onset and offset, patients need to use it as needed throughout the day. TENS machines can be bought over the counter and patients can use them straight away as it pre-programmed with stimulation patterns [97]. For example, a TENS machine can be used in adjunct to physical therapy in the case of chronic pain to reduce pain [98]. The intensity of the electrical current need to be high enough to reach the afferent nerve A-β. For that, amplitude needs to be increased until the patient senses a comfortable tingling sensation with high pulse frequency or tapping sensation with low pulse frequency without motor contraction, indicating muscle stimulation [98].

2.7.2 Electrical Muscle Stimulation (EMS)

Electrical muscle stimulation (EMS) happens when injecting an electrical current through electrodes attached to the skin that activate the muscle causing an involuntary contraction [99]. The placement of the electrodes determines which muscle or muscle group to be activated. The muscle activation level is controlled through the manipulation of the electrical current parameters such as intensity, duration and pattern [99]. The intended use of EMS was for rehabilitation medicine to restore lost motor functions after spinal cord injuries [100]. In addition, EMS can be used as a supplement to conventional training for patients with muscle atrophy [101].

In recent years, researchers started to explore the potential of EMS in human-computer interactions. For example, a new pedestrian navigation system was developed by Pfeiffer *et al.* [102] where they attached electrodes to the thigh muscles of the user and sent a cue by actuating one of the muscles indicating the direction of where to walk without the need to attend to the navigation task. Lopes *et al.* [103] proposed a mobile force feedback device that used EMS to actuate users' forearm muscles when interacting with a video game on a mobile phone where the user steered an aeroplane through wind. The use of EMS also expanded into virtual reality for a more immersive experience. Impacto, a device developed by Lopes *et al.* [104] generates the haptic feedback of hitting and being hit in virtual reality. The tactile aspect of feeling the hit was done by tapping the skin with a solenoid and the impact of the hit was done using EMS to contract the user backwards.

2.7.3 Summary

The electrical current can be used on the human body in many ways. It can be applied to the skin to stimulate deeper nerve afferents to help relieve pain through TENS machines. When using a stronger electrical current through EMS machines, it activates the muscles involuntarily, which helps in physical therapy and can be used in some HCI applications. The technologies in the section are not related to the work carried out in this thesis, but share the use of electrical current.

2.8 Literature Review Conclusions

This chapter in Section 2.2 provided an overview of the aspects of the haptic sensory system, especially the cutaneous system responsible for touch perception/ tactile input and how it interacts with the electrical current for the design of electrotactile messages such as *Electrotactons*. The review of the perception of electrotactile parameters in Section 2.3 indicated which parameters can be manipulated to evoke different sensations or encode information. These parameters were either basic such as amplitude, pulse width and pulse frequency, or complex such as intensity, spacial location and rhythm. Moreover, the review showed how essential the calibration stage is for any electrotactile display. The review of the subjective perception of different tactile modalities in Section 2.4 showed how tactile cues affect urgency, annoyance, valence and arousal and their potential for the design of electrotactile feedback, and the use of each parameter based on many distinguishable levels of each sensation that can be perceived. Section 2.5 presented studies on electrotactile feedback used in different applications, demonstrating its capabilities. The concept behind the design of the *Electrotactons* was explained in Section 2.6 along with the approach used to choose the suitable parameters.

Research Question 1 will provide an initial evaluation of electrotactile feedback parameters to see which ones are suitable to the design of *Electrotactons* by measuring their influence on subjective perception such as urgency, annoyance (influenced by [14]), valence and arousal (influenced by [15]).

Research Question 1: *What parameters of electrotactile stimulation can be used to influence subjective perception?*

The results from Research Question 1 will be used to inform Research Question 2, how many distinguishable levels the parameters can produce in a forced-choice design inspired by and adapted from [69] and [54]. This will provide insights into how to encode more information in electrotactile messages for creating *Electrotactons*. For instance, each distinguishable level of electrotactile parameters could encode one dimension of information; therefore, multiple dimensions of information could be encoded. This motivated the research question:

Research Question 2: *How can the parameters of electrotactile feedback be used to encode information in Electrotactons?*

Encoding two or three dimensions of information into the parameters of electrotactile feedback for the creation of *Electrotactons* was inspired by Tactons as discussed in Section 2.6.2 and Section 2.6.3. The evaluation of these *Electrotactons* was done by conducting absolute identification experiments and measuring their performance by recording the percentage correct of the individual parameters and the complete cue to check their suitability for conveying information. So, the following research question was formed:

Research Question 3: *What levels of performance can be achieved when these parameters are combined to create Electrotactons to present multidimensional information?*

The results of these research questions form a baseline of performance for any future *Electrotactons*, as this thesis represent the first attempt to design structured and abstract electrotactile messages. Besides answering these research questions, an additional outcome of this thesis is a set of design recommendations that will help interface designers to create effective *Electrotactons*. The next chapters will demonstrate in detail all the experiments conducted to explore and understand the parameter space of electrotactile feedback to create *Electrotactons*.

Chapter 3

Investigating Basic Parameters of Electrotactile Stimulation

3.1 Introduction

In the previous chapter, the literature showed that researchers had investigated the perception of electrotactile stimulation on the fingers [23], forearms and wrists [6, 79] and have shown that people are very sensitive to it, making it suitable for delivering feedback. However, there is a lack of work investigating subjective responses to the feedback, which makes it difficult to use in interaction design. Therefore, experiments were designed and conducted to gain insight into how manipulating basic electrotactile parameters affects subjective experiences to better understand the design space and see how many distinguishable levels each parameter can produce. Then use these levels to create *Electrotactons* and measure their recognition rate. The aim of this chapter is to answer the following Research Questions:

- *What parameters of electrotactile stimulation can be used to influence subjective perception (Experiments 1, 2 & 4)?*
- *How can the parameters of electrotactile feedback be used to encode information in Electrotactons(Experiments 1, 2 & 4)?*
- *What levels of performance can be achieved when these parameters are combined to create Electrotactons to present multi-dimensional information(Experiment 3)?*

This chapter describes four experiments investigating the subjective perception of urgency, annoyance, valence and arousal through manipulating electrotactile basic parameters such as pulse width, amplitude and pulse frequency. Experiment 1 investigated the effect of the first parameter combination by manipulating pulse width and pulse frequency on perceived sensations. Experiment 2 investigated the effect of the second parameter combination; amplitude and pulse frequency. Experiment 3 investigated the first design of *Electrotactons* that was informed by the first experiments' findings, where each electrotactile basic parameter conveyed one piece of information and measured the recognition rate. Experiment 4 investigated the effect of the last combination of the parameters on perceived sensations: pulse width and amplitude. A conclusion will discuss the findings and revisits the research questions in Section 3.10.

3.2 Subjective Perception of Electrotactile feedback

This chapter describes four experiments that provide an initial evaluation of electrotactile feedback on the palm and investigate its influence on the subjective perception of alertness (urgency and annoyance) and emotion (valence and arousal). This will allow interface designers to utilise sensations to produce cues that provoke a specific reaction from the user, resulting in more than just a simple cue. By using the sensations of alertness, emotion, or a combination of both, researchers can better understand the design possibilities for electrotactile feedback. The literature in Section 2.3.1 discussed evoking different sensations and conveying information through manipulating basic parameters of electrotactile feedback such as amplitude, pulse width and pulse frequency. This inspired the investigation of manipulating two parameters independently to elicit different sensations. In addition, investigating the same basic parameters to convey three types of information simultaneously as the first step to creating *Electrotactons*. The first experiment measured the subjective perception of electrotactile feedback cues by manipulating pulse width and pulse frequency; in the second, amplitude and pulse frequency; in the third, used pulse width, amplitude and pulse frequency to present multi-dimensional information to create *Electrotactons*; in the fourth, measured subjective perception when manipulating intensity (the combination of pulse width and amplitude). These experiments explore the underlying parameter space of electrotactile feedback and bring an understanding of the parameters' effect on subjective responses to understand how to design *Electrotactons*.

3.3 Apparatus

The experiments in this thesis used the same hardware. Two Axion 60x30mm self-adhesive electrodes (https://axion.shop/en/electrodes/stimulation-current-electrode-pads-for-fingers-and-wrists) with 2mm jack connections (Figure 3.2) were placed on the palm of the participants' non-dominant hand, One placed across the thenar and hypothenar eminences, the other on the distal palmar to deliver the electrotactile cues (Figure 3.3). The functional

Figure 3.1: A participant interacting with the interface during Experiment 1. The electrodes used for the electrotactile display are on the non-dominant hand, and the dominant hand controls the experiment using a mouse.

electrical stimulator (FES) used to generate the electrotactile cues was the MOTIONSTIM 8 (Figure 3.4) made by Medel Medicine Electronics (https://www.medel-hamburg.de/).

It produces a biphasic voltage pulse and can manipulate only pulse width, amplitude and Pulse frequency. It was connected to a Mackbook pro 13' laptop running macOS through USB. A Python script was written using Python 2.7 to control the parameters for the electrotactile cues and the user interface for the experiments. The experiments were conducted in a lab where participants sat in front of a 23.6-inch HannsG HE247 monitor connected to a laptop. A mouse was used in the participant's dominant hand to interact with the experiment interface (Figure 3.1).

3.4 Experiment 1 (Pulse Width and Pulse Frequency)

The first experiment investigated the first pair of electrotactile basic parameters, pulse frequency and pulse width by manipulating 6 levels of pulse frequency and 3 levels of pulse width and see how it can affect the ratings of perceived urgency, annoyance, valence and arousal and how many of these levels are distinguishable from each other. The aim was to

Figure 3.2: Two Axion 60x30mm self-adhesive electrodes with 2mm jack connections.

evaluate what effects electrotactile cues had on the functional aspects of alertness (urgency and annoyance) and emotion (valence and arousal). The results of this experiment will contribute to Research Questions 1 & 2.

3.4.1 Experimental Design

The experiment used a within-subjects design, consisting of three phases: calibration, training and experiment. The stimulation parameters (pulse frequency and pulse width) were the independent variables. Six equally spaced frequencies (10 pulses per second, 30 PPS, 50 PPS, 70 PPS, 90 PPS and 110 PPS), and three values for pulse width were used to create the electrotactile cues. The first value for pulse width as a baseline value was 70 μs. The second value was measured during the calibration phase as the discomfort threshold because each participant's impedance is different. Therefore, the same pulse width value cannot be used across all participants: what might be a weak stimulus for one participant could be strong for others. In addition, if the electrodes are moved, calibration must be repeated. The third value was the mean between the baseline value and the discomfort threshold. The combination of both parameters yielded a total of 18 stimuli.

The dependent variables were: perceived urgency, annoyance, valence and arousal. These variables give information about a range of different subjective aspects of cues [14] that are important for cue design. Perceived urgency is important where messages of different importance need to be communicated. Annoyance is important as cues must be acceptable to users. Electrotactile cues also feel different to the more common vibrotactile ones, so one of the objectives of this experiment was to understand more about this. Valence and

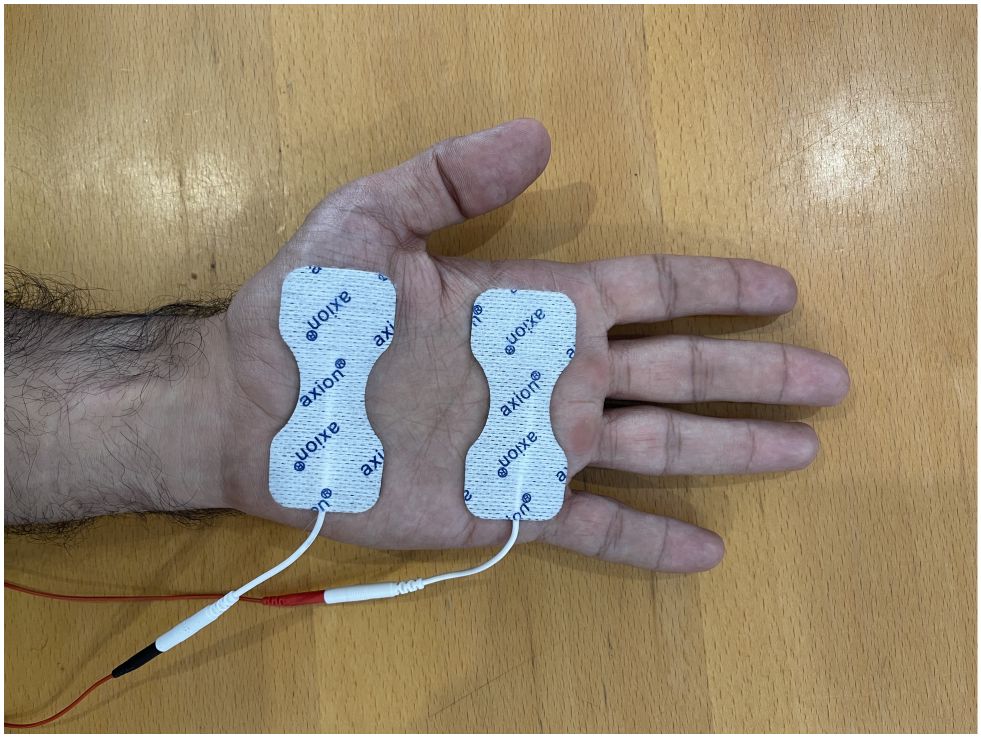

Figure 3.3: The electrodes placement on the palm of the hand.

arousal are part of the Circumplex model of emotion [10]. Valence is the emotional pleasantness of a signal (higher valence meaning more pleasant, lower valence less pleasant) and arousal is the physiological activation (low arousal meaning calmer emotions, high arousal more excitement). Others have begun to look at the emotional experiences of vibrotactile cues [15] but there is little work on this in the electrotactile domain. Investigating emotional responses is important to ensure the creation of acceptable cues.

A qualitative assessment was done at the end of the experiment. A list of terms was adopted from Pohl *et al.* [6] (Figure 2.10) to be used in this assessment to see what words participants would use to describe how they felt about electrotactile stimulation. To make sure that participants would understand these terms as some participants were expected to be non-native speakers, 10 international students from the department were asked to circle the terms they recognized from the 21-terms at the time of designing the experiment. 6 terms out of the 21, the students did not recognize as much, so they were eliminated. The final list of 15-terms to be used in the qualitative assessment in all experiments in this thesis can be seen in (Figure 3.5). In addition, three questions will be asked about the participant's experience during the experiment, which the details of are in Section 3.4.3.

In accordance with the results of the study made by Kajimoto *et al.* [17], it was hypothesised that participants will not be able to discriminate between frequencies above 30 PPS. However, According to Saunders *et al.* [53], the ideal range for pulse frequency in electrotactile stimulation is between 2-100 PPS. So, the range used was 10-110PPS because

Figure 3.4: The functional electrical stimulator (FES) used to generate the electrotactile cues.

the electrical stimulator in this experiment differed from these two studies and wanted to know its usable range. Moreover, low pulse width and high frequency should make participants' rate valence higher based on Djozic *et al.* [79]. Furthermore, knowing that pulse width influences sensation intensity perception [6], a higher rating of urgency is expected with high pulse width. With that, a higher urgency will induce higher arousal based on Russell's Circumplex Model of Affect [10] and higher annoyance.
Therefore, the hypotheses for this experiment were:

- ***Hypothesis 1:*** *Pulse frequencies above 30 PPS will not have a significant effect on perception;*
- ***Hypothesis 2:*** *When pulse width is low and pulse frequency is high, valence will increase;*
- ***Hypothesis 3:*** *When pulse width increases, perceived urgency will increase;*
- ***Hypothesis 4:*** *When the rating of urgency increases, both arousal and annoyance will increase.*

3.4.2 Participants

Twenty people (4 female) between the ages of 18 and 36 (*Mean=30, SD=5.42, Median=31*), one left-handed took part. Most were students. None had dermatitis or other skin conditions or cardiovascular issues. Each participant read an information sheet and signed a consent form before the start of the experiment, and was compensated with an

Localized	Squeezing	Gentle	Strong	Calming
Vibrating	Forceful	Itching	Hurting	Stabbing
Pulling	Prickling	Irritating	Tickling	Twitching

Figure 3.5: The list of 15-terms used in the qualitative assessment of Experiment 1.

£8 Amazon voucher for participating.

3.4.3 Procedure

For all three phases, participants sat at a desk with a monitor and mouse, which they controlled with their dominant hand. The two electrodes were attached to the palm of their non-dominant hand. One was placed across the thenar and hypothenar eminences, the other on the distal palmar (Figure 3.3). As described in Section 2.3.4, calibrating the stimulation of electrotactile is essential to set up the detection and discomfort threshold for each participant. The calibration depends on pulse width and amplitude as they dictate the strength of the stimulation [5], independent of pulse frequency. The amplitude was increased from 0 mA until participants detected a sensation, while the pulse width was kept at the lower limit of 70 μs. This recorded amplitude was kept the same throughout the rest of the experiment and marked as the detection threshold. Then the pulse width was slowly increased from 70 μs until it reached a level where participants felt uncomfortable and marked it as the discomfort threshold. The maximum value for the pulse width was capped at 200 μs to avoid any pain sensation [20]. Figure 3.6 shows the calibration interface that was used in this phase. At the end of this phase, the three values of pulse width will be set up as described in Section 3.4.1.

In the training phase, participants were briefed on how to interact with the interface in Figure 3.7 and what the meaning of all sensations measured. Urgency was defined as the feeling of something urgent being conveyed, annoyance is the feeling of annoyance towards the cue, valence is the feeling of pleasantness towards the cue and arousal is the feeling of excitement towards the cue. Once ready, they clicked 'next stimulation' to receive the first stimulus. Participants went through one block consisting of 10 randomly ordered stimuli that lasted for 1s. The random ordering of the stimuli was done by using the randint method in Python. After the stimulation, participants rated how they felt for each dependent variable on a 7-point Likert scale by answering four questions related to each of the four sensations. The 'next stimulation' button was not activated until

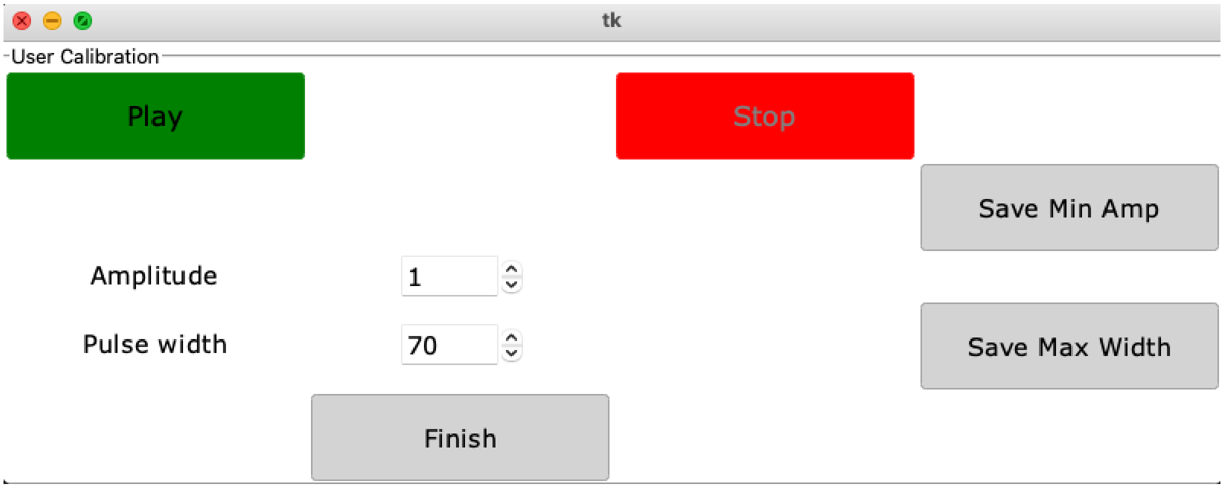

Figure 3.6: The calibration interface used in Experiment 1.

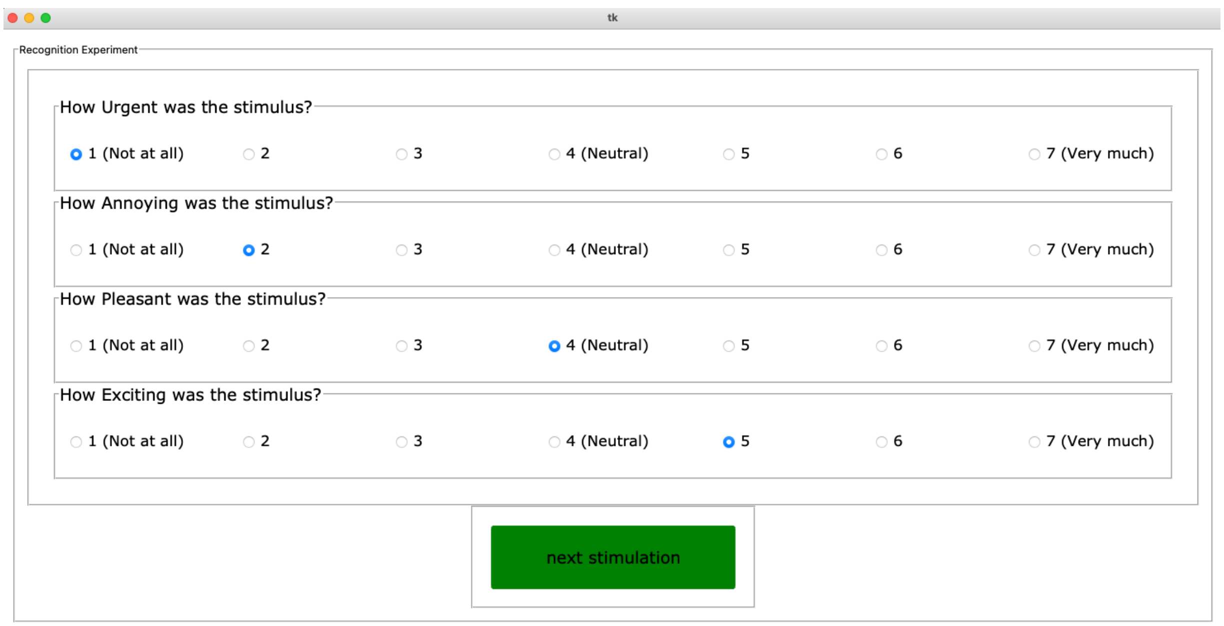

Figure 3.7: The training interface after a participant answered all four questions.

all ratings had been given as seen in Figure 3.7. The goal of this phase was to allow participants to experience the stimuli and the interface before the main experiment phase.

The experiment phase had the same setup and steps as the training phase but was longer. It had four blocks, and each consisted of 18 stimuli, making 72 trials in total. There was a 5-minute break between each block to avoid any fatigue. After the experiment phase was done, the qualitative assessment started. Participants were handed a piece of paper that have the 15-terms on it (Figure 3.5). They were instructed to circle any of the terms based on the level of strength of the electrotactile cues received during the experiment with three different colours. The colour red was for high strength, blue for middle strength and green for low strength. They can circle a single term with more than one colour if they associate it with more than one level. Then, they were asked the following questions:

1-Did your sensitivity change with time?
2-What is the difference in sensation between the electrotactile feedback and the vibration you get from a phone?
3-how do you think electrotactile feedback could be used on a steering wheel in a car for navigation or notification?

3.4.4 Results

The Aligned Rank Transform [105] was used to transform the data from non-parametric to parametric. Then a two-factor (pulse frequency and pulse width) repeated-measures ANOVA was performed for each dependent variable (urgency, annoyance, valence and arousal). For urgency, both pulse width ($F(2,323) = 448.6$, $p < 0.001$) and pulse frequency ($F(5,323) = 7.41$, $p < 0.001$) had a significant main effect, with no interaction. A pairwise *Post hoc* Tukey tests on urgency showed that all levels of pulse width had a significant effect suggesting three uniquely distinguishable levels: (High), (Middle) and (Low) (Table 3.1). In addition, for pulse frequency, the significant effect was only between 10 PPS and all other pulse frequencies suggesting two uniquely distinguishable levels: (10 PPS), (30 PPS, 50 PPS, 70 PPS, 90 PPS, 110 PPS)(Table 3.2). For annoyance, both pulse width ($F(2,323) = 279.6$, $p < 0.001$) and pulse frequency ($F(5,323) = 14.42$, $p < 0.001$) had a significant main effect. There was an interaction effect ($F(10,323) = 3.28$, $p < 0.001$). A pairwise *Post hoc* Tukey tests on annoyance showed that all levels of pulse width had a significant effect suggesting three uniquely distinguishable levels same as urgency (Table 3.1). Moreover, for pulse frequency, the significant effect was only between 10 PPS and all other frequencies in addition to the pair 30 PPS and 90 PPS suggesting three uniquely distinguishable levels (Table 3.2). As for the interaction effect between pulse width and pulse frequency on annoyance, a *post hoc* Tukey test showed that the difference between low and high pulse width with 10 PPS was significantly different when with 50 PPS, 70 PPS and 90 PPS.

For valence, only pulse width ($F(2,323) = 13.7$, $p < 0.001$) had a significant main effect, with no interaction. A pairwise *Post hoc* Tukey tests on valence showed that only two levels of pulse width had a significant effect suggesting two uniquely distinguishable levels: (High, Low), (Middle) (Table 3.1). For arousal, both pulse width ($F(2,323) = 391.39$, $p < 0.001$) and pulse frequency ($F(5,323) = 6.28$, $p < 0.001$) had a significant main effect, with no interaction. After performing *post hoc* Tukey tests on arousal, all levels of pulse width had a significant effect providing three uniquely distinguishable levels same as urgency and annoyance Table 3.1. In addition, for pulse frequency, the significant effect was only between 10 PPS and all other pulse frequencies except for 110 PPS suggesting two uniquely

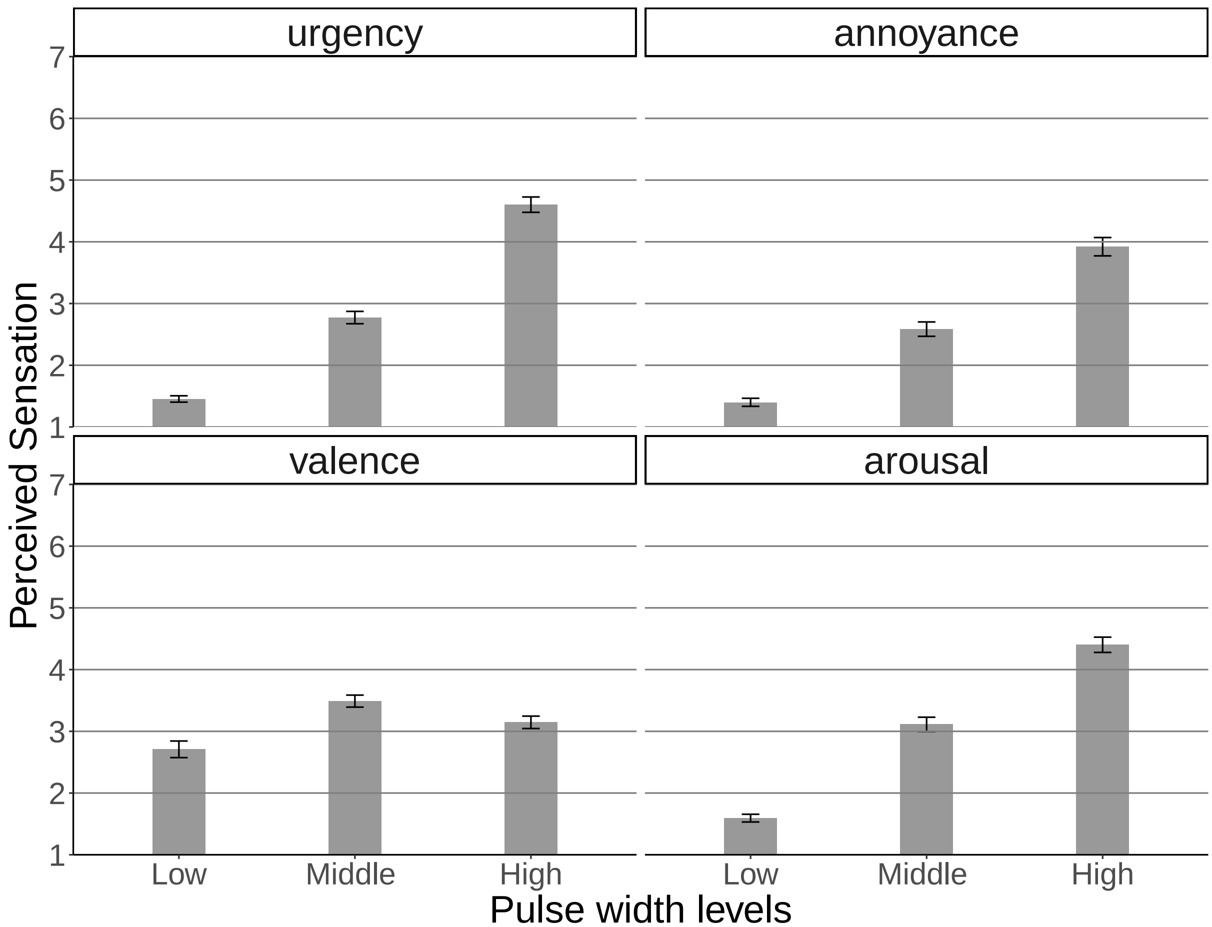

Figure 3.8: The effect of pulse width on all dependent variables for Experiment 1 (the errors bar in all graphs present standard error).

distinguishable levels as seen in Table 3.2. Furthermore, participants' performance was the same for all parameters across blocks, indicating no learning effects as seen in Figure 3.10.

Table 3.1: *Post hoc* pairwise Tukey tests comparing stimulus levels of pulse width for Experiment 1.

Stimulus pairs	Urgency	Annoyance	Valence	Arousal
High - Low	p<.0001*	p<.0001*	p=0.1252	p<.0001*
High - Middle	p<.0001*	p<.0001*	p=0.0039*	p<.0001*
Low - Middle	p<.0001*	p<.0001*	p<.0001*	p<.0001*

* marks a significant difference (P<0.05).

3.4.5 Qualitative Results

Figure 3.11 shows that the most common sensation was strong for high strength, which was selected 14 times, and gentle for low strength, which was selected 12 times. Participants circled a total of 217 terms. The total number of terms participants chose for high strength

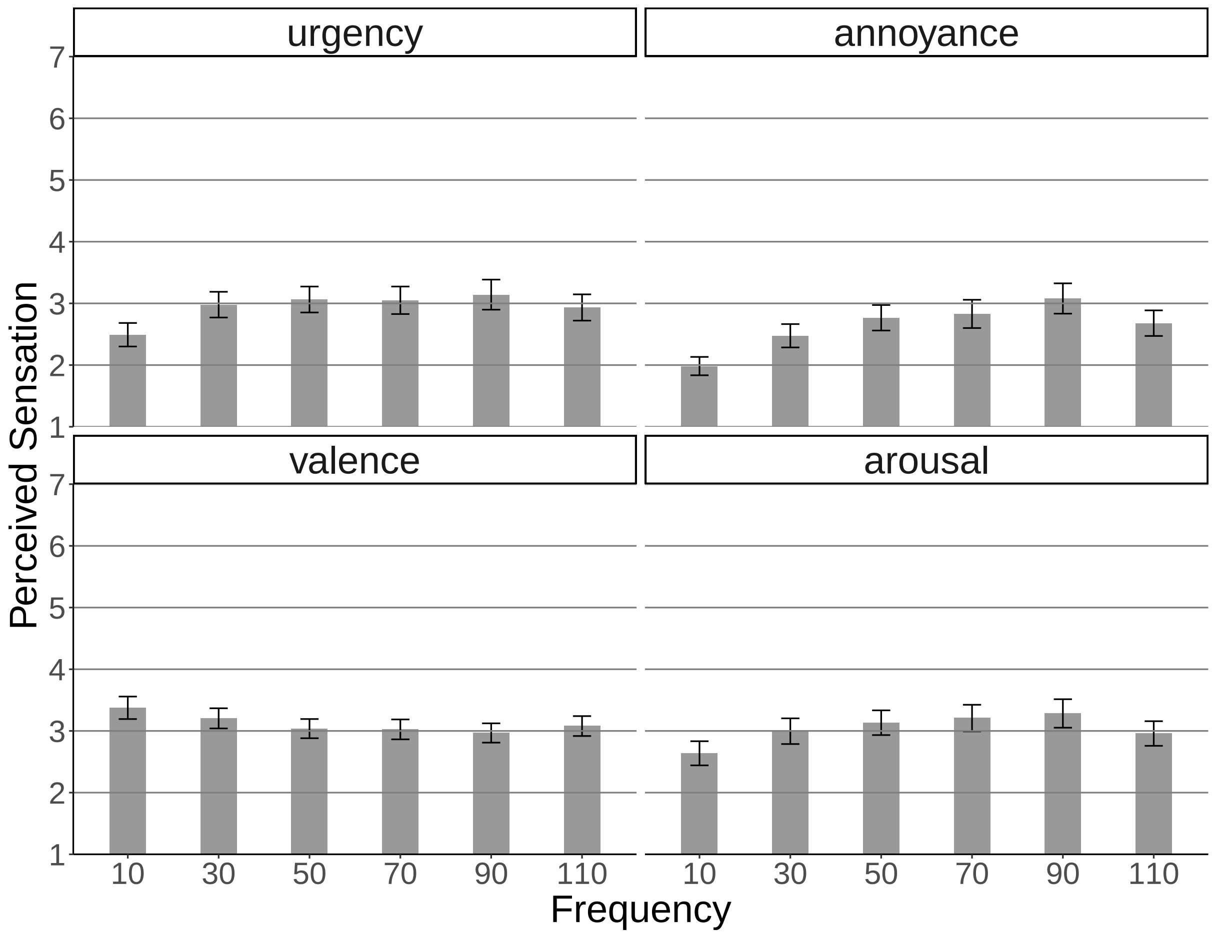

Figure 3.9: The effect of pulse frequency on all dependent variables for Experiment 1.

was 89, middle strength 79 and low strength 49, so there was a general trend for more sensations being selected the higher the strength. The recorded answers revealed that 16 out of 20 participants reported that their sensitivity changed over time and that they got used to the stimuli in distinguishing different intensities. From the recorded answers for Question 1: *Did your sensitivity change with time?*, P02 reported that he *"was able to detect better later than the beginning. I was surprised at the beginning, but later got used to it"*. P05 added that *"at the beginning, I could not detect a lot of stimuli. Later on, I felt them. Also, they became less annoying and got used to the sensation"*. Some participants reported that they felt the electrotactile inside their hands. P05 mentioned that *"it feels right in the skin"*, while P08 described it as *"Feels like in my hand. Moving through me"*. P03 came in with the preconceived idea that they would be electrically shocked and said *"it felt so odd on my hand. I would not buy a device that uses it "*.

For Question 2, *What is the difference in sensation between the electrotactile feedback and the vibration you get from a phone?*, P06 reported *"electrotactile had more variety, a lot more settle sensations"*. P08 added *"It was more intense than my phone. Felt like in my hand moving through me."*. P16 said *"Some cues were very strong and some were very*

Table 3.2: *Post hoc* pairwise Tukey tests comparing stimulus levels of pulse frequency for Experiment 1.

Stimulus pairs	Urgency	Annoyance	Arousal
10 - 30	p<.0006*	p=0.0017*	p=0.0175*
10 - 50	p=0.0001*	p<.0001*	p=0.0175*
10 - 70	p<.0001*	p<.0001*	p=0.0001*
10 - 90	p<.0001*	p<.0001*	p<.0001*
10 - 110	p=0.0099*	p<.0001*	p=0.1700
30 - 50	p=0.9964	p=0.3166	p=0.9851
30 - 70	p=0.9856	p=0.1613	p=0.7848
30 - 90	p=0.8839	p=0.0021*	p=0.6108
30 - 110	p=0.9743	p=0.7476	p=0.9573
50 - 70	p=1.0000	p=0.9994	p=0.9887
50 - 90	p=0.9909	p=0.4780	p=0.9431
50 - 110	p=0.8123	p=0.9836	p=0.6505
70 - 90	p=0.9982	p=0.7030	p=0.9998
70 - 110	p=0.7135	p=0.9081	p=0.2634
90 - 110	p=0.4351	p=0.1369	p=0.1476

* marks a significant difference (P<0.05).

good. Vibration from the phone was static, here is different". P20 reported *"I felt it inside my hand. Feels closer than the vibrotactile, yet annoying"*. Answering Question 3, P02 said *"For slowing down, use the most urgent ones (pulsating). Gentle for navigation"*. P13 added *"the more intense ones were more disruptive, grab your attention right away in a negative way (for very urgent matters). More annoying you get close to the turn"*. P14 expressed their concern about safety *"you might use it, but it may not be safe"*.

3.4.6 Calibration

Even though calibration was not a part of the experiment, reporting the calibration values does help in understanding how electrotactile feedback works in haptic applications. As described in Section 2.3.4, calibration plays a crucial role in setting up the detection and discomfort thresholds for each participant individually, as what might be perceived as comfortable to one participant, might be uncomfortable to another participant. Looking at Figure 3.12 and Figure 3.13, it shows the distribution of values for the minimum amplitude values and maximum pulse width across all participants where light grey bars represent the minimum values (detection threshold) for amplitude and dark grey bars represent the maximum values (discomfort threshold) for pulse width. The average value for amplitude was 8.8 mA, SD= 2.04 mA and median= 9 mA, whereas for pulse width the average value was 166.55 μs, SD= 39.61 μs and median= 190 μs. The calibration for the electrotactile

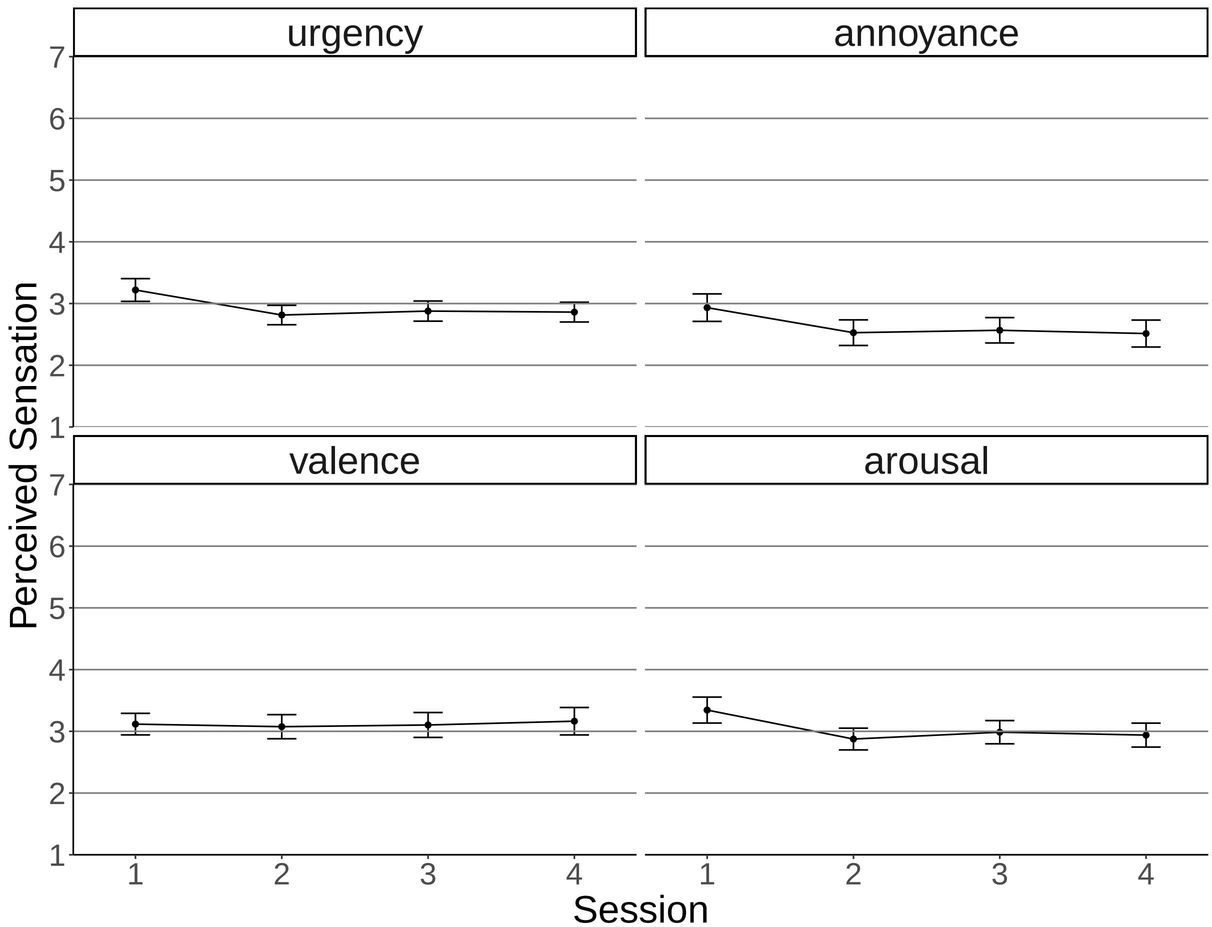

Figure 3.10: Learning effect graph across all four sessions.

signals was by increasing the value of amplitude by steps of 1 mA and for pulse width by steps of 10 μs. From Figure 3.12 for amplitude, it can be seen that participants started to detect electrotactile stimulation at different values as their impedance differs from each other. Nine out of the 20 participants reached the maximum value of 200 μs (Figure 3.13)

3.4.7 Experiment 1 Discussion

The results showed that the effect of pulse frequency on perception was between 10 PPS and higher levels. One possible reason for not finding significance between the rest of the frequencies could be that, at above 30 PPS, sensory adaptation occurred. This may have caused participants problems distinguishing between higher frequencies as found in [106]. Therefore, *Hypothesis 1* is supported.

Pulse width was the only independent variable with a significant effect on valence. There was no significance between high and low levels indicating that the valence threshold is somewhere between middle-high and middle-low pulse width. Therefore, *Hypothesis 2* is not supported. The perceived intensity of an electrotactile stimulus is governed by pulse

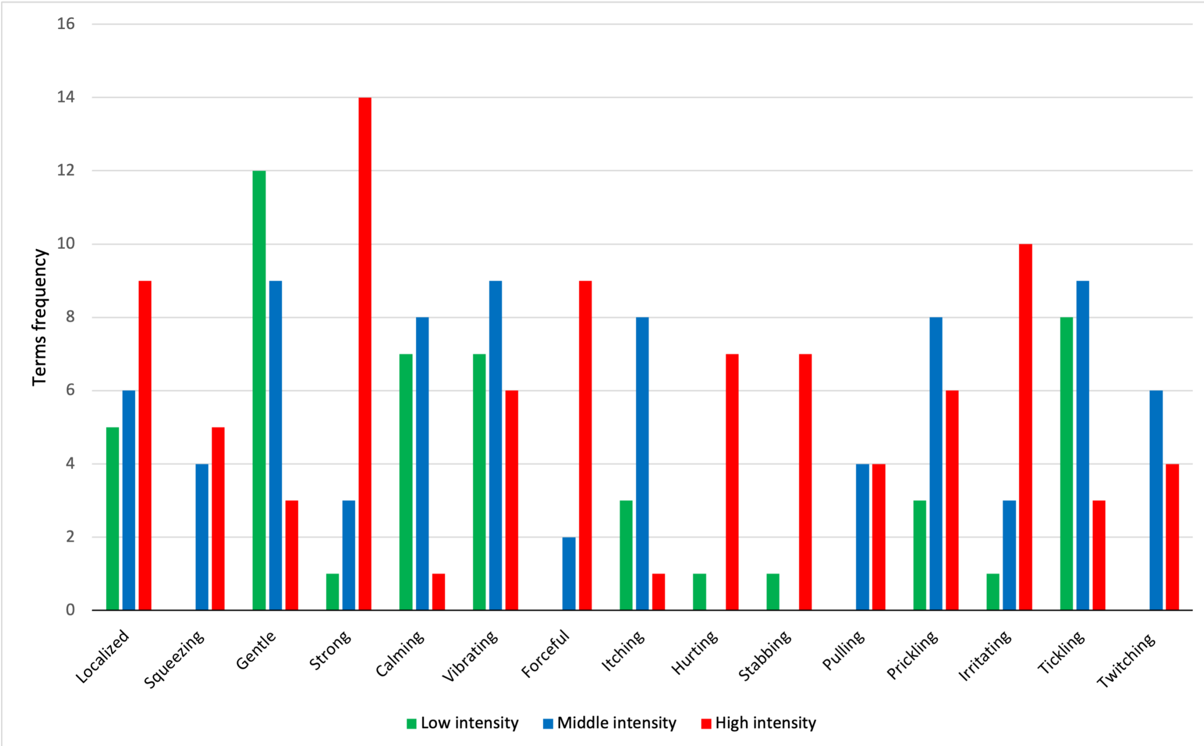

Figure 3.11: The 15 terms that participants can select from based on the strength of the stimulus for Experiment 1.

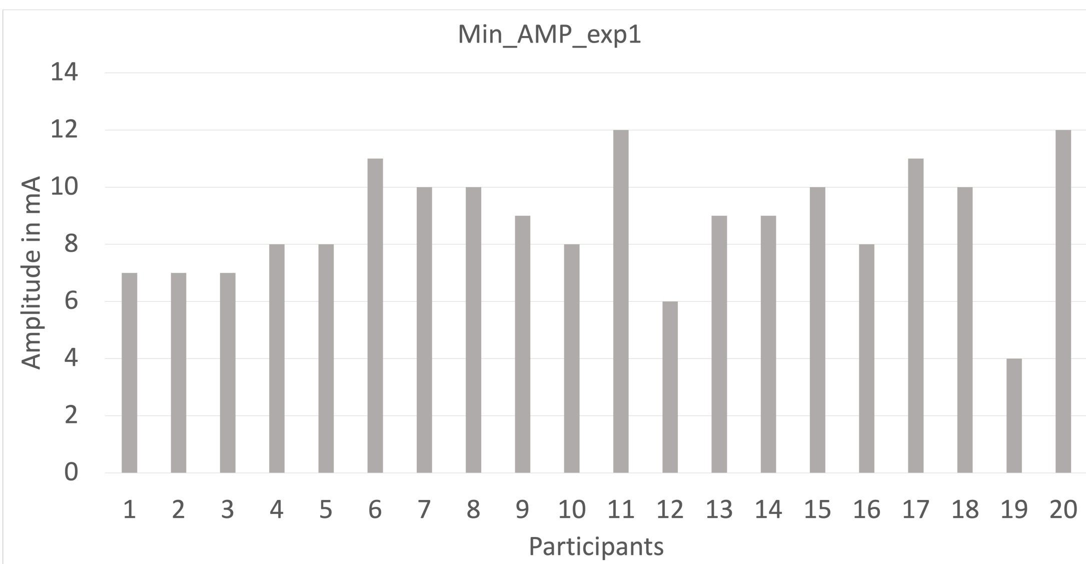

Figure 3.12: The distribution of minimum values (detection level) of amplitude across participants for Experiment 1.

width and amplitude [6], so an increase of one of them (pulse width in this experiment) would increase the level of intensity. The results showed that the higher the level of intensity, the higher the perceived urgency. Therefore, *Hypothesis 3* is supported.

The results showed a direct relationship between urgency, arousal and annoyance across

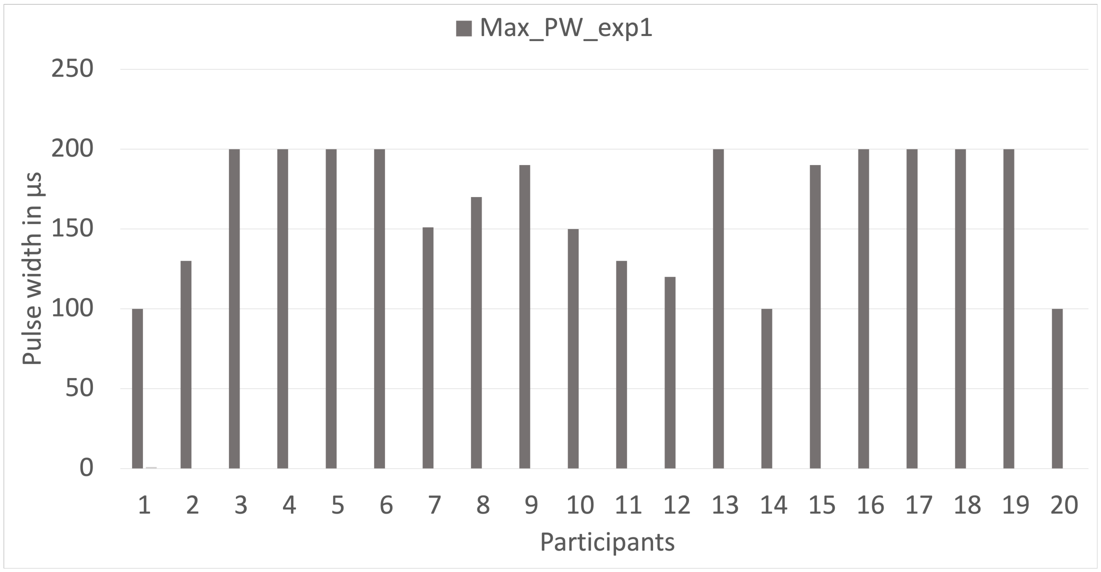

Figure 3.13: The distribution of maximum values (discomfort level) for pulse width across participants for Experiment 1.

both independent variables. Having a stimulus with higher urgency and arousal would induce a higher sense of alertness and reaction [72, 107]. Although stimuli were more annoying as their urgency increased, the rating of perceived annoyance was always lower than the perceived urgency. This finding is in line with [108] and suggests that urgency had more impact on the rating than annoyance. This is crucial since stimuli with a higher annoyance can be ineffective [14]. Therefore, *Hypothesis 4* is supported.

In terms of the Circumplex model of emotion [10], manipulating pulse width and pulse frequency of electrotactile stimuli used to give some coverage of the emotion space. The ability to create messages with negative valences and create three different levels of arousal can be seen in Figure 3.8. As valence and arousal average scores were below neutral except for a high level in arousal, it suggests that participants did not find the stimulation particularly pleasant or exciting. This could be due to various factors, such as the intensity of the electrical current caused by manipulating pulse width or pulse frequency, the specific electrode placement on the skin, or individual differences in sensory perception. One possible explanation is that the electrotactile feedback is perceived as uncomfortable or irritating due to the electrical nature of the stimulation. The findings showed that electrotactile cues are capable of generating simple emotional experiences, which could be used for negative messages/emojis, for example. This experiment is just a first step into the emotional aspects of electrotactile cues and will continue to explore the space further by manipulating other parameters.

3.4.8 Summary

The aim of this experiment was to investigate the effect of manipulating 3 levels of pulse width and 6 levels of pulse frequency on the ratings of perceived urgency, annoyance, valence and arousal and how many of these levels are distinguishable from each other will contribute to answering Research Questions 1 & 2 of this thesis:

- *What parameters of electrotactile stimulation can be used to influence subjective perception?*
- *How can the parameters of electrotactile feedback be used to encode information in Electrotactons?*

The finding of this experiment showed that both pulse width and pulse frequency had a significant effect on all subjective perceptions. Increasing pulse width increased all of the perceived sensations and gave three clear levels of the parameter, except for valence having only two clear levels. Furthermore, pulse frequency generally had little effect on valence but did affect the other sensations. It had two clear levels of urgency and arousal and three of annoyance. These clear levels of sensations from the parameters dictate its usability to encode information in the design of *Electrotactons*. A follow-up experiment, therefore, is needed to explore another range of pulse frequencies as it was revealed that participants couldn't distinguish between pulse frequencies 30 PPS and above yielding few usable levels of the parameter.

3.5 Experiment 2 (Amplitude and Pulse Frequency)

The second experiment investigates the second pair of electrotactile basic parameters, amplitude and pulse frequency. The aim was to measure subjective perception and how many distinguishable levels there were of urgency, annoyance, valence and arousal by manipulating 9 levels of pulse frequency from a wider range of frequencies (5 PPS to 45 PPS) informed by the results of Experiment 1, and 3 levels of amplitude. This experiment uses the same apparatus and setup as before. The results of this experiment will continue to contribute to answering Research Questions 1 & 2.

3.5.1 Experimental Design

The experiment used a within-subjects design, consisting of the same three phases as Experiment 1. In this experiment, the stimulation parameters amplitude and pulse frequency were the independent variables. Nine equally spaced frequencies (5 PPS, 10 PPS, 15 PPS, 20 PPS, 25 PPS, 30 PPS, 35 PPS, 40 PPS, 45 PPS), and three values for amplitude were used to create the electrotactile cues. This gave 27 stimuli from both parameters.

The pulse frequency range tested in Experiment 1 was extended to find if participants could discriminate frequencies at lower levels below 30 PPS. Following the rationale for H3 in Experiment 1, higher ratings of urgency, annoyance and arousal were expected with high amplitude. Pohl *et al.* [6] described that high amplitudes caused a stronger sensation; amplitude was expected to influence perception more than pulse width.
The hypotheses of this experiment therefore were:

- ***Hypothesis 1:*** *Frequencies below 30 PPS will have a significant effect on perception;*
- ***Hypothesis 2:*** *When amplitude increases, urgency, annoyance and arousal will increase, while valence decreases.*

3.5.2 Participants

Twenty new participants (9 female) were recruited, aged 18 - 43 (*Mean=26.6, SD=6.8.42, Median=25*); one was left-handed. Most were students. None of them had dermatitis or other skin conditions or cardiovascular issues. Each participant read the information sheet and signed a consent form before the start of the experiment, and was paid £8 in Amazon vouchers.

3.5.3 Procedure

The procedure was the same as the first experiment with the following additions to the calibration phase. After recording the discomfort threshold of the pulse width, the pulse width was set to the mean value for the rest of the experiment. Then amplitude was increased from detection threshold until the participant felt uncomfortable and this value was saved as the amplitude discomfort threshold. The maximum value for the amplitude was capped at 20 mA to avoid any pain sensation. Figure 3.14 shows the calibration interface used for this experiment. In the training phase, 10 randomly ordered stimuli that lasted for 1s were presented using randint method in Python. In the experiment phase, participants did four blocks, and each block contained 27 stimuli. The total number of trials was 108 across the four blocks. Qualitative assessment was the same as Experiment 1 in which participants were handed a piece of paper that had the 15-terms on it (Figure 3.5) and were instructed to circle any of the terms based on the level of strength of the electrotactile cues received during the experiment with three different colours. In the end, they were asked the following questions:

1-Did your sensitivity change with time?
2-What is the difference in sensation between the electrotactile feedback and the vibration you get from a phone?

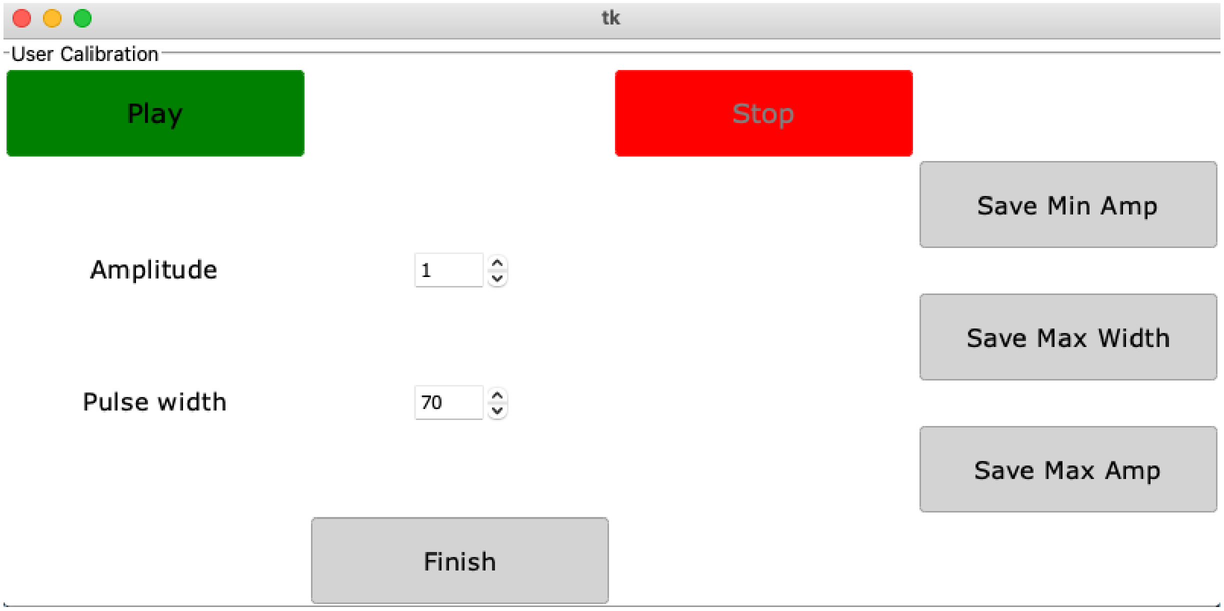

Figure 3.14: The calibration interface for Experiment 2 to save the maximum value of amplitude.

3-how do you think electrotactile feedback could be used on a steering wheel in a car for navigation or notification?

3.5.4 Results

The same method was used as the first experiment for two-factor (amplitude and pulse frequency) repeated-measures ANOVA. For urgency, both amplitude ($F(2,494) = 476.4$, $p < 0.001$) and pulse frequency ($F(8,494) = 28.9$, $p < 0.001$) had a significant main effect, with no interaction. For annoyance, both amplitude ($F(2,494) = 259.42$, $p < 0.001$) and pulse frequency ($F(8,494) = 17.26$, $p < 0.001$) had a significant main effect, with no interaction. For valence, both amplitude ($F(2,494) = 53.10$, $p < 0.001$) and pulse frequency ($F(8,494) = 3.13$, $p < 0.001$) had a significant main effect, with no interaction. For arousal, both amplitude ($F(2,494) = 494.63$, $p < 0.001$) and pulse frequency ($F(8,494) = 25.23$, $p < 0.001$) have a significant main effect, with no interaction. No learning effects across blocks were observed.

A pairwise *post hoc* Tukey tests was performed on all significant effects of amplitude, and there were some observations. All levels of amplitude had a significant effect across all dependent variables, with valence decreasing as amplitude increased (Figure 3.15, Table 3.3). This suggests that all received sensations had 3 uniquely distinguishable levels: (High), (Middle) and (Low).

Performing a pairwise *post hoc* Tukey tests on all significant effects of pulse frequency, it showed that the significant effect was found only when comparing the range 5 PPS

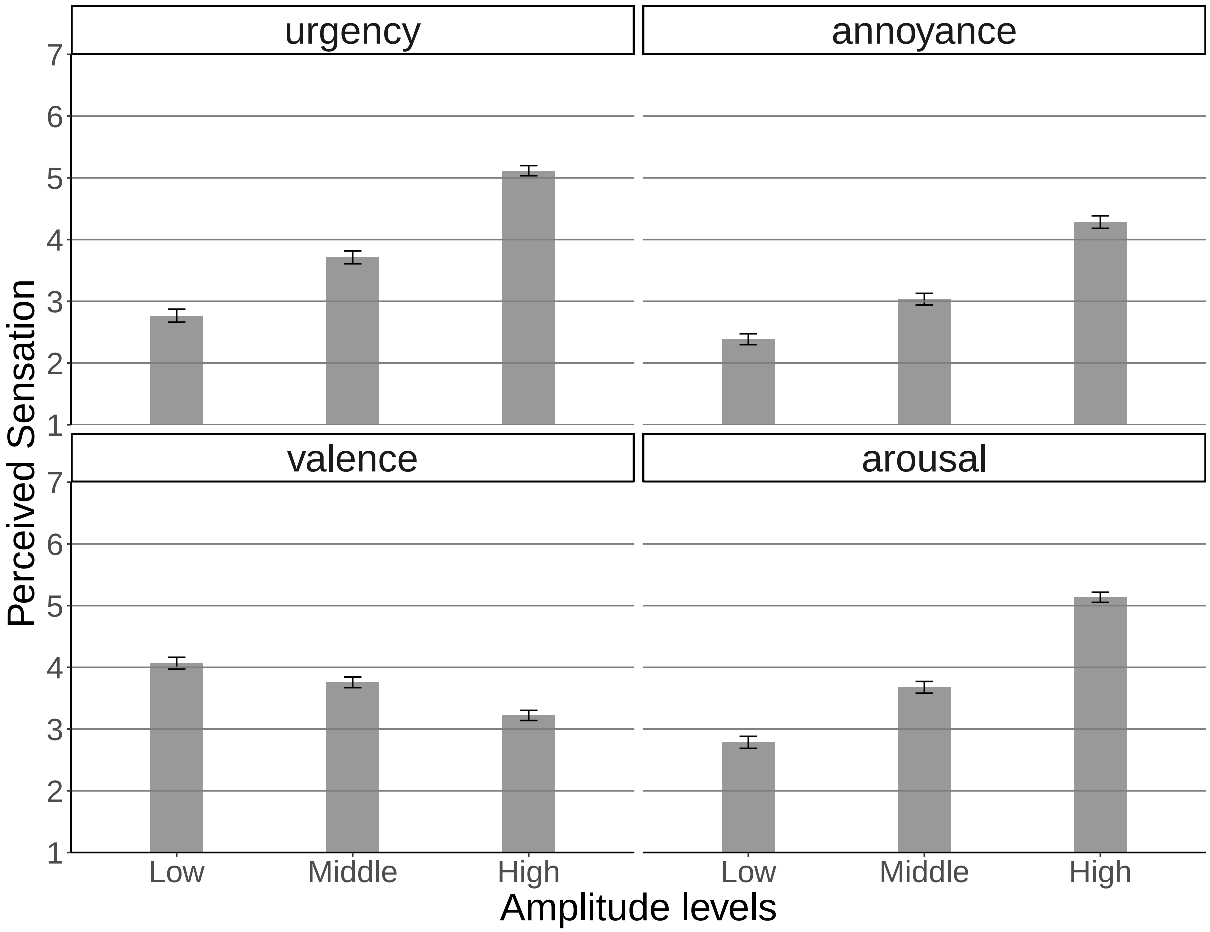

Figure 3.15: The effect of amplitude on all dependent variables.

to 20 PPS to higher frequencies, with some exceptions (Figure 3.16 and Table 3.4). For urgency, there were five uniquely distinguishable levels: (5 PPS), (10 PPS), (15 PPS), (20 PPS), (25 PPS, 30 PPS, 35, PPS, 40 PPS, 45 PPS) with the condition that the difference between frequencies must be higher than 5 PPS to have significance. For example, there was no significance between the pair 5 PPS- 10 PPS and the same goes with the pair 10 PPS- 15 PPS.

Table 3.3: *Post hoc* pairwise Tukey tests comparing stimulus levels of amplitude for Experiment 2.

Stimulus pairs	Urgency	Annoyance	Valence	Arousal
High - Low	p<.0001*	p<.0001*	p<.0001*	p<.0001*
High - Middle	p<.0001*	p<.0001*	p<.0001*	p<.0001*
Low - Middle	p<.0001*	p<.0001*	p=0.0028*	p<.0001*

* marks a significant difference (P<0.05).

For annoyance, a significant effect is found when comparing the range of 5 PPS to 20 PPS to higher frequencies, suggesting five uniquely distinguishable levels: (5 PPS), (10

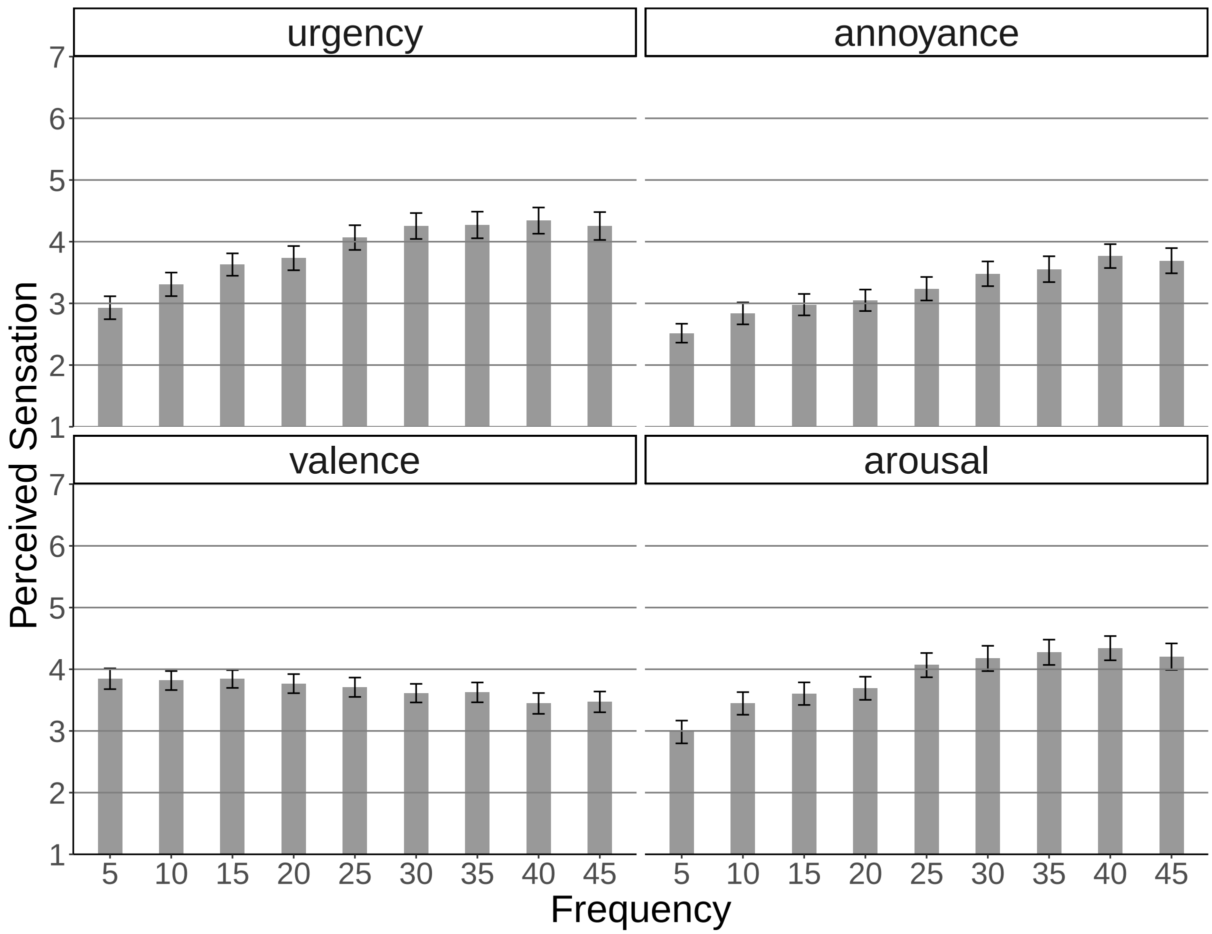

Figure 3.16: The effect of pulse frequency on all dependent variables.

PPS), (15 PPS), (20 PPS), (25 PPS, 30 PPS, 35, PPS, 40 PPS, 45 PPS) with some exceptions. When comparing 5 PPS to other frequencies, the difference must be higher than 5 PPS. For the rest of the range, the difference must be higher than 15 PPS. The pair 25 PPS-40 PPS was the only pair with a significant difference outside of the range. For valence, the significance was only found when comparing three pairs of frequencies 5 PPS-40 PPS, 15 PPS-40 PPS and 15 PPS-45 PPS. For arousal, a significant effect is found when comparing the range of 5 PPS to 20 PPS to higher frequencies, suggesting five uniquely distinguishable levels: (5 PPS), (10 PPS), (15 PPS), (20 PPS), (25 PPS, 30 PPS, 35, PPS, 40 PPS, 45 PPS) with some exceptions. When comparing 10 PPS with other frequencies, the difference must be higher than 10 PPS to have a significant effect. In the case of 15 PPS and 20 PPS, the difference must be higher than 5 PPS to have a significant effect.

3.5.5 Qualitative Results

Figure 3.17 shows that the most common sensation from Figure 3.5 was gentle for low strength, which was selected 16 times, and forceful for high strength, which was selected

Table 3.4: *Post hoc* pairwise Tukey tests comparing stimulus levels of pulse frequency for Experiment 2.

Stimulus pairs	Urgency	Annoyance	Valence	Arousal
5 - 10	p=0.1658	p=0.2789	p=1.0000	p=0.0159*
5 - 15	p<.0001*	p=0.0038*	p=1.0000	p=0.0001*
5 - 20	p<.0001*	p=0.0011*	p=1.0000	p<.0001*
5 - 25	p<.0001*	p<.0001*	p=0.9719	p<.0001*
5 - 30	p<.0001*	p<.0001*	p=0.7772	p<.0001*
5 - 35	p<.0001*	p<.0001*	p=0.6746	p<.0001*
5 - 40	p<.0001*	p<.0001*	p=0.0381*	p<.0001*
5 - 45	p<.0001*	p<.0001*	p=0.0598	p<.0001*
10 - 15	p=0.2109	p=0.8724	p=1.0000	p=0.9368
10 - 20	p=0.0171*	p=0.6922	p=1.0000	p=0.5050
10 - 25	p<.0001*	p=0.0694	p=0.9972	p=0.0001*
10 - 30	p<.0001*	p=0.0002*	p=0.9250	p<.0001*
10 - 35	p<.0001*	p<.0001*	p=0.8630	p<.0001*
10 - 40	p<.0001*	p<.0001*	p=0.0964	p<.0001*
10 - 45	p<.0001*	p<.0001*	p=0.1416	p<.0001*
15 - 20	p=0.9925	p=1.0000	p=0.9999	p=0.9975
15 - 25	p=0.0148*	p=0.8368	p=0.9522	p=0.0156*
15 - 30	p=0.0001*	p=0.0480*	p=0.7134	p=0.0003*
15 - 35	p<.0001*	p=0.0154*	p=0.6034	p<.0001*
15 - 40	p<.0001*	p<.0001*	p=0.0276*	p<.0001*
15 - 45	p=0.0002*	p=0.0003*	p=0.0442*	p=0.0002*
20 - 25	p=0.1917	p=0.9529	p=0.9987	p=0.1471
20 - 30	p=0.0035*	p=0.1159	p=0.9464	p=0.0068*
20 - 35	p=0.0007*	p=0.0430*	p=0.8953	p=0.0003*
20 - 40	p=0.0004*	p=0.0001*	p=0.1174	p=0.0001*
20 - 45	p=0.0071*	p=0.0010*	p=0.1697	p=0.0050*
25 - 30	p=0.9300	p=0.8096	p=0.9998	p=0.9846
25 - 35	p=0.7519	p=0.5787	p=0.9988	p=0.6977
25 - 40	p=0.6735	p=0.0182*	p=0.4799	p=0.4347
25 - 45	p=0.9719	p=0.0726	p=0.5871	p=0.9747
30 - 35	p=1.0000	p=1.0000	p=1.0000	p=0.9977
30 - 40	p=0.9999	p=0.6504	p=0.8268	p=0.9668
30 - 45	p=1.0000	p=0.9001	p=0.8958	p=1.0000
35 - 40	p=1.0000	p=0.8611	p=0.8993	p=1.0000
35 - 45	p=0.9997	p=0.9825	p=0.9467	p=0.9990
40 - 45	p=0.9988	p=1.0000	p=1.0000	p=0.9791

* marks a significant difference (P<0.05).

15 times. Participants circled a total of 259 terms, which is 18% more than Experiment 1. The reason for this increase might be that amplitude was kept at the detection value (minimum value) in Experiment 1, and in Experiment 2 pulse width was kept at the mean value (middle value), making higher strength cues in Experiment 2. The total number of terms circled for high strength was 102, middle strength 85 and low strength 72. It follows the same trend as Experiment 1, the higher the strength, the more sensations were

selected.

From the recorded answers for Question 1: *Did your sensitivity change with time?*, 15 out of 20 participants reported that they felt their sensitivity changed over time and that they got used to the stimuli and distinguishing different intensities. P05 said *"Yes, got more used to the feeling. From painful to less painful"*. P07 added *"Yes, at the beginning the stimuli felt less urgent and later on it felt more urgent"*. P09 reported *"My sensing stayed the same, maybe got used to it towards the end"*.

From the answers for Question 2: *What is the difference in sensation between the electrotactile feedback and the vibration you get from a phone?*, 5 participants pointed out that they felt that electrotactile had different levels of stimulation compared to the vibration of a mobile phone, as P09 put it *"the phone is not as strong or detailed as the electrotactile. The phone feels like the same thing for everything, the electrotactile is more varied with different strengths"*. P01 reported *"the Vibration from the phone is always the same, wherewith electrotactile, you don't know what to expect. It can be really intense or really soft"*. P06 added *"The cellphone is softer, not irritating"*.

Answering Question 3: *how do you think electrotactile feedback could be used on a steering wheel in a car for navigation or notification?*, P02 said *"It would be nice to use the high-strength ones for very urgent situations, and the mid-strength ones for navigation"*. P17 suggested *"It might have a negative effect because it will shock you"*. P18 reported *"For notifications, it needs to move fast and with high strength. I would not use it for massages"*.

3.5.6 Calibration

As one of the aims of this experiment was to investigate the effect of manipulating amplitude on perception, measuring the maximum value of amplitude was added to the calibration phase. This value will help improve calibrating electrotactile parameters in the rest of the experiments in his thesis. Figure 3.18 shows the distribution of amplitude values across participants. The average minimum value was 9.85 mA, SD= 2.88 mA and median= 10.5 mA, whereas the average maximum value was 13.8 mA, SD= 3.42 mA and median= 14 mA. The average maximum value for pulse width was 155 μs, SD= 40.45 μs and median = 145 μs. Eight out of 20 participants reached the cap value of pulse width of 200 μs that was set up to avoid any pain sensation (Figure 3.19).

3.5.7 Experiment 2 Discussion

Having smaller steps in the range of pulse frequencies compared to the first experiment, helped to locate what pulse frequencies have a significant effect on perception. The results showed that the significant effect was between the range of 5 PPS to 20 PPS and the

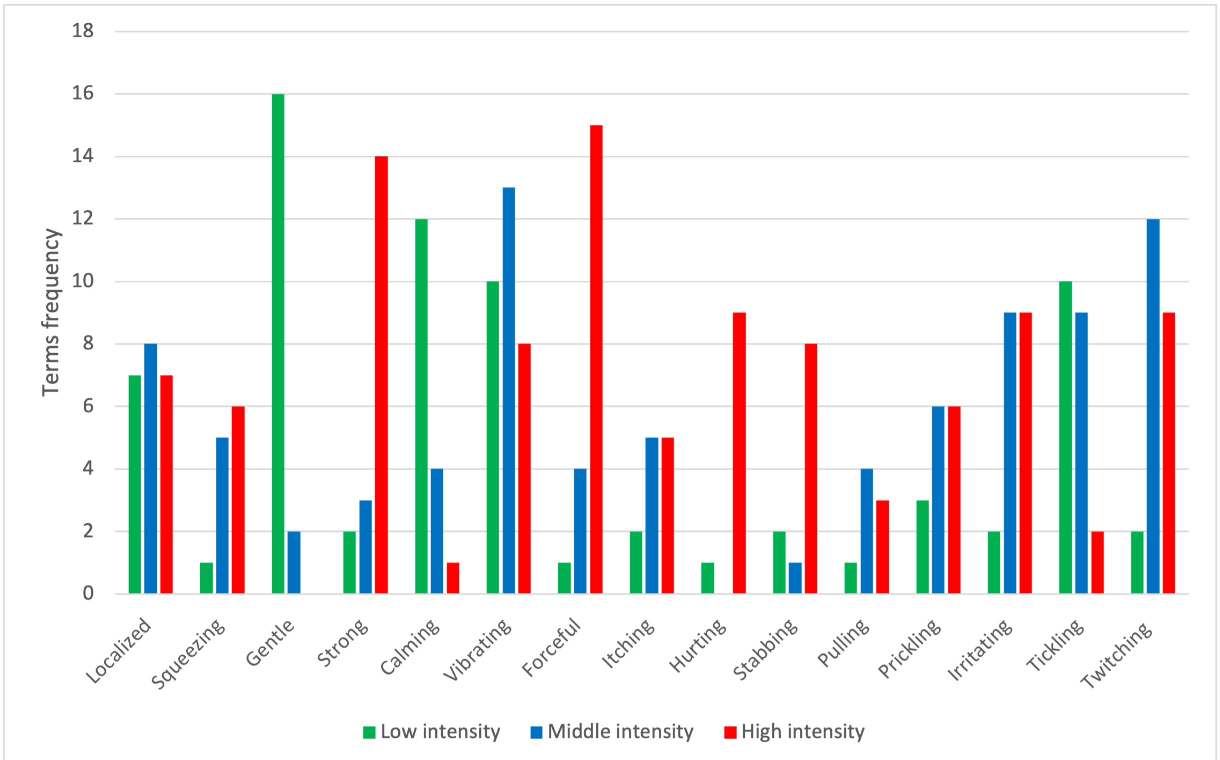

Figure 3.17: The 15 terms that participants can select from based on their strength level perception Experiment 2.

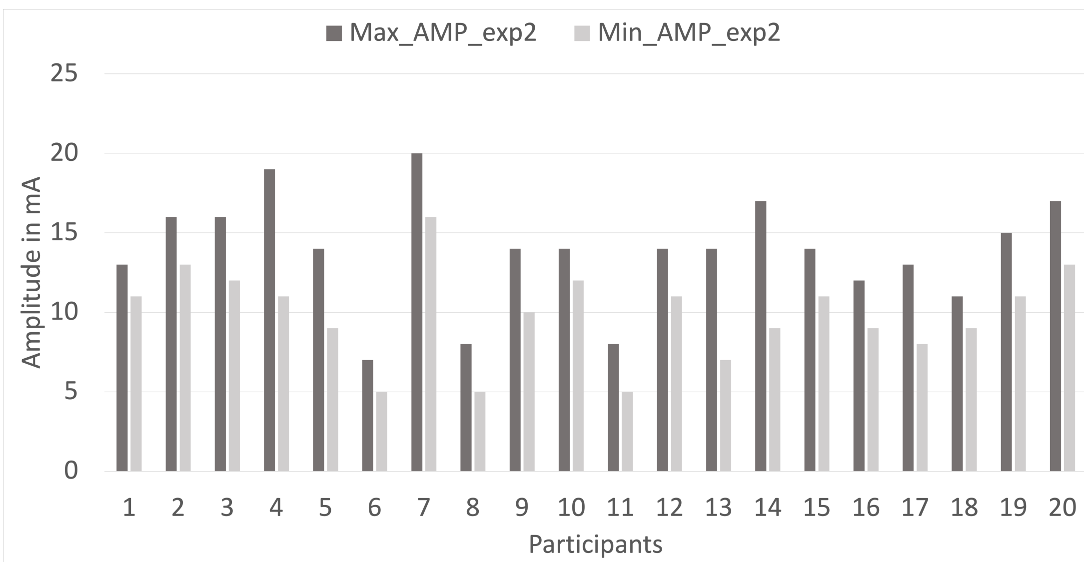

Figure 3.18: The distribution of maximum and minimum calibration values for amplitude across participants for Experiment 2.

other pulse frequencies. At that range, Only Meissner corpuscles that detect motion [30] are activated, leading participants to distinguish between different stimuli more reliably, as pulse frequencies higher than 20 PPS will activate mechanoreceptors beyond Meissner corpuscles [17]. Therefore, *Hypothesis 1* is supported. In line with related work, [6]

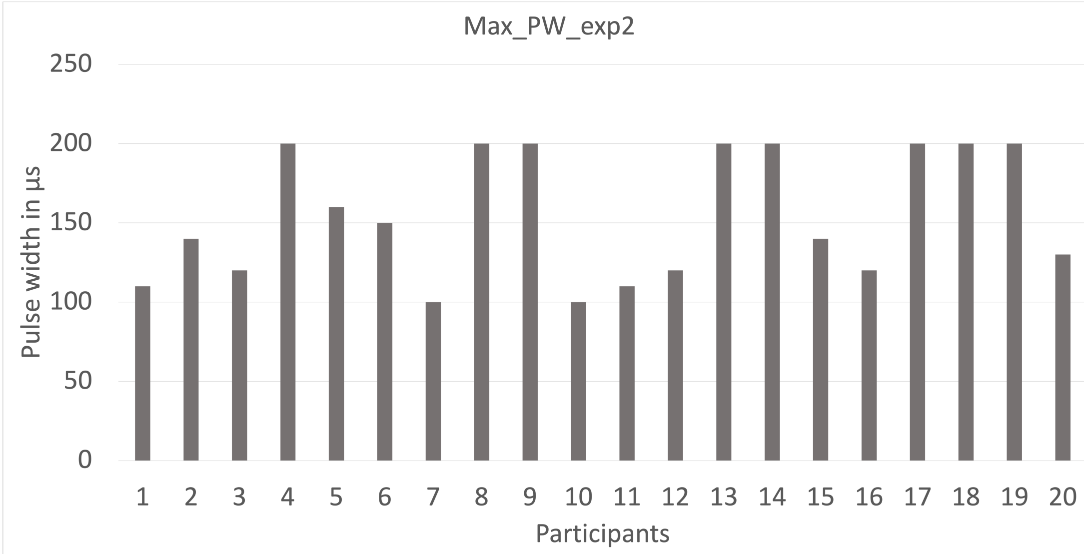

Figure 3.19: The distribution of maximum values for pulse width calibration across participants for Experiment 2.

and Figure 3.15, the higher the level of amplitude, the higher the rating of urgency, annoyance and arousal. Moreover, the lower the rating of valence. Therefore, *Hypothesis 2* is supported.

3.5.8 Summary

This experiment was a continuation to investigate electrotactile basic parameters such as amplitude and pulse frequency. The aim was to study the effect of 3 levels of amplitude and 9 levels of pulse frequencies on the ratings of perceived urgency, annoyance, valence and arousal, and how many distinguishable levels these parameters can produce. The range of pulse frequency was informed by the results of Experiment 1 to find more distinguishable levels. This aim continues to contribute an answer to Research Questions 1 & 2 of this thesis:

- *What parameters of electrotactile stimulation can be used to influence subjective perception?*
- *How can the parameters of electrotactile feedback be used to encode information in Electrotactons?*

The results of this experiment indicate that amplitude had a significant effect on all subjective perceptions of sensations, and gave three clear levels of the parameter. Increasing amplitude caused a higher rating of urgency, annoyance and arousal while causing a lower rating of valence. Pulse frequency also had a significant effect on subjective perception and showed more distinguishable levels than what was found in Experiment 1. There were five distinguishable levels in urgency, annoyance and arousal, while valence had only three pairs of frequencies. The findings of both Experiments 1 & 2 showed that pulse width, amplitude and pulse frequency did influence subjective perception with clear distinguishable levels, making it suitable to encode information into these levels to crate *Electrotactons*. The next experiment will test the use of these levels to design *Electrotactons* to present multi-dimensional information and measure their recognition rate.

3.6 Experiment 3 (Electrotactons with Basic Parameters)

Experiment 3 investigated the possibility of using the three electrotactile parameters (pulse width, amplitude and pulse frequency) to convey three pieces of information encoded into an electrotactile stimulus on the palm to allow the creation of complex, multi-dimensional electrotactile cues called *Electrotactons*, similar to those that can be created with vibrotactile actuators [12]. The finding from Experiments 1 & 2 identified the number of distinguishable levels of each pulse width, amplitude and pulse frequency which might be suitable in the design of *Electrotactons*. Moreover, this experiment establishes a baseline performance level for *Electrotactons* to which any future experiments can be compared to. The results of this experiment will contribute to Research Questions 2 & 3.

3.6.1 Experimental Design

As stated in Section 2.2.4, the focus of this thesis is to design *Electrotactons* which are structured and abstract messages, not tied to a specific meaning. Therefore, the *Electrotactons* can be mapped to different meanings based on the application. This experiment presented the first attempt at designing and evaluating *Electrotactons* and used the same application that has been used to evaluate Tactons [71]. The design of this experiment used the same appointment task as Brown *et al.* [71] and encoded three dimensions of data (*Time* until appointment, *Type* of appointment and *Importance* of the appointment) in each stimulus using the parameters: pulse width, amplitude and pulse frequency. Each dimension of data was encoded into one distinguishable level of one of the parameters that were reported by the results of Experiments 1 & 2. There were three clear levels in pulse width and amplitude, and five in pulse frequency. The three levels of pulse width were mapped to Type as follows: (high->meeting, middle->lecture, low->tutorial), amplitude was mapped to Importance as follows: (high->high importance, middle->middle importance, low->low importance) and pulse frequency to *Time* (5 PPS->30 min, 15 PPS->15 min and 30 PPS->5 min). As *Electrotactons* uses an abstract approach to encode information, where there is no direct link between the electrotactile parameter and the information that is represents, therefore the mapping need to be learned.

A pilot study was conducted to investigate the suitability of the mapping between the parameters and the information. However, participants were not clearly able to identify these levels (as Brown *et al.* [71] also found for vibrotactile cues). For pulse frequency especially, participants faced a hard time distinguishing between its levels. Therefore, a simplified design using two levels for each Type and Importance was implemented, and three different pulse frequencies (2 PPS, 8 PPS and 16 PPS) that were tested in the pilot and participants could easily distinguish between them.

Mapping onto a categorical variable like *Type* of appointment (meeting, tutorial) does not have a natural order, meaning there is no inherent hierarchy or numerical relationship between the categories. In this case, using different levels of pulse width to convey different types of appointment can be intuitive for some people, but it may not be for others. It depends on the individual's familiarity with the specific mapping and their ability to perceive and interpret the electrotactile cue. On the other hand, mapping onto an ordinal variable like *Importance* of appointment (high or low) or an interval variable like *Time* of appointment can convey a natural order or hierarchy between the levels. When mapping onto ordinal or interval variables, it is crucial to ensure that the levels are logically and intuitively ordered, and in the case of pulse frequency can be used to indicate different time intervals until the appointment. In general, the mapping of the electrotactile cue onto different variables needs to consider the cognitive abilities and limitations of the user, as well as the context of use. An intuitive mapping can improve the learning and interpretation of the information conveyed by the cue [109, 110].

This experiment used a 3x2x2 within-subjects design, consisting of three phases: calibration, training and experiment. The independent variables were: pulse width to convey the *Type* of the appointment (high->meeting, low->tutorial), amplitude to convey the *Importance* of the appointment (high->high importance, low->low importance) and pulse frequency to convey *Time* until the appointment (2 PPS->30 min, 8 PPS->15 min and 16 PPS->5 min). This gave 12 stimuli from all three parameters. The dependent variables were the overall recognition rate of the combined cues (all three parts correct), and the recognition rates of the individual component parameters. Based on the results of the first two experiments, the following hypotheses were made for this experiment:

- ***Hypothesis 1:*** *Pulse frequency will have a higher recognition rate than amplitude and pulse width;*
- ***Hypothesis 2:*** *An increase in pulse frequency will cause an increase in recognition rate;*

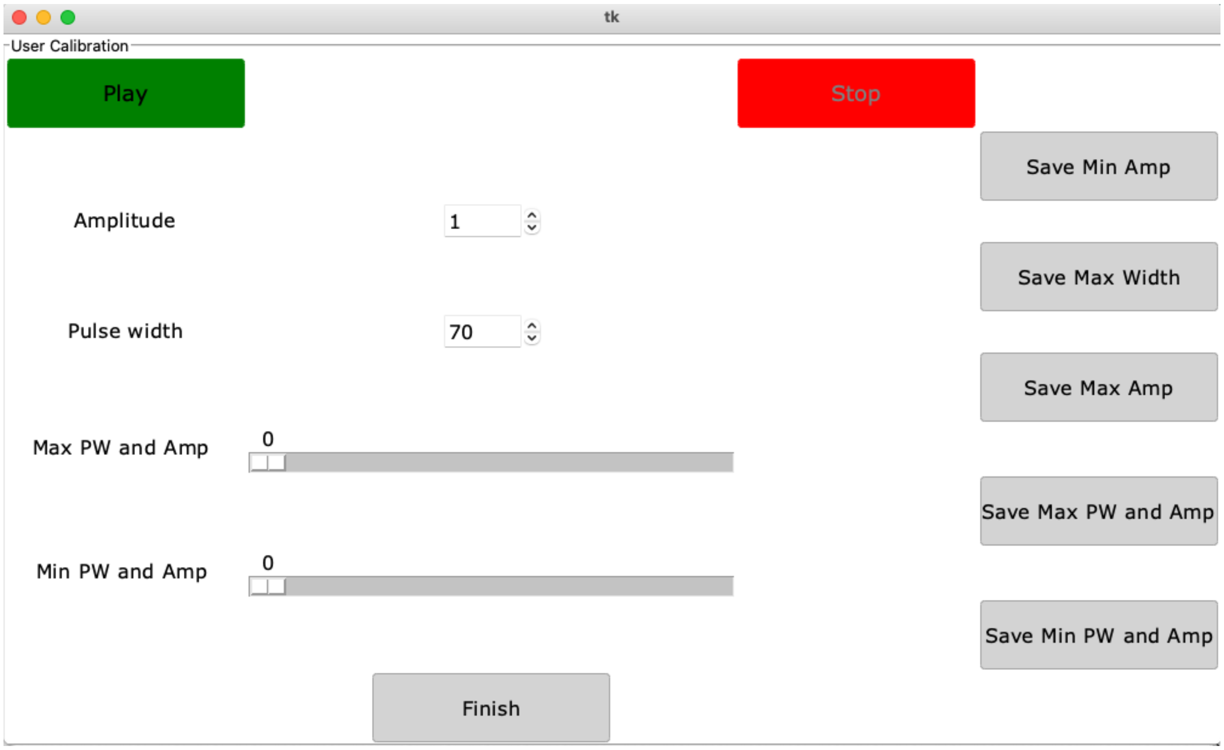

Figure 3.20: The calibration interface for Experiment 3. The last two steps show increasing pulse width and amplitude simultaneously to discomfort values, then to detection values.

- ***Hypothesis 3:*** *An increase in pulse width will cause an increase in recognition rate;*
- ***Hypothesis 4:*** *An increase in amplitude will cause an increase in recognition rate.*

3.6.2 Participants

Twenty people (12 female, 7 male and 1 non-binary) between the ages of 17 and 53 (Mean=29.2, SD=9.8, Median=27), one left-handed, most were students, took part in this experiment. None had dermatitis or other skin conditions, or cardiovascular issues. Each participant read an information sheet and signed a consent form before the start of the experiment and was compensated £10 Amazon voucher for participating.

3.6.3 Procedure

The calibration steps were the same as in Experiment 2. Additionally, pulse width and amplitude were both increased simultaneously from their middle values until the discomfort threshold to avoid their combination causing additional discomfort. Then, the same step was done again, but from their low values until detection threshold to ensure participants could detect the stimulus combination. Figure 3.20 shows the interface used for the calibration phase of this experiment.

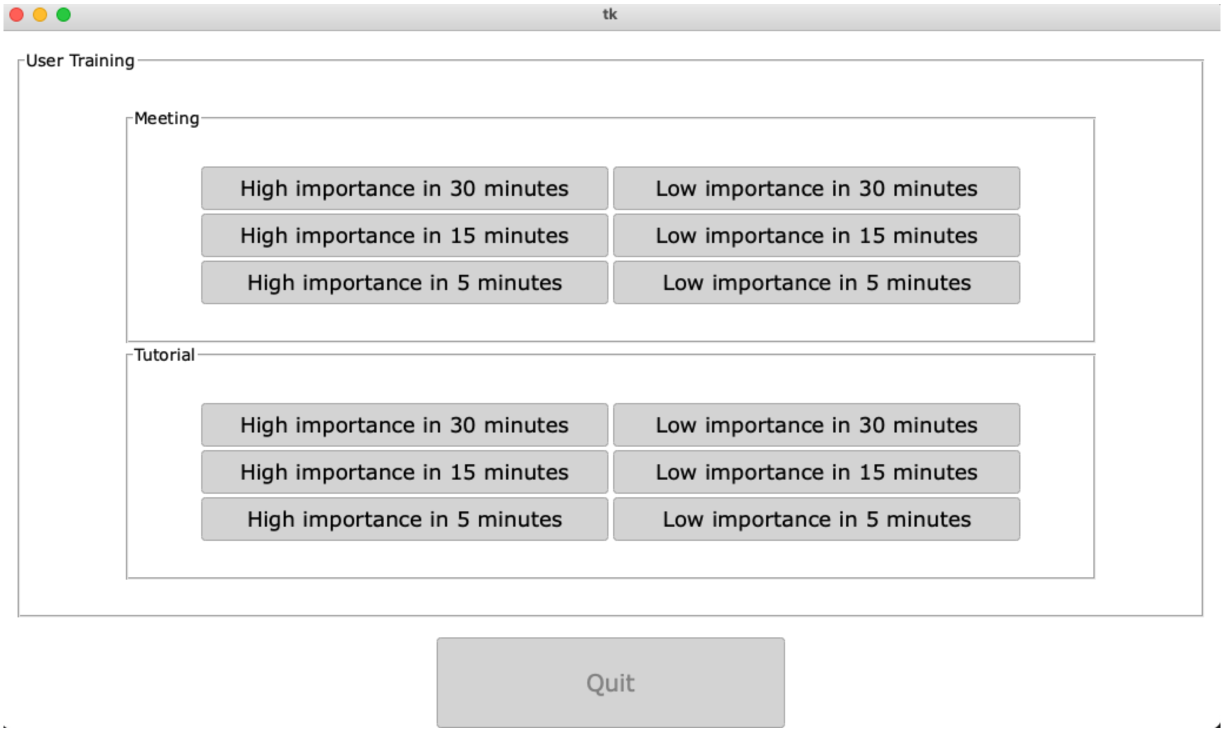

Figure 3.21: The training interface for Experiment 3.

In the training phase, a 6x2 grid of buttons representing all possible stimuli were presented to the participants (Figure 3.21). The duration of each stimulus was set to be 2 seconds. They were instructed to try each stimulus at least twice and to try to distinguish between them. When a button was clicked twice, the button's colour turned green. When all buttons were green, the quit button turned red, indicating that participants could quit the training phase if they wished to.

In the experiment phase, participants received the 12 stimuli in random order. After each stimulus, they had to identify the type, importance and time until meeting and register their answers using the interface seen in Figure 3.22. They did three blocks, giving 36 trials in total. To avoid fatigue, there was a 5 minute break between blocks. Then, for the qualitative data, they were asked the following questions and their answers were recorded:
1-How confident were you in distinguishing between different cues?
2-How would you compare the cues you just had with the ones you usually feel from your phone in terms of notifications?

3.6.4 Results

Recognition rates were calculated for complete stimuli and for each component parameter, and the change level of every parameter is not the same for the different rates. The mean overall recognition rate was 38.19%. Within this, recognition rates varied across the stimuli as seen in Figure 3.23. Figure 3.24 shows that (*Type*: meeting, *Importance*: high, *Time*:

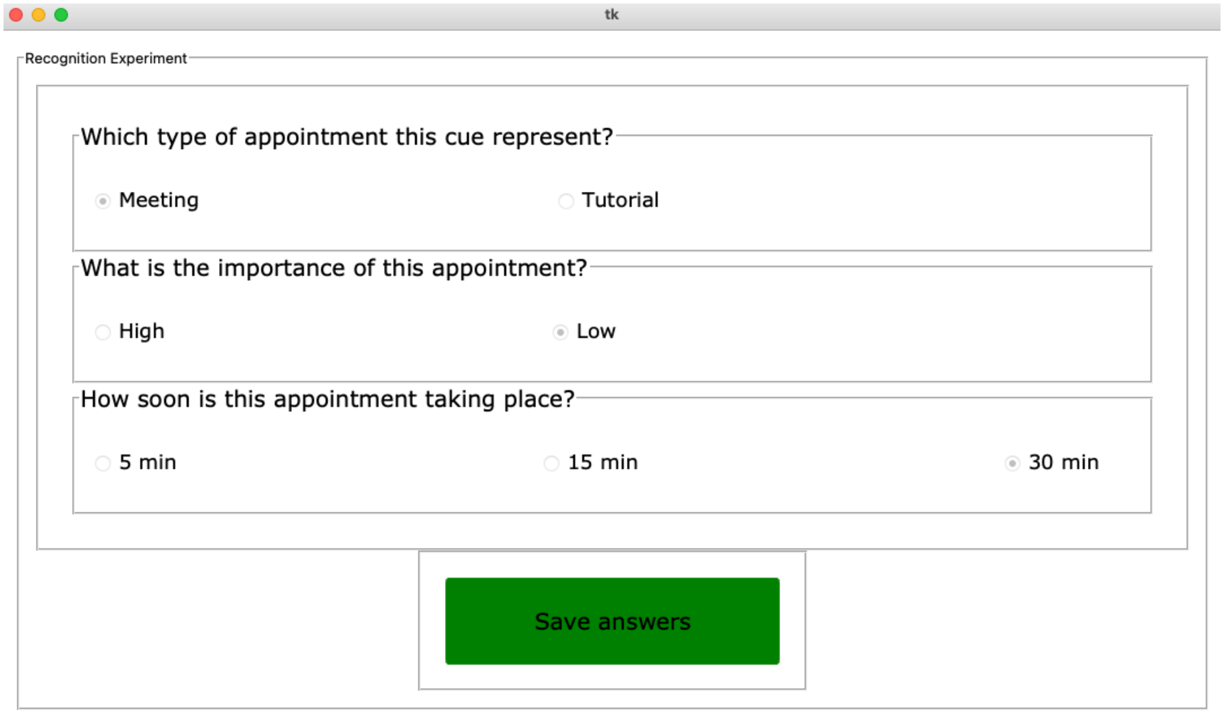

Figure 3.22: The experiment interface for Experiment 3.

5 mins) had the highest overall recognition rate (61.6%), while meeting and tutorial with low importance in 15 min both had the lowest (21.6%). For the individual component parameters, pulse width had a recognition rate of 71.67%, amplitude 70.27%, and pulse frequency 66.36%.

To see which parameter (pulse width, amplitude or pulse frequency) had the most significant effect on recognition rate, ART was used to transform the data into a parametric form. A one-factor repeated-measures ANOVA was then performed on the recognition rates of the three parameters. The results showed that parameter had no significant effect ($F(2,38)=0.245$, $p=0.783$), as can be seen in Figure 3.25. A one-factor ANOVA was performed on each component parameter individually to see if there was any difference in recognition rates between the levels within a parameter. For pulse width (*Type* of appointment) and amplitude (*Importance* of the appointment), there was no significant effect on recognition rate (Pulse width: ($F(1,38)=2.533$, $p=0.12$) as shown in Figure 3.26. For amplitude: ($F(1,38)=0.04$, $p=0.842$)), as shown in Figure 3.27.

For pulse frequency (*Time* until appointment), there was a significant effect on recognition rate ($F(2,38)=8.066$, $p<0.001$)). *Post hoc* Tukey tests showed significant differences for 8 PPS(15 min)-2 PPS(30 min) ($p=0.032$) and 8 PPS(15 min)-16 PPS(5 min) ($p=0.0009$), but not for 2 PPS(30 min)-16 PPS(5 min)($p=0.392$), as shown on the right in Figure 3.28.

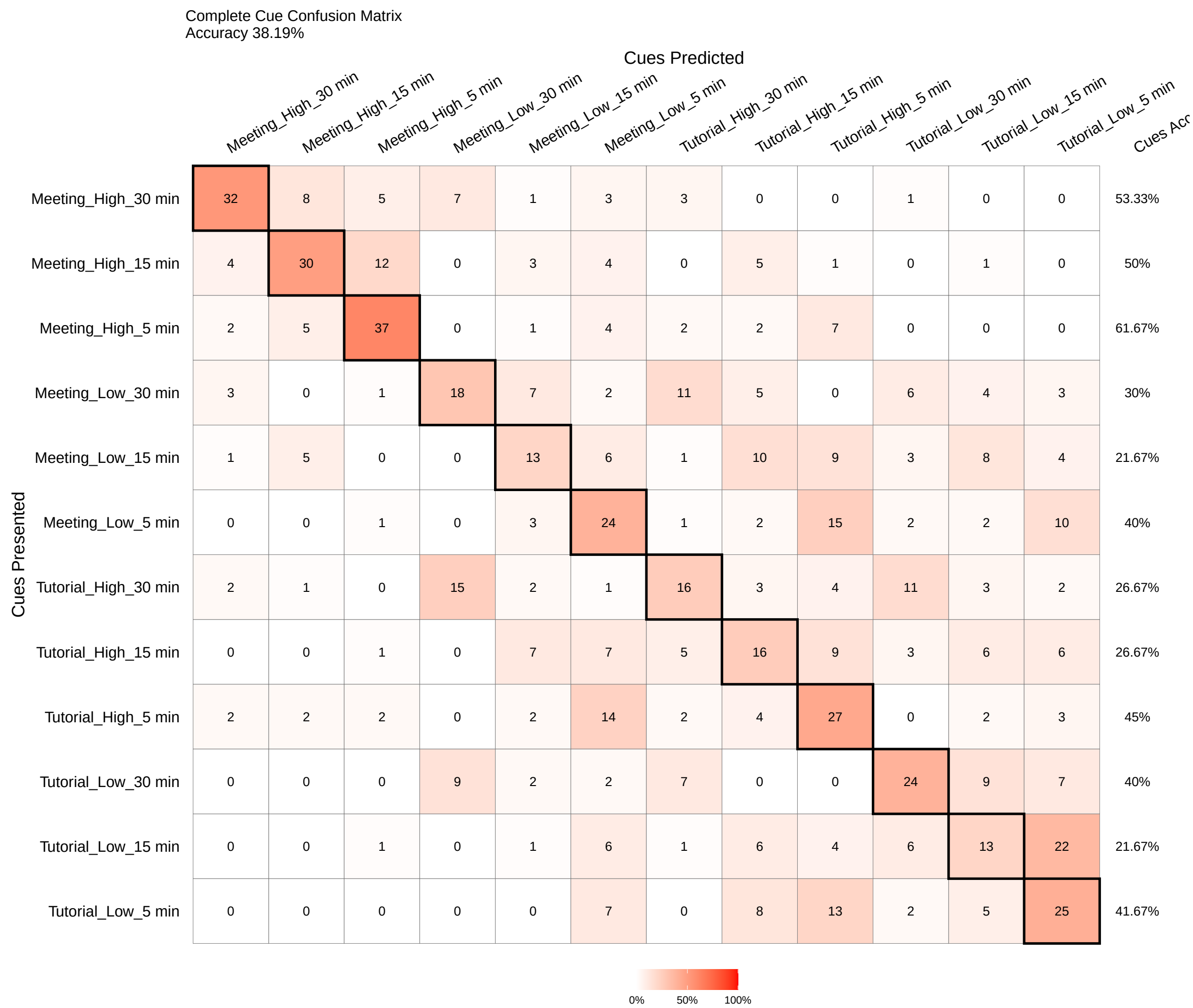

Figure 3.23: Heatmap for the recognition rate for all stimuli in Experiment 3.

3.6.5 Qualitative Results

From the recorded answers for Question 1: *How confident were you in distinguishing between different cues?*, P01 answered *"Some of the cues I was confident. The ones conveying time it was relatively straightforward, but the ones between tutorial and meeting were quite difficult. Between high and low importance is difficult, some were easier than others"*. P04 added *"Not that good. I think I got better with time, but in general, I found it difficult to distinguish between the low importance meeting and the high importance tutorial and the 5 min and the 15 min cues"*. P17 reported *"I was confident in low and high importance and time until the appointment, but not really with the type"*.

For Question 2: *How would you compare the cues you just had with the ones you usually feel from your phone in terms of notifications?*, P03 said *"The meeting low importance ones were similar to the ones from the phones. It can get more powerful than the phone with meeting high importance"*. P07 added *"These are more intrusive because I felt most*

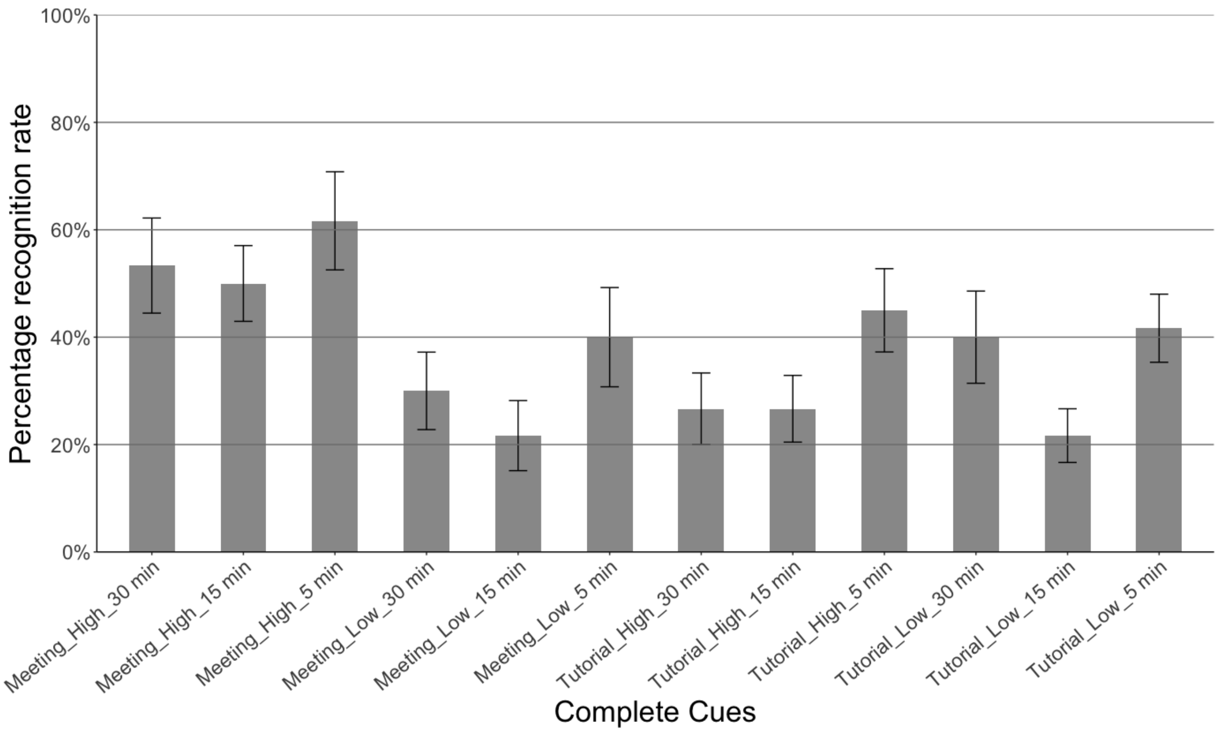

Figure 3.24: The recognition rate for all stimuli in Experiment 3.

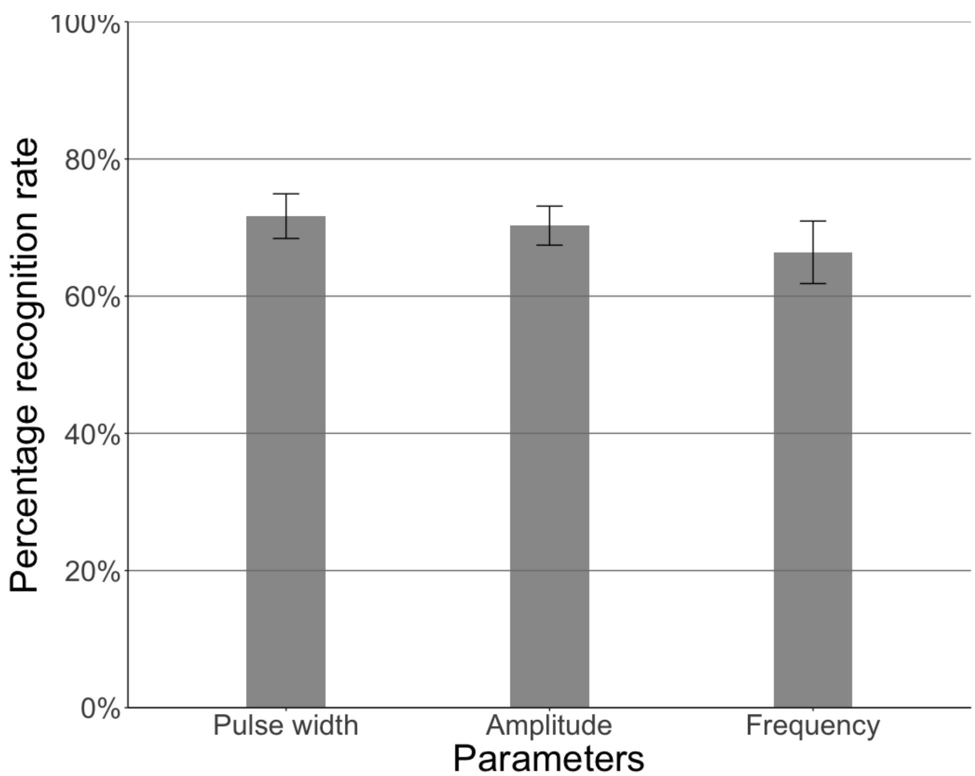

Figure 3.25: The overall recognition rate for each of the parameters in Experiment 3.

of the cues in my body. I will dread getting them, but the low importance tutorial was nice. Meeting high was dreadful". P11 reported *"It was quite different. The middle cues were like vibration, the high one is so intense."*

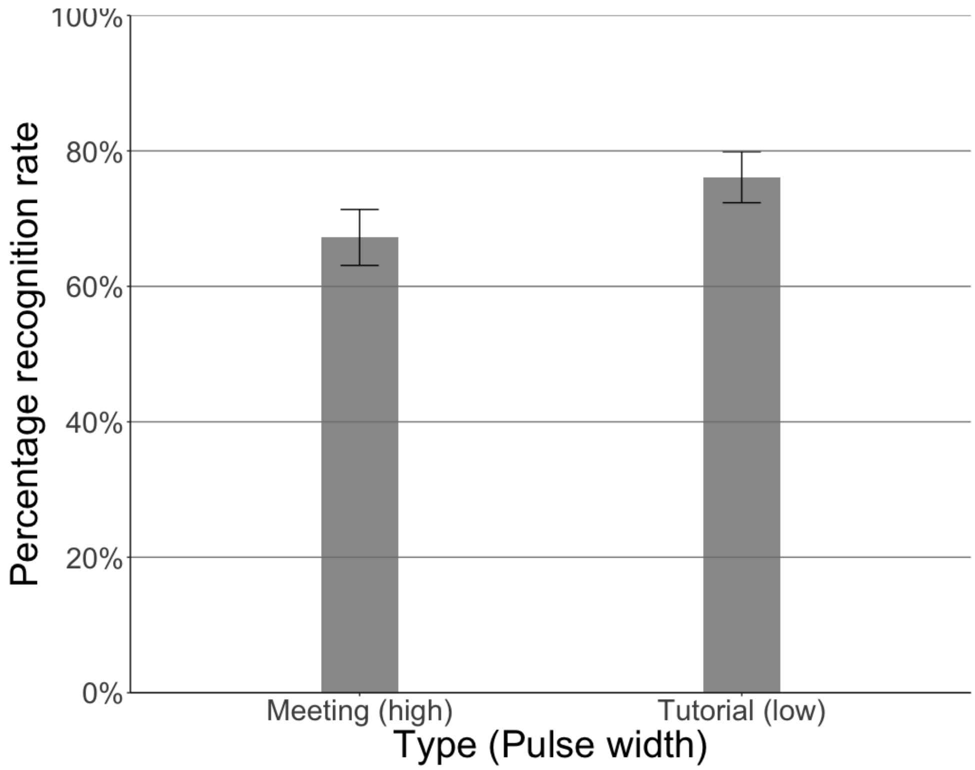

Figure 3.26: The recognition rate for type (pulse width) in Experiment 3.

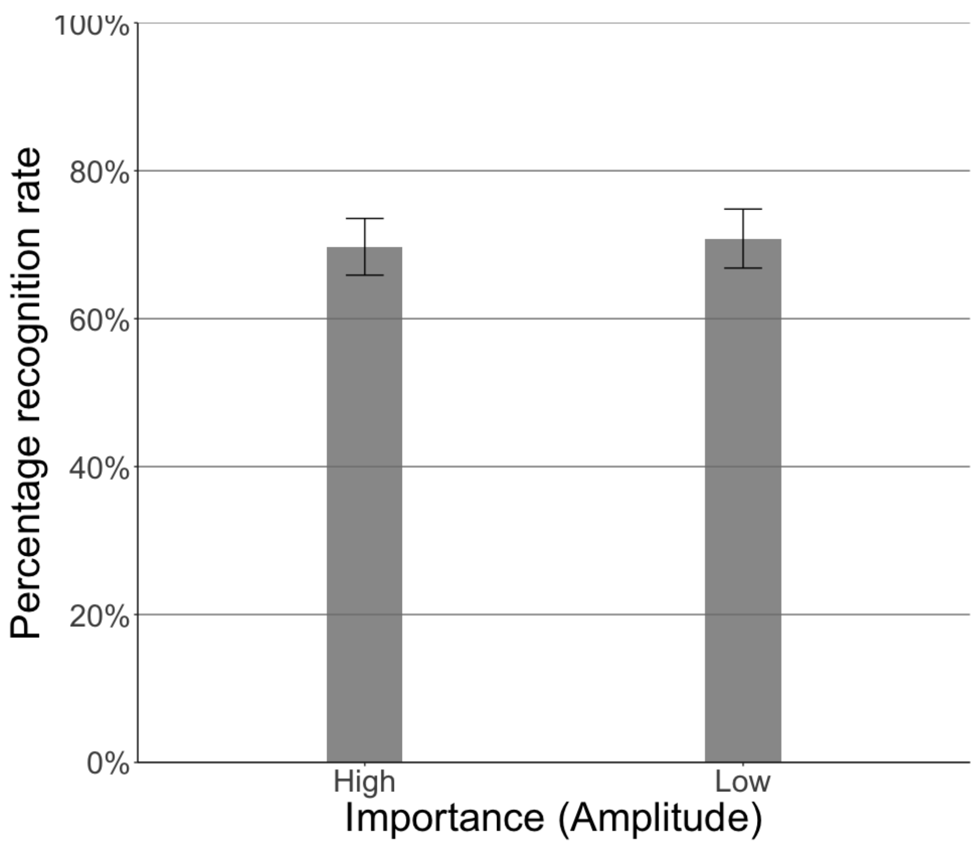

Figure 3.27: The recognition rate for importance (amplitude) in Experiment 3.

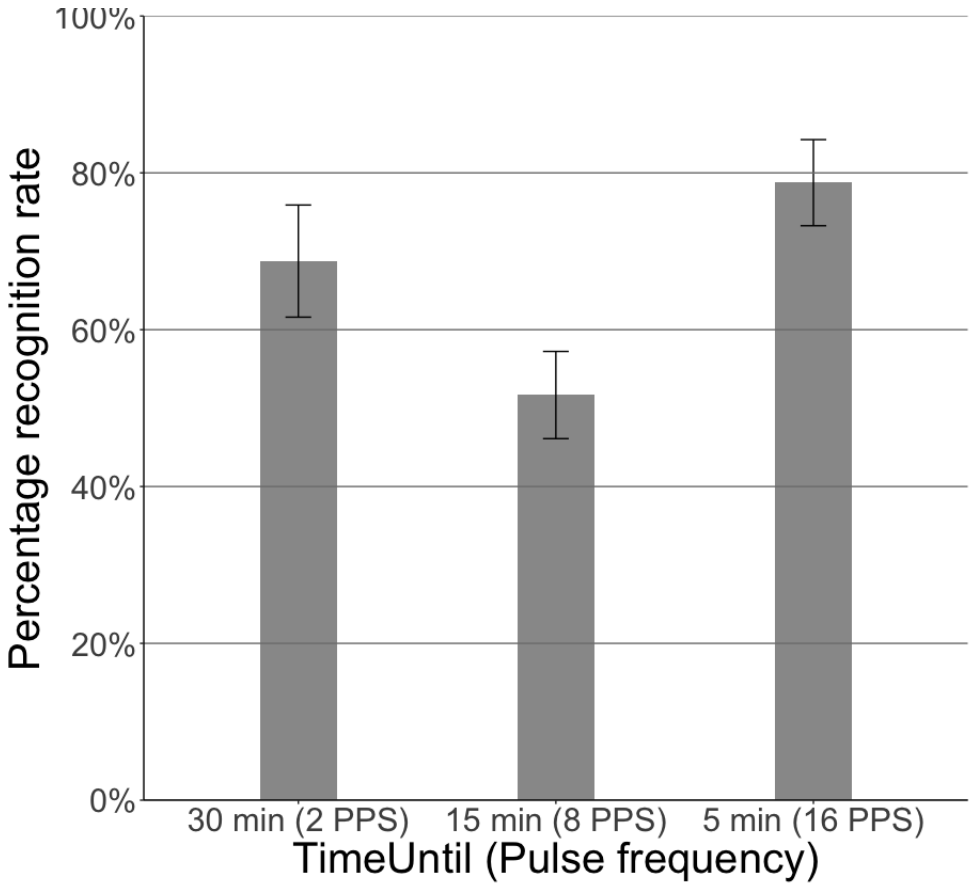

Figure 3.28: The recognition rate for time until (pulse frequency) in Experiment 3.

3.6.6 Calibration

The calibration phase for this experiment had two more steps compared to the previous experiments. In the pilot study, participants complained that the most intense stimuli were painful, so changes were made as mentioned in the procedure section. The method of calibrating the discomfort thresholds that were used in the first two experiments for pulse width and amplitude was adjusted to make sure that *Electrotactons* would not be painful by increasing pulse width and amplitude at the same time. For amplitude, the average minimum value was 11.9 mA, SD= 2.49 mA and median= 12.5 mA, 20.81% higher than Experiment 2. The average maximum value was 17.65 mA, SD= 3.71 mA and median= 18.5 mA, 27.9% higher than Experiment 2. Figure 3.29 shows the distribution of amplitude values across participants.

For pulse width, the average minimum value was 84.35 μs, SD= 8.93 μs and median= 84 μs. There was no average minimum value to compare to as this experiment was the first to increase the minimum value of pulse width from 70 μs. The average maximum value was 171.65 μs, SD= 28.31 μs and median= 175 μs, 10.74% higher than Experiment 2. Figure 3.29 shows the distribution of amplitude values across participants. The distribution of pulse width values across participants can be seen in Figure 3.30. The reason for the increase in values for both amplitude and pulse width was because of the additional two steps in the calibration phase. When reaching the last two additional steps as seen in Figure 3.20, participants were used to the electrotactile stimulation and where higher values of amplitude and pulse width were required to reach both detection and discomfort levels.

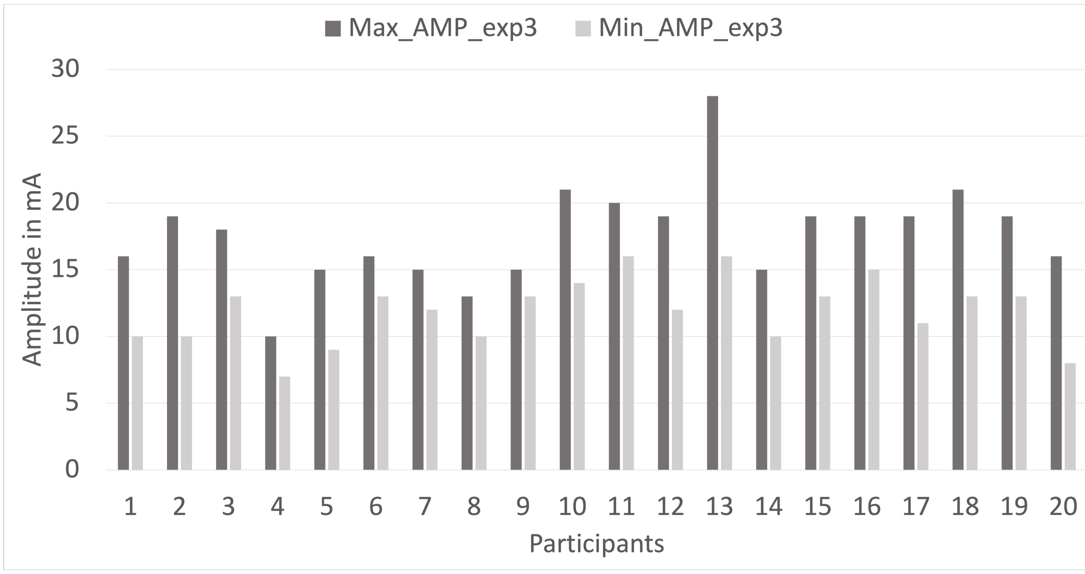

Figure 3.29: The distribution of maximum and minimum values for amplitude across participants for Experiment 3.

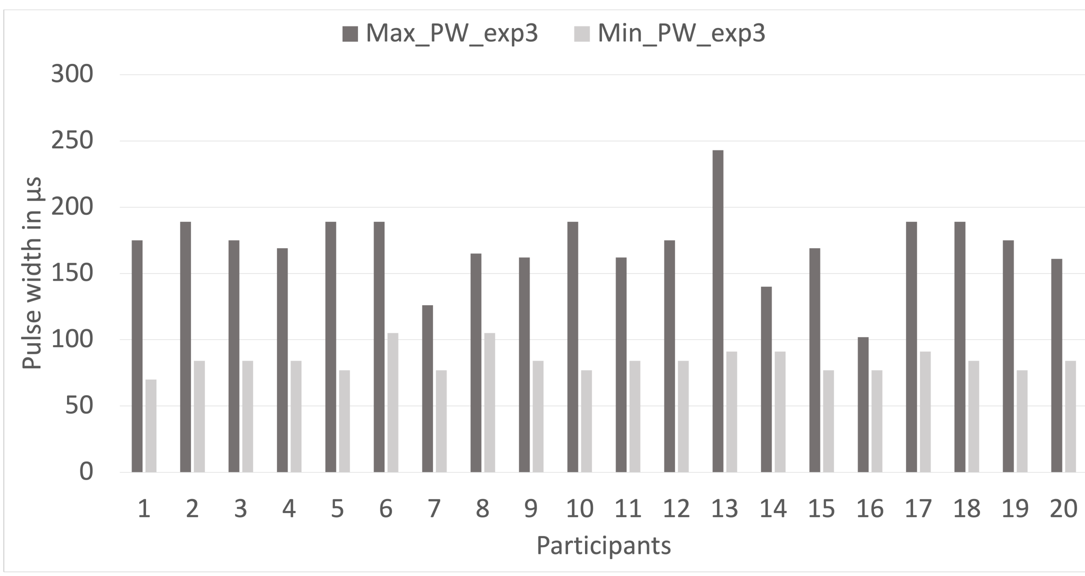

Figure 3.30: The distribution of maximum and minimum values for pulse width across participants for Experiment 3.

3.6.7 Experiment 3 Discussion

The overall recognition rate for the complete cues only reached a mean of 38.19%, suggesting that users struggled to identify the whole cues. However, some individual stimuli were better recognised with the (High Importance Meeting in 5 minutes) cue reaching 61.6%. For the individual component parameters, the change level of every parameter is not the same for the different rates and the results showed that there was no parameter had a significant effect more than another on recognition rate, and when looking at Figures (3.25, 3.26, 3.27, 3.28), it can be seen that there were no large differences in recognition rates between the parameters. Therefore, the results suggest that *Hypothesis 1* is not supported. From Figure 3.28, an observation can be made that pulse frequency 16 PPS had the highest recognition rate, followed by 2 PPS then 8 PPS. Participants recognised the two ends of pulse frequency range more accurately than the middle. Therefore, *Hypothesis 2* is not supported. For pulse width and amplitude in Figure (3.26, 3.27), there was no significant difference between their levels. Therefore, *Hypothesis 3* and *Hypothesis 4* are not supported.

The pulse frequency parameter had three levels of stimulation but had the lowest overall recognition rate. The highest and lowest levels of pulse frequency had rates of 78.75% and 68.75% with the middle at 51.66% (Figure 3.28). Reducing pulse frequency to two levels could substantially improve recognition performance. A simple averaging would suggest 73.75% could be achieved, which would improve the overall recognition rate for the combined cues. However, this is at the cost of reducing the size of the parameter space. This mirrors what Brown *et al.* [71] did for their vibrotactile cues, which had the same problem. Another suggestion would be to choose pulse frequency levels from a wider range, as it might feel different in an absolute identification scenario. A further study will be conducted to evaluate these in more detail. When looking at Figure 3.24, the three meeting high cues recognition rate was 50% and higher and the rest of the cues were lower than that. In addition, from the recorded answers of the participants, some of them reported that they could not easily distinguish meeting low (high pulse width, low amplitude) and tutorial high (low pulse width, high amplitude), and it can be seen in Figure 3.24 when crossing meeting low cues with tutorial high. This suggests that the use of pulse width and amplitude individually might not be an efficient way to encode information.

3.6.8 Summary

This experiment introduced the first *Electrotactons* design combining the three electrotactile parameters pulse width, amplitude and pulse frequency to encode multi-dimensional information. The aim was to map these three parameters with different information and measure how well this design of *Electrotactons* performs when presented in a notification application scenario. This aim contributed to answering Research Questions 2 & 3 of this thesis:

- *How can the parameters of electrotactile feedback be used to encode information in Electrotactons?*
- *What levels of performance can be achieved when these parameters are combined to create Electrotactons to present multi-dimensional information?*

The results of this experiment indicate that three-dimensional *Electrotactons* can be created by manipulating pulse width, amplitude and pulse frequency and that participants were able to learn these *Electrotactons* with less than ten minutes of training. The overall recognition rate was 38.19%, where pulse width had 71.67%, amplitude 70.27% and pulse frequency 66.36%. However, the recognition rate of *Electrotactons* was low and, therefore, methods in which performance can be improved must be regarded. Combining pulse width and amplitude into one parameter is one of these methods, but the cost would be reducing the number of parameters of *Electrotactons*. In addition, reducing the levels used of pulse frequency from three to two could help improve the recognition rate.

3.7 Experiment 4 (Pulse Width and Amplitude)

During the pilot of Experiment 3, it was noticed that some participants had difficulty distinguishing between pulse width and amplitude levels when encoding information. This led to the realization that utilizing both parameters independently may not be adequate. As a result, this experiment was conducted to explore the combination of pulse width and amplitude into a singular parameter, which was referred to as intensity. Section 2.3.2 described the use of intensity as a parameter for electrotactile feedback, as both pulse width and amplitude dictate the amount of electrical current that stimulates the skin, therefore controlling the intensity. The aim of this experiment was to investigate the perception of electrotactile intensity by manipulating pulse width and amplitude, in terms of subjective sensations of urgency, annoyance, valence and arousal. In addition, investigated which of these two parameters had more influence on the perception of these sensations. The results of this experiment will contribute to Research Questions 1 & 2.

3.7.1 Experimental Design

The experiment used a within-subjects repeated measures design, consisting of the same three phases as the previous experiments. In addition, this experiment combined three levels of pulse width and amplitude (High, Middle and Low) into one parameter called intensity with 9 levels (3 levels of pulse width x 3 levels of amplitude = 9 levels of intensity). It investigated them to create electrotactile cues and see how many distinguishable levels of different perceived sensations they can produce. The independent variable was the *intensity of the stimulus* (L-L, L-M, L-H, M-L, M-M, M-H, H-L, H-M, H-H) where the first letter indicates one of three levels of pulse width and the second one of three levels of amplitude. The Low level for pulse width used a baseline value of 70 μs the same as the first two experiments, and for amplitude was the detection threshold. The High level for both was the discomfort threshold, and the Middle for both was the mean value between High and Low. In this experiment, pulse frequency was kept constant at 20 PPS to ensure participants could detect the stimulus as the results from Experiment 2 showed. The dependent variables were: perceived urgency, annoyance, valence and arousal, the same as in the first two experiments.

From Kaczmarek *et al.* [57], it was expected that the perception of intensity would be influenced by the magnitude of the stimulus. The previous two experiments had not compared amplitude and pulse width directly to assess their relative effects on perceived sensation. Pohl *et al.* [6] has stated that amplitude produced a stronger sensation, so both were compared in the same experiment to investigate this further. The hypotheses for this experiment were:

- ***Hypothesis 1:*** *Intensity will have an effect on perceived urgency, annoyance valence and arousal;*
- ***Hypothesis 2:*** *Amplitude will have higher ratings of perceived urgency, annoyance, valence and arousal than pulse width.*

3.7.2 Participants

This experiment was conducted right after the COVID-19 lockdown was lifted. For this reason, it was conducted back to back with Experiment 3. Participants were given a 5-minutes rest between the experiments.

3.7.3 Procedure

The procedure was the same as Experiment 2, including the calibration phase. In the training phase, participants were presented with 9 randomly ordered stimuli, the total number of intensity levels. In the experiment phase, participants did four blocks, and each block contained 9 trials. In each trial, one physical level of intensity was presented. The total number of trials was 36 across the four blocks. Then, for the qualitative data, they were asked the following questions and their answers were recorded and transcribed:
1-Did your sensitivity change with time?
2-How would you describe how you felt about the electrotactile cues?

3.7.4 Results

The Aligned Rank Transform (ART) [105] was used to transform the data to a parametric form for statistical testing. A one-factor (intensity of the stimulus) repeated-measures ANOVA was then performed for each dependent variable (urgency, annoyance, valence and arousal). The intensity of the stimulus had a significant effect on perceived urgency ($F(8,152)=98.08$, $p < 0.001$), with increasing values causing a greater sense of urgency. The intensity of the stimulus had a significant effect on annoyance ($F(8,152)=35.21$, $p < 0.001$), with increasing values causing a greater sensation of annoyance. It also had a significant effect on valence ($F(8,152)=20.74$, $p<0.001$), with increasing values causing a lower sensation of valence, and arousal ($F(8,152)=51.10$, $p<0.001$), with increasing values causing a greater sensation of arousal (Figure 3.31 shows the results in detail). The results of *Post hoc* Tukey tests can be seen in Table 3.5. From the table, for urgency, it had the following five uniquely distinguishable levels: (H-H), (H-M, M-H), (H-L, L-H, M-M), (M-L, L-M), (L-L). For annoyance, it had three unique levels: (H-H, H-M, M-H), (H-L, L-H, M-M), (L-L, L-M, M-L). For valence, it had two unique levels: (H-H, H-M, M-H), (H-L, L-H, L-M, M-M, M-L, L-L). For arousal, it had three unique levels: (H-H, H-M, M-H), (H-L, L-H, M-M), (L-L, L-M, M-L).

To see if either parameter of intensity (pulse width or amplitude) and its level (High, Middle and Low) had more influence on Intensity than the other, a two-factor (parameter and level) repeated-measures ANOVA was performed for each dependent variable (urgency, annoyance, valence and arousal). As expected, level had a significant effect on perceived urgency ($F(2,95)=280.28$, $p < 0.001$), annoyance ($F(2,95)=112.68$, $p < 0.001$) and arousal ($F(2,95)=148.16$, $p<0.001$), with increasing values causing a greater sensation. Level had a significant effect on valence ($F(2,95)=68.61$, $p<0.001$), with increasing values causing a lower sensation of valence. *Post hoc* Tukey tests showed that all levels had significant effects on all perceived sensations, all $p<0.001$). Parameter had no significant effect on any of the perceived urgency ($F(1,95)=0.011$, $p=0.91$), annoyance ($F(1,95)=0.061$, $p=0.80$), valence ($F(1,95)=0.0008$, $p=0.97$) or arousal ($F(1,95)=0.002$, $p=0.96$). There were no interactions between parameter and level.

The same method was used to test the effect of both pulse width and amplitude as their combination creates the parameter intensity on all perceived sensations. A two-factor (pulse width and amplitude) repeated-measures ANOVA was performed. For urgency, both pulse width ($F(2,152) = 173.73$, $p < 0.001$) and amplitude ($F(2,152) = 193.03$, $p < 0.001$) had a significant effect, with no interaction. For annoyance, both pulse width ($F(2,152) = 68.72$, $p < 0.001$) and amplitude ($F(2,152) = 73.25$, $p < 0.001$) had a significant effect, with no interaction. For valence, both pulse width ($F(2,152) = 43.30$, $p < 0.001$) and amplitude ($F(2,152) = 45.94$, $p < 0.001$) had a significant effect, with no

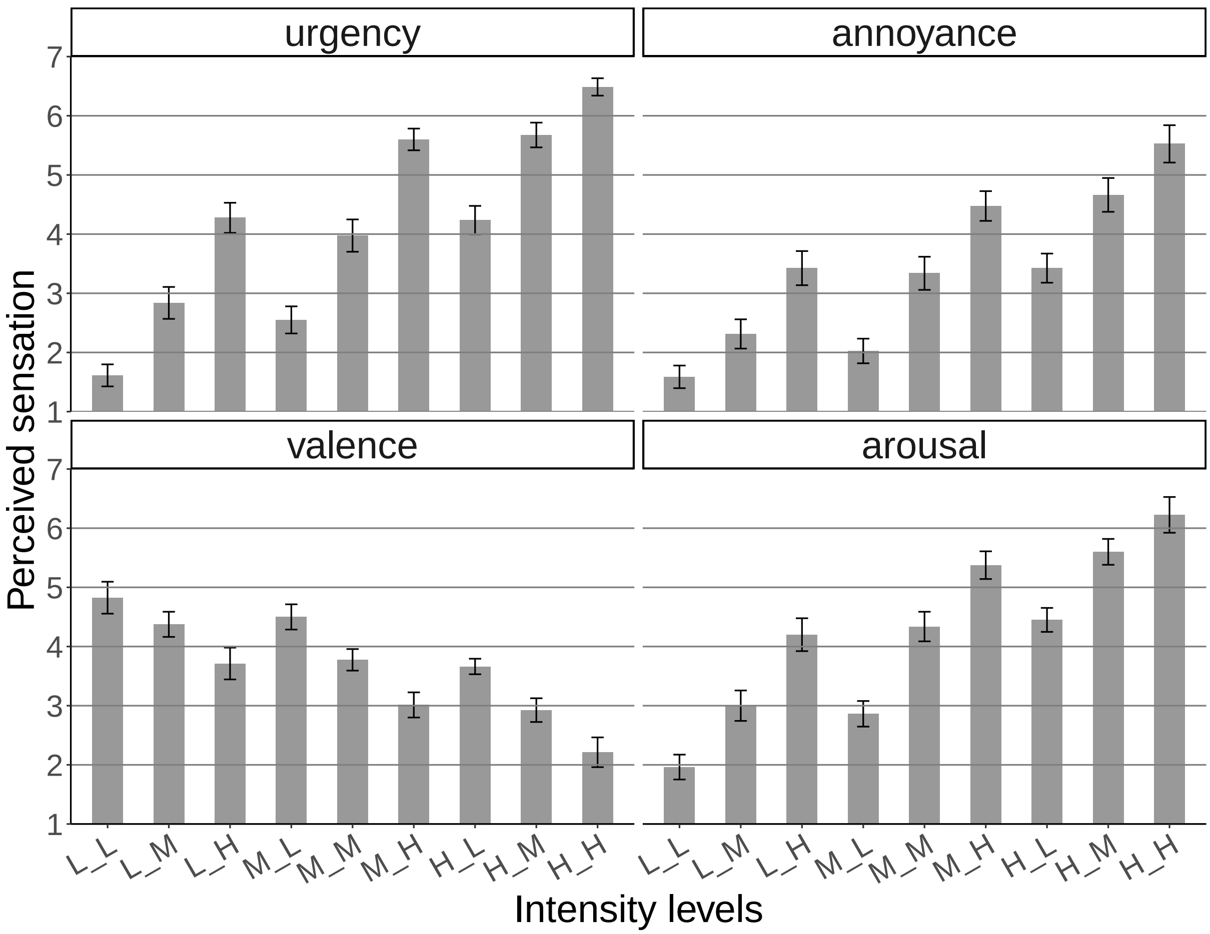

Figure 3.31: Effect of intensity on all dependent variables in Experiment 4. The levels of intensity were ordered from the weakest (far left) to the strongest (far right). The letters on the x-axis mean the following: L L -> Low pulse width & Low amplitude, L M -> Low pulse width & Middle amplitude , L H -> Low pulse width & High amplitude, M L -> Middle pulse width & Low amplitude, M M -> Middle pulse width & Middle amplitude, M H -> Middle pulse width & High amplitude, H L -> High pulse width & Low amplitude, H M -> High pulse width & Middle amplitude, H H -> High pulse width & High amplitude.

interaction. For arousal, both pulse width ($F(2,152) = 124.83$, $p < 0.001$) and amplitude ($F(2,152) = 102.23$, $p < 0.001$) have a significant effect, with no interaction. Pairwise *post hoc* Tukey tests were performed on all significant effects of pulse width and amplitude, and all levels of both had a significant effect across all dependent variables.

3.7.5 Calibration

As this experiment measured subjective perception for different sensations, it used the same calibration phase as Experiment 2. Figure 3.32 shows the distribution of amplitude values across participants. For amplitude, the average minimum value was 10 mA, SD= 2.07 mA and median= 9.5 mA which was almost the same as Experiment 2. The average maximum value for amplitude was 13.8 mA, SD= 2.89 mA and median= 15 mA which

Table 3.5: *Post hoc* pairwise Tukey tests comparing stimulus levels for Experiment 4. As mentioned in the experiment design, the first letter (L,M,H) is the level of pulse width, and the second letter (L,M,H) is the level of amplitude of the stimulus.

Stimulus pairs	Urgency	Annoyance	Valence	Arousal
H H - H L	p<.0001*	p<.0001*	p<.0001*	p<.0001*
H H - H M	p=0.0181*	p=1.0000	p=0.8154	p=0.8903
H H - L H	p<.0001*	p<.0001*	p<.0001*	p<.0001*
H H - L L	p<.0001*	p<.0001*	p<.0001*	p<.0001*
H H - L M	p<.0001*	p<.0001*	p<.0001*	p<.0001*
H H - M H	p=0.0057*	p=0.5898	p=0.6152	p=0.0553
H H - M L	p<.0001*	p<.0001*	p<.0001 *	p<.0001*
H H - M M	p<.0001*	p<.0001*	p<.0001*	p<.0001*
H L - H M	p<.0001*	p=0.0087*	p=0.0844	p=0.0002*
H L - L H	p=1.0000	p=1.0000	p=1.0000	p=1.0000
H L - L L	p<.0001*	p<.0001*	p=0.0039*	p<.0001*
H L - L M	p<.0001*	p=0.0044*	p=0.1959	p=0.0001*
H L - M H	p<.0001*	p=0.0328*	p=0.1185	p=0.0078*
H L - M L	p<.0001*	p=0.0001*	p=0.0320*	p<.0001*
H L - M M	p=1.0000	p=1.0000	p=1.0000	p=1.0000
H M - L H	p<.0001*	p=0.0036*	p=0.1193	p<.0001*
H M - L L	p<.0001*	p<.0001*	p<.0001*	p<.0001*
H M - L M	p<.0001*	p<.0001*	p<.0001*	p<.0001 *
H M - M H	p=1.0000	p=1.0000	p=1.0000	p=1.0000
H M - M L	p<.0001*	p<.0001*	p<.0001*	p<.0001*
H M - M M	p<.0001 *	p=0.0020*	p=0.0204*	p=0.0001*
L H - L L	p<.0001*	p<.0001 *	p=0.0026*	p<.0001*
L H - L M	p<.0001*	p=0.0105 *	p=0.1404	p=0.0026*
L H - M H	p<.0001*	p=0.0144 *	p=0.1661	p=0.0003*
L H - M L	p<.0001*	p=0.0003 *	p=0.0219*	p=0.0002*
L H - M M	p=1.0000	p=1.0000	p=1.0000	p=1.0000
L L - L M	p=0.0004*	p=0.3538	p=1.0000	p=0.0591
L L - M H	p<.0001*	p<.0001 *	p<.0001*	p<.0001*
L L - M L	p=0.0293*	p=1.0000	p=1.0000	p=0.4127
L L - M M	p<.0001*	p<.0001 *	p=0.0186*	p<.0001*
L M - M H	p<.0001*	p<.0001 *	p<.0001*	p<.0001*
L M - M L	p=1.0000	p=1.0000	p=1.0000	p=1.0000
L M - M M	p=0.0003*	p=0.0180 *	p=0.6459	p=0.0003*
M H - M L	p<.0001*	p<.0001 *	p<.0001*	p<.0001*
M H - M M	p<.0001*	p=0.0084 *	p=0.0296*	p=0.0032*
M L - M M	p<.0001*	p=0.0005 *	p=0.1272	p<.0001*

* marks a significant difference (P<0.05).

was 10% higher than Experiment 2. The average maximum value for pulse width was 171 μs, SD= 33.22 μs and median= 185 μs which was 8.19% higher than Experiment 2. Eight out of 20 participants reached 200 μs which was the same as Experiment 2 (Figure 3.33).

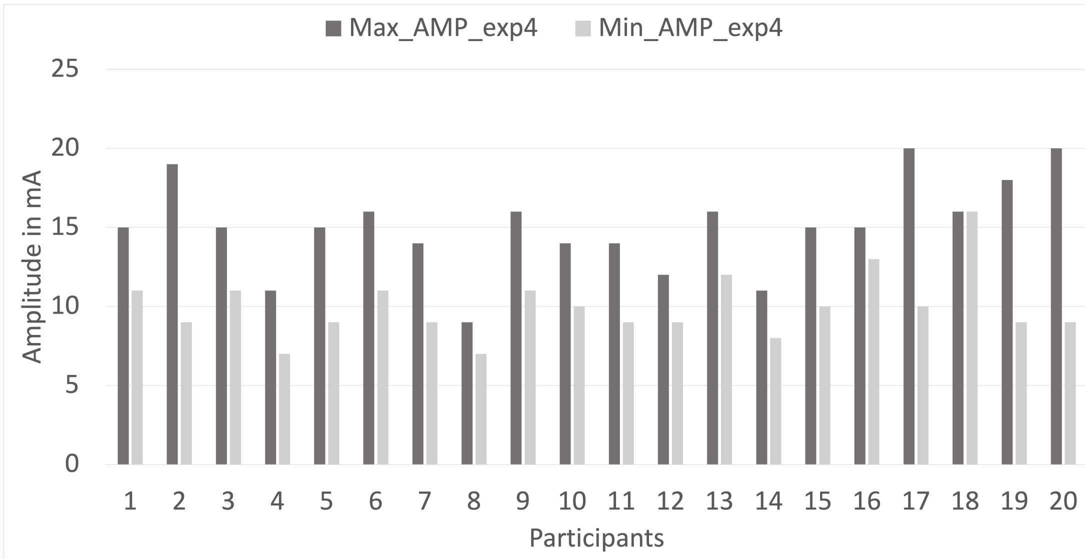

Figure 3.32: The distribution of maximum and minimum values for amplitude across participants for Experiment 4.

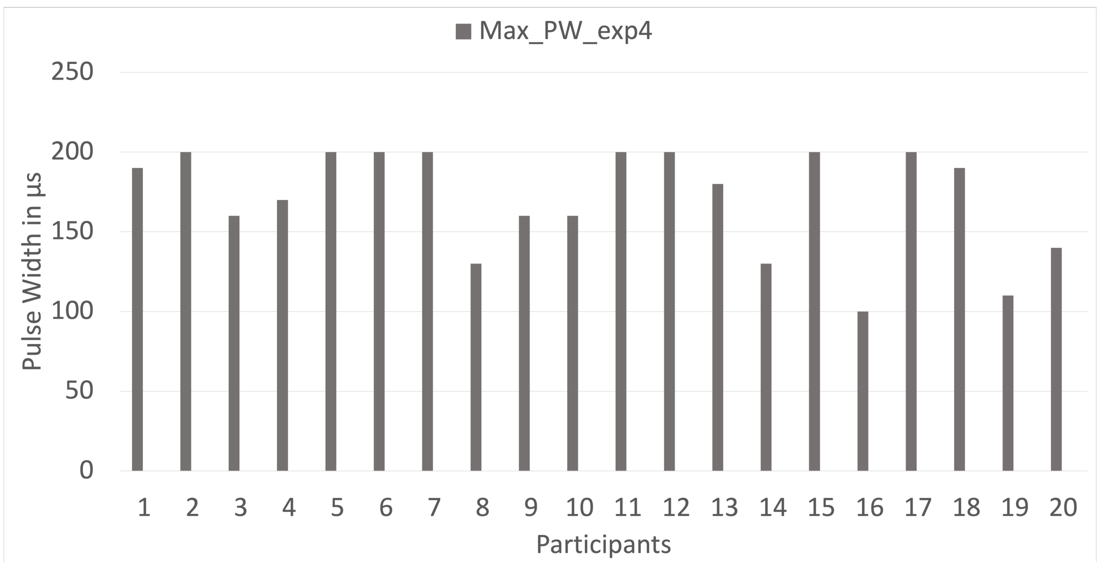

Figure 3.33: The distribution of maximum values for pulse width across participants for Experiment 4.

3.7.6 Qualitative Results

Figure 3.34 shows that the most common sensations were strong for high intensity and gentle for low intensity, both were selected 18 times. Participants circled a total of 264 terms. Only 5 more terms compared with the number of selected terms of Experiment 2. The total number of counts for high intensity was 122, middle intensity 76 and low intensity 66. This goes with the general trend found in Experiments 1 and 2 that the more sensations were selected the higher the intensity.

From the recorded answers for Question 1: *Did your sensitivity change with time?*, P04

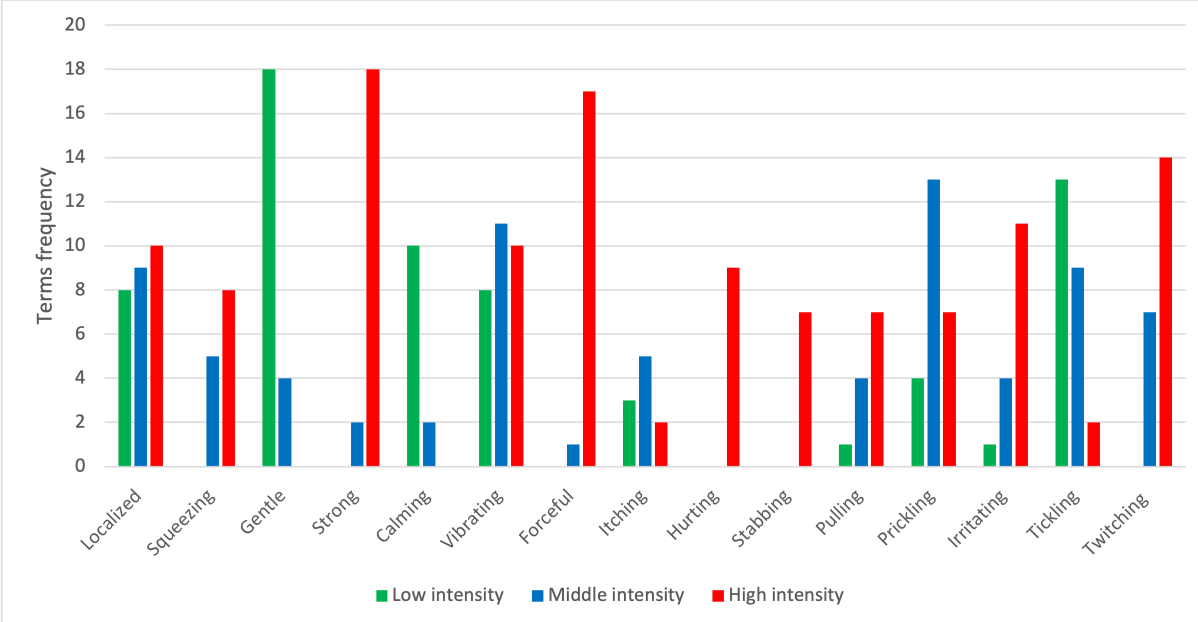

Figure 3.34: The 15 terms that participants can select from based on their intensity level perception for Experiment 4.

said *Yes, I got used to it and it became less irritating"*. P06 reported *Yes. With time I became more aware of it and used to it"*. P07 added *"I think so, with time the stimuli become less annoying and sometimes pleasant"*. For Question 2: *How would you describe how you felt about the electrotactile cues?*, P02 answered *"It was cooler than what I thought. I have never experienced anything like this"*. P03 added *"It was fine. They were not that irritating because they were on for a very short time, but if they were to be longer, they might be. Some of the urgent ones can be grabby"*. P08 said *"They induce different levels of alertness"*. P12 reported *I felt them in two different parts of my hand, and they felt so tingly"*. P16 added *"It didn't feel good at all. I felt with the strongest one needles at the tip of my figures"*.

3.7.7 Experiment 4 Discussion

Results showed that intensity had a significant effect on all perceived sensations. In Figure 3.31, when the intensity of the stimulus increased, the ratings of urgency, annoyance and arousal also increased, with valence decreasing (the stronger sensation causing a less pleasant, more negative feeling). This indicates the ability to control the level of the perceived sensations by manipulating the intensity of the stimulus. This is important for designing interfaces using electrotactile cues that need to elicit particular responses from users through the manipulation of 9 physical levels of intensity. The results also confirm Djozic *et al.*'s [79] findings where valence was rated higher when intensity was low, and, additionally, the results showed the two unique levels of it. Therefore, *Hypothesis 1* is supported.

Looking at Figure 3.31, it can be seen that urgency spanned the range of ratings from low to high. This means the ability to create cues with a wide range of different urgencies, as required for designing messages. Annoyance also had a wide range. This indicates the possibility of designing electrotactile cues which do not annoy the receiver, which is important in interface design. But as Politis *et al.* [14] found for his multimodal cues, urgency and annoyance are closely related, with the most urgent cues being the most annoying. If the cue has a higher rating of annoyance than urgency, the effectiveness of the cue will be affected. This suggests that the most urgent messages should be used with care so as not to annoy users.

The detailed results showed how many unique levels of sensation could be identified for each dependent variable. For urgency, it has five levels, annoyance three, valence two, and arousal three levels. This then gives a range of different cues to communicate different meanings, with multiple similar cue choices at some of the levels. For example, designing the most urgent cue possible for a vitally important message, (H-H, high pulse width, high amplitude) would be a good choice as it is the most urgent feeling with the highest arousal. However, this will cause the highest annoyance and feel the most negative to the recipient which could make the cue less acceptable. When designing a cue to indicate a low-priority event, the choices would be (L-L, low pulse width and low amplitude). This cue was rated lowest for urgency, low for annoyance, a more positive valence and low arousal. Changing the cue to (M-L) would increase its urgency to the next level, leaving the other aspects the same. The knowledge gained from the experiment gives novel useful guidance when designing with electrotactile cues.

Neither amplitude nor pulse width appeared to have a more significant impact on perceived sensation than the other. Therefore, *Hypothesis 2* is not supported. Furthermore, each one of them had a significant perceived sensation. Therefore, combining them into a single intensity parameter is the most effective way to use them. When looking at some of the intensity levels, such as (L-M) and (M-L), it can be seen that their subjective perception was not significantly different from each other. This does not mean that both intensity levels have the same electrical output value, and the same goes for (M-H)(H-M) and (M-L)(L-M). The effect on perception resulted from the combination of pulse width and amplitude. Overall, these results give a more detailed understanding of how to manipulate perceived urgency, annoyance, valence and arousal by changing the intensity level of electrotactile stimulation.

3.8 Summary

The aim of this experiment was to investigate the effect of manipulating 9 levels of intensity on the ratings of perceived urgency, annoyance, valence and arousal and measure how many distinguishable levels there are that will contribute to answering Research Questions 1 & 2 of this thesis:

- *What parameters of electrotactile stimulation can be used to influence subjective perception?*
- *How can the parameters of electrotactile feedback be used to encode information in Electrotactons?*

The results of this experiment showed that the intensity of the electrotactile stimulation had a significant effect on all subjective perceptions. The higher the intensity the higher the rating of urgency, annoyance and arousal, but the lower the valence. Individually, both pulse width and amplitude had the same impact on perception. Intensity can evoke these sensations with clear distinguishable levels making it a good candidate to improve the design of *Electrotactons*. It had five levels of urgency, three of annoyance and arousal and two for valence.

3.9 Chapter 4 Discussion

The experiments in this chapter investigated the effects of basic electrotactile feedback parameters on urgency, annoyance, valence and arousal through the manipulation of pulse width, amplitude and pulse frequency. The aim was to explore the design space of electrotactile feedback to design effective *Electrotactons* cues and understand the relative importance of the different parameters. All of the parameters had a significant effect on subjective perception. Results from the first two experiments showed the perception of pulse frequency peaked at 25-30 PPS; above that, increases were not recognised. Pulse frequency generally had little effect on valence but did affect the other sensations. However, there are only a few usable levels of the parameter.

In the first experiment, increasing pulse width increased all of the perceived sensations, and gave three clear levels of the parameter. In the second experiment, increasing amplitude increased the ratings of urgency, annoyance and arousal, but decreased the ratings for valence, again giving three clear levels of the parameter to use. The third experiment investigated the creation of *Electrotactons*, which are more complex electrotactile cues that would be useful for richer messages or notifications. Cues encoded three pieces of information by manipulating the parameters pulse frequency, pulse width and amplitude, in parallel. Overall identification of the combined cues was low at 38.19%. However, within this pulse width and amplitude (each with two levels) had recognition rates of 71.67% and 70.27%, and pulse frequency (with three levels) 66.36%. Reducing pulse frequency to two levels could improve recognition performance, as found by Brown *et al.* [71] for vibrotactile cues. In the fourth experiment, pulse width and amplitude were combined into one parameter named intensity. An increase in intensity increased perceived urgency, annoyance and arousal, but caused a decrease in perceived valence. There was no difference between amplitude and pulse width in this experiment, with results suggesting that both had similar effects.

For user interface design, this means the possibility of generating cues with clearly different levels of perceived sensation by using manipulating electrotactile parameters with a greater number of discriminable levels that would evoke a wide range of sensations from calm, non-urgent and not annoying, to highly urgent, alarming and annoying. This gives it great potential for making meaningful messages/emojis with an emotional dimension, especially for handheld devices that touch the palm. Moreover, these clear levels also can be used in the creation of *Electrotactons* to convey information in applications where other modalities can not be used.

These findings present insights into the parameter space and how it influences subjective perception to design electrotactile cues to elicit desired sensations and convey information. Messages can be designed with clearly different levels of arousal and urgency, and the effect on annoyance; however, valence appears harder to manipulate using electrotactile cues. In addition, multi-dimensional information can be delivered using *Electrotactons*; yet its design needs to be improved to archive higher levels of performance.

3.10 Conclusions and Research Questions

This chapter reported four experiments that aimed to answer the Research Questions of this thesis:

- *What parameters of electrotactile stimulation can be used to influence subjective perception?*

The finding in this chapter suggested that it is possible to manipulate electrotactile parameters, such as pulse width, amplitude and pulse frequency to influence subjective perception with clear distinguishable levels, providing an understanding of the design space for using such feedback in user interfaces. Messages with desired sensations can be designed with different levels of arousal and urgency, and can see the effects on annoyance; however, valence appears harder to manipulate using electrotactile cues.

- *How can the parameters of electrotactile feedback be used to encode information in*

Electrotactons?

The distinguishable levels have been used to encode complex multi-dimensional information for the creation of *Electrotactons*. Abstract mapping between these levels and its meaning was implemented as it is the feature of *Electrotactons*. Participants learned the mapping between these levels and their meaning, indicating that it can be applied to different applications, such as wearable devices where visual interaction is limited.

- *What levels of performance can be achieved when these parameters are combined to create Electrotactons to present multi-dimensional information?*

Three-dimensional *Electrotactons* were presented to participants through the manipulation of pulse width, amplitude and pulse frequency and the results showed that they achieved an overall recognition rate of 38.19%. In addition, there was confusion between some levels of pulse width and amplitude making use of these two parameters individually to present information not efficient, and that it might be better to combine them into one parameter named intensity. Pulse frequency had three levels and had the lowest recognition rate among all the parameters, so reducing its levels to two could substantially improve performance. These findings will be implemented in the next chapter to improve the design of *Electrotactons*, thus improving its performance.

Chapter 4

Investigating Complex Electrotactile Parameters

4.1 Introduction

The previous chapter investigated the effect of basic parameters of electrotactile feedback on subjective perception which provided insight into the emotional experience that comes with the feedback. Pulse width, amplitude and pulse frequency were found to have a significant effect on perception with clear different levels of different sensations, making it suitable for designing user interfaces. It showed the possibility of using these parameters for the creation of *Electrotactons*, but the design needed improvements to achieve a higher recognition rate. The results suggested the following improvements: combining pulse width and amplitude into one parameter forming a complex parameter called intensity and reducing the levels of pulse frequency from three levels to two.

Before implementing these improvements, this chapter will investigate intensity and pulse frequency in a force-choice method that would provide additional insights into how to encode information in *Electrotactons* for absolute identification applications. Experiment 5 has been designed to measure how many levels of intensity and pulse frequency that participants could discriminate and to answer Research Question 2:

- *How can the parameters of electrotactile feedback be used to encode information? (Experiment 5)*

Experiment 6 implemented and tested the improved design of the *Electrotactons* informed by the findings from Experiment 5. Moreover, it investigated other potential parameters such as the size of the electrodes and the location of the stimulation on the body. The aim of this experiment was to answer the following Research Question 3:

- *What levels of performance can be achieved when these parameters are combined to create Electrotactons to present multidimensional information? (Experiment 6)*

A conclusion will discuss the findings and revisits the research questions in Section 4.6.

4.2 Experiment 5 (Intensity and Roughness)

This experiment investigated the complex electrotactile parameters' intensity and pulse frequency using a force-choice method. The aim was to compare two stimuli and indicate which stimulus felt "more intense" when using different levels of intensity, or which stimulus felt "rougher" when using different levels of pulse frequency to show how many distinguishable levels each parameter can produce, vital for its use in designing *Electrotactons*. The same 9 levels of intensity as in Experiment 4 and 6 levels of pulse frequency as in Experiment 1 were used in this experiment focusing only on discriminating between different levels, whereas in the previous experiments the focus was on the subjective perception of different sensations. By naming these levels in terms of intensity and roughness, participants may be able to discriminate between them more easily, making such choices practicable for use in *Electrotactons* for in absolute identification scenarios [90]. The apparatus used was the same one in the previous experiments. The results of this experiment will continue to contribute to answering Research Question 2.

4.2.1 Experimental Design

The experiment was designed as a within-subjects design and consisted of two parts. The first part investigated the discriminability of the same 9 levels of intensity from Experiment 4. The second part investigated the discriminability of 6 levels of pulse frequency from Experiment 1. In both parts, the method used was the same as Brown *et al.* [69] to test the discriminability of roughness for vibrotactile cues.

For intensity, the independent variable was: strength of the stimulus (as before: L-L, L-M, L-H, M-L, M-M, M-H, H-L, H-M, H-H). In each trial, participants were presented with pairs of stimuli (e.g. L-H followed by M-M). As with Brown *et al.*, pairs of the same strength (for example, H-H followed H-H) were excluded as the aim was to find the number of discriminable levels. Therefore, there were 36 stimuli, with each one presented twice (9*9 stimulus levels = 81 stimulus pairs, - 9 pairs of the same level = 72, / 2 because each pair occurred twice = 36 possible unique pairs). The dependent variable was the count of intensity: how many times each stimulus was rated to be more intense than another.

For pulse frequency, the independent variable was: frequency (10 PPS, 30 PPS, 50 PPS, 70 PPS, 90 PPS, 110 PPS). In each trial, participants were presented with a pair of stimuli excluding pairs of the same frequency (e.g., 10PPS, 10PPS). Therefore, there were 15 stimuli, with each one presented twice (6*6 = 36 stimulus pairs, - 6 pairs of same Frequency = 30, / 2 because each pair occurred twice = 15 possible pairs). While the sensation of roughness is typically linked to the perception of tactile stimuli that result from actively moving across a surface in a lateral direction [111]; previous research showed a relationship between the pulse frequency of electrotactile stimulation and the sense of roughness [54]. As pulse frequency is quite abstract, participants rated the stimuli in terms of perceived roughness. The term "pulse frequency" may be incomprehensible to someone without a scientific background, and even those familiar with the term may not have a clear idea of what it feels like. By using roughness as a descriptive label for these pulse frequencies, participants may be able to better comprehend and categorize them, as the aim was to measure the distinguishability of the levels, not how they feel [12]. The dependent variable was the count of roughness: how many times each stimulus was rated to be rougher than another. For the intensity part, there were three phases: calibration, training and experiment. For the Pulse Frequency part, there were two phases: training and experiment, as the calibration was reused.

Based on Experiment 4, it was hypothesised that the strength of the electrotactile stimulus would have a significant effect on the perception of different sensations and it is expected to have a similar effect on discriminating between different levels of intensity. Previous research indicated a relationship between the pulse frequency of electrotactile stimulation and the sense of roughness [54]. The aim was to investigate this in more detail. It was hypothesised that increasing pulse frequency would increase perceived roughness. Therefore, the hypotheses for this experiment were:

- ***Hypothesis 1:*** *Participants will be able to discriminate between Intensity levels based on the strength of the stimulus;*
- ***Hypothesis 2:*** *Perceived intensity will increase as the strength of the stimulus increases;*
- ***Hypothesis 3:*** *Participants will be able to discriminate between roughness levels based on the level of Pulse Frequency;*
- ***Hypothesis 4:*** *Perceived roughness will increase as the level of Pulse Frequency increases.*

4.2.2 Participants

Twenty new participants (12 female, 7 males and 1 transgender) between the ages of 17 and 53 (mean=26.75, SD=7.64, median=25.5), one left-handed, most were students, took

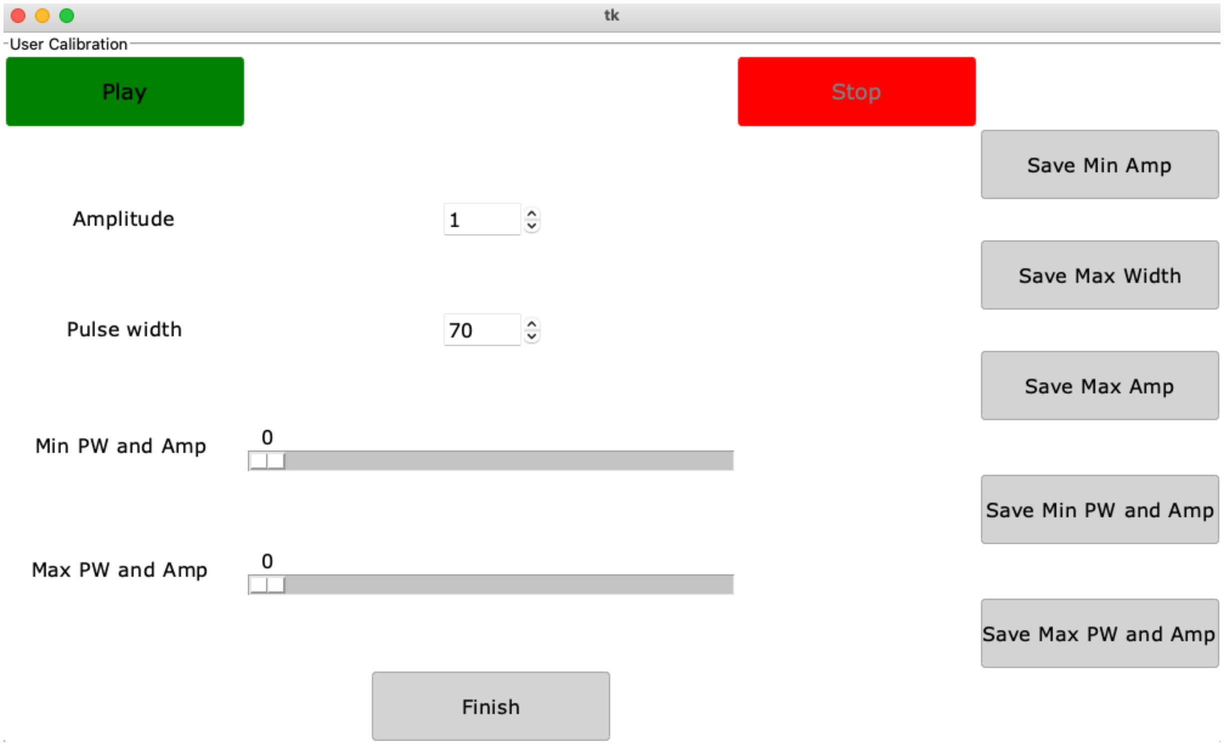

Figure 4.1: The calibration interface for Experiment 5.

part in this experiment. None had dermatitis or other skin conditions, or cardiovascular issues. Each participant read an information sheet and signed a consent form before the start of the experiment and was compensated £10 Amazon voucher for participating.

4.2.3 Procedure

The setup for this experiment and the calibration steps were the same as Experiment 3 with the following adjustment. After setting up the initial detection value for amplitude and the discomfort values for pulse width and amplitude individually, both pulse width and amplitude were increased simultaneously from their detection values until participants detected a sensation and saved these values as detection threshold. For the discomfort threshold, both pulse width and amplitude were increased simultaneously again, but from the average values until participants felt discomfort and save these values as discomfort threshold. The reason for this additional step was to avoid the combination of pulse width and amplitude causing additional discomfort during the experiment. Figure 4.1 shows the interface used for the calibration phase.

Intensity was tested first. In the training phase, participants were presented with two stimuli, each for 1s with 1s in between. Then they were asked to compare the two stimuli in a forced-choice design, answering the question: "Which stimulus felt more intense?", as seen in Figure 4.2. They did 10 training trials. The experiment phase was the same as

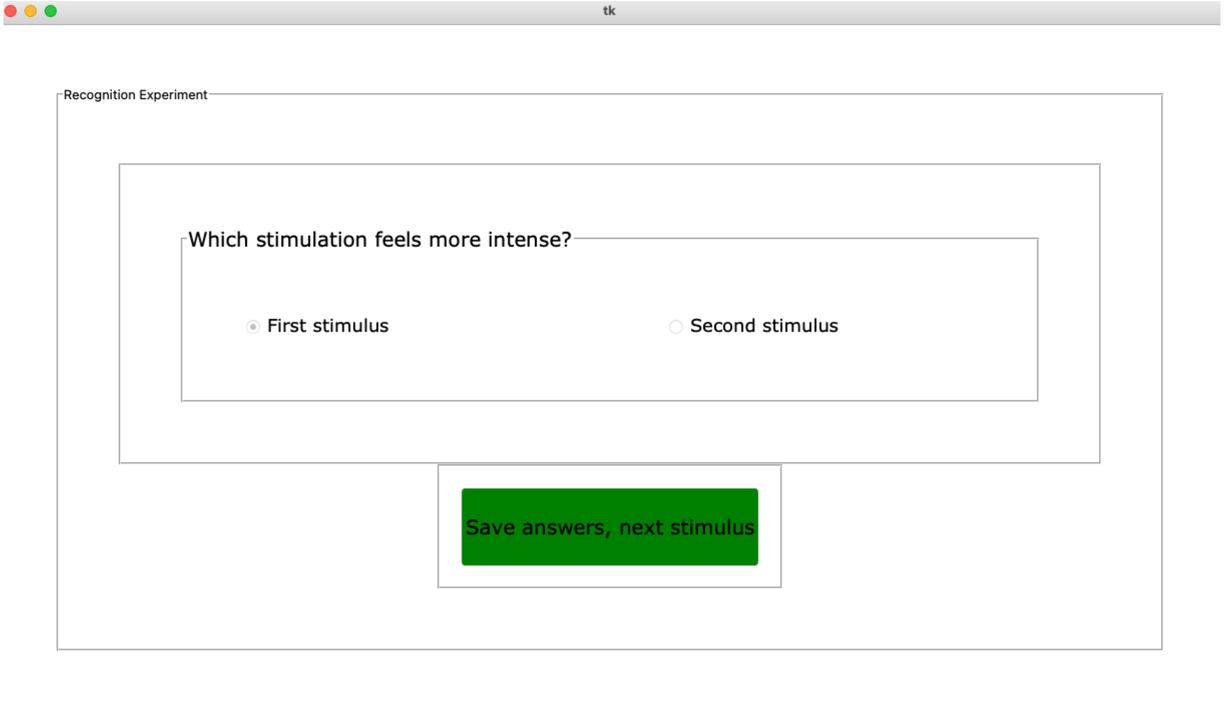

Figure 4.2: The training interface for Experiment 5.

the training but with two blocks. In each block, all 36 possible pairs were presented in a randomised order twice, where each pair was presented in two formats: (A,B) and (B,A). To avoid fatigue, there was a 5-minute break between blocks and at the end of this part, giving 72 trials in total.

In the second part, pulse frequency was tested. The same calibrated values from the intensity part were reused. The training and experiment phases were the same as for intensity, but with the question changed to: "Which stimulus felt rougher?", giving 60 trials in total. Participants did not receive any instructions on what was meant by "more intense" or "rougher" [69]; the aim was to see their own subjective judgements, rather than to train them to perceive certain stimuli as more intense or rougher than others.

For the qualitative part of the experiment, participants were handed the same paper for circling terms as in the previous experiments. Then, they were asked the following questions and recorded their answers:
1-How confident were you in distinguishing between different stimuli in general?
2-How would you compare the stimuli you just felt with the ones you usually feel from your phone?
3-Did your sensitivity change with time?
4-How would you describe your experience with electrotactile feedback?

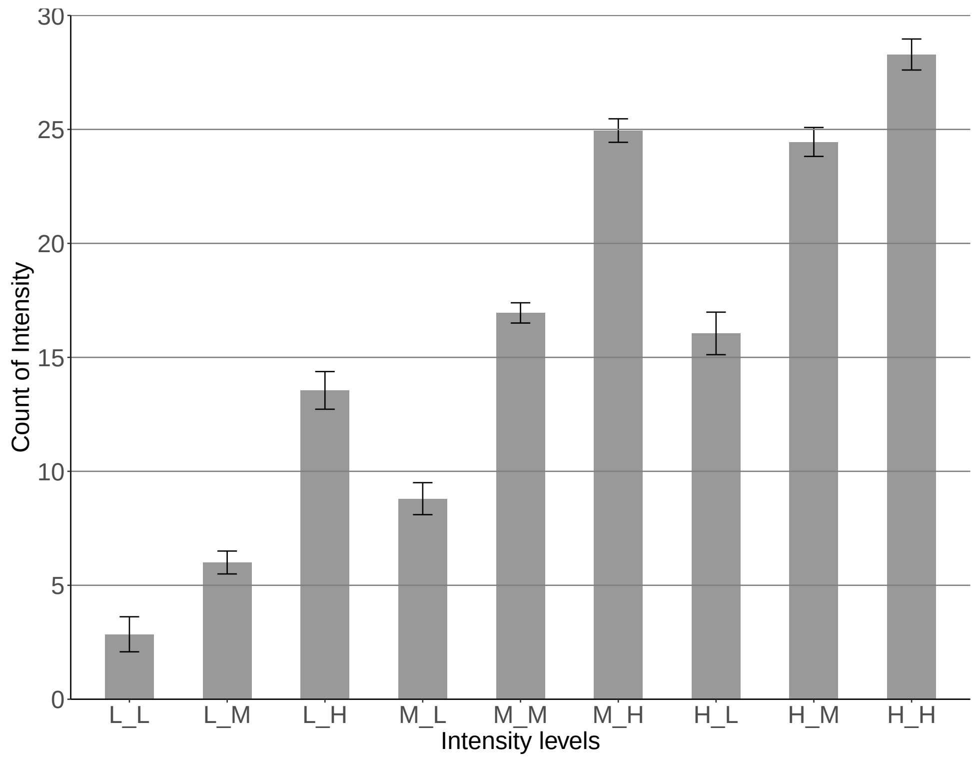

Figure 4.3: Effect of intensity on perception in Experiment 5.

4.2.4 Results

ART was again used to transform the data to a parametric form. Two one-factor repeated-measures ANOVAs were then performed on the count of intensity and then on the count of roughness. Intensity level had a significant effect on perception ($F(8,152)=192.74$, $p < 0.001$), with increasing level causing higher ratings of intensity (Figure 4.3). *Post hoc* Tukey test results can be seen in Table 4.1 and showed 4 uniquely distinguishable levels: (H-H), (H-M, M-H), (H-L, M-M, L-H), (M-L, L-M, L-L) that participants could discriminate (Figure 4.3).

Pulse frequency had a significant effect on the perception of roughness ($F(5,95)=2.64$, $p = 0.02$). *Post hoc* Tukey tests showed only a significant difference for one pair: (10PPS-90PPS)(Figure 4.4). This suggests there are only two discriminable levels for this parameter.

4.2.5 Qualitative Results

Figure 4.5 shows that the most common sensation was gentle for low intensity, which was selected 15 times. The second most selected sensation was vibrating for middle intensity, which was selected 14 times. Participants circled a total of 212 terms. The total number of counts for high intensity was 87, middle intensity 59 and low intensity 66. Compared to Experiments 1, 2 and 4, the count for low intensity was higher than middle intensity. That

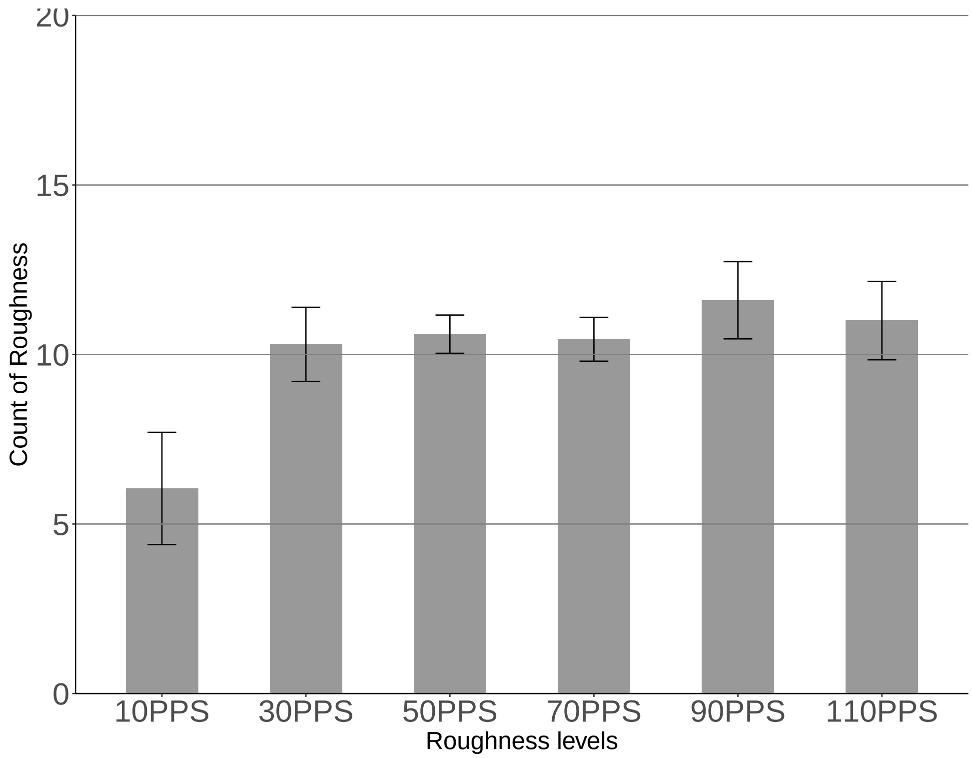

Figure 4.4: Effect of pulse frequency on perception in Experiment 5.

might be because the calibration steps were changed, where pulse width and amplitude were increased together to set up the detection and discomfort levels.

From the recorded answers for Question 1: *How confident were you in distinguishing between different stimuli in general?*, 18 participants said that they were confident distinguishing between the different stimuli, whereas only 2 said they were not confident. P03 mentioned *"I was confident for the stronger cues, but for the weak ones, I wasn't"*. P15 reported *"I was confident in distinguishing between different intensities but not roughness"*. For Question 2: *How would you compare the stimuli you just felt with the ones you usually feel from your phone?*, P01 answered *"It's a different experience. It gives me various levels of feedback compared to the one from the phone"*. P09 said *"It is quite different because some of the cues felt localized, and others were all over my palm"*. Answering Question 3: *Did your sensitivity change with time?*, 14 participants said that their sensitivity changed with time, were 6 said it didn't. P11 reported *"No, my sensitivity was constant throughout the experiment"*. P16 answered *"Yes, I got used to the cues over time"*. For Question 4: *How would you describe your experience with electrotactile feedback?*, P05 reported *"It was nice and I enjoyed it"*. P09 mentioned *"Overall it was good. Sometimes it can be too much. It is very attention-grabbing"*. P12 said *"It was confusing and interesting at the same time. Initially, I was afraid that electricity would be applied to my hand, but later on, it was ok"*.

Table 4.1: *Post hoc* Tukey tests comparing intensity levels for Experiment 5. As before, the first letter (L,M,H) is the level of pulse width, and the second letter (L,M,H) is the level of amplitude of the stimulus.

Stimulus pairs	count of Intensity
H H - H L	p<.0001*
H H - H M	p<.0001*
H H - L H	p<.0001*
H H - L L	p<.0001*
H H - L M	p<.0001*
H H - M H	p<.0001*
H H - M L	p<.0001*
H H - M M	p<.0001*
H L - H M	p<.0001*
H L - L H	p=0.2810
H L - L L	p<.0001*
H L - L M	p<.0001*
H L - M H	p<.0001*
H L - M L	p<.0001*
H L - M M	p=1.0000
H M - L H	p<.0001*
H M - L L	p<.0001*
H M - L M	p<.0001*
H M - M H	p=1.0000
H M - M L	p<.0001*
H M - M M	p<.0001*
L H - L L	p<.0001*
L H - L M	p<.0001*
L H - M H	p<.0001*
L H - M L	p<.0001*
L H - M M	p=0.0013*
L L - L M	p=0.0726
L L - M H	p<.0001*
L L - M L	p<.0001*
L L - M M	p<.0001*
L M - M H	p<.0001*
L M - M L	p=0.0663
L M - M M	p<.0001*
M H - M L	p<.0001*
M H - M M	p<.0001*
M L - M M	p<.0001*

* marks a significant difference (P<0.05).

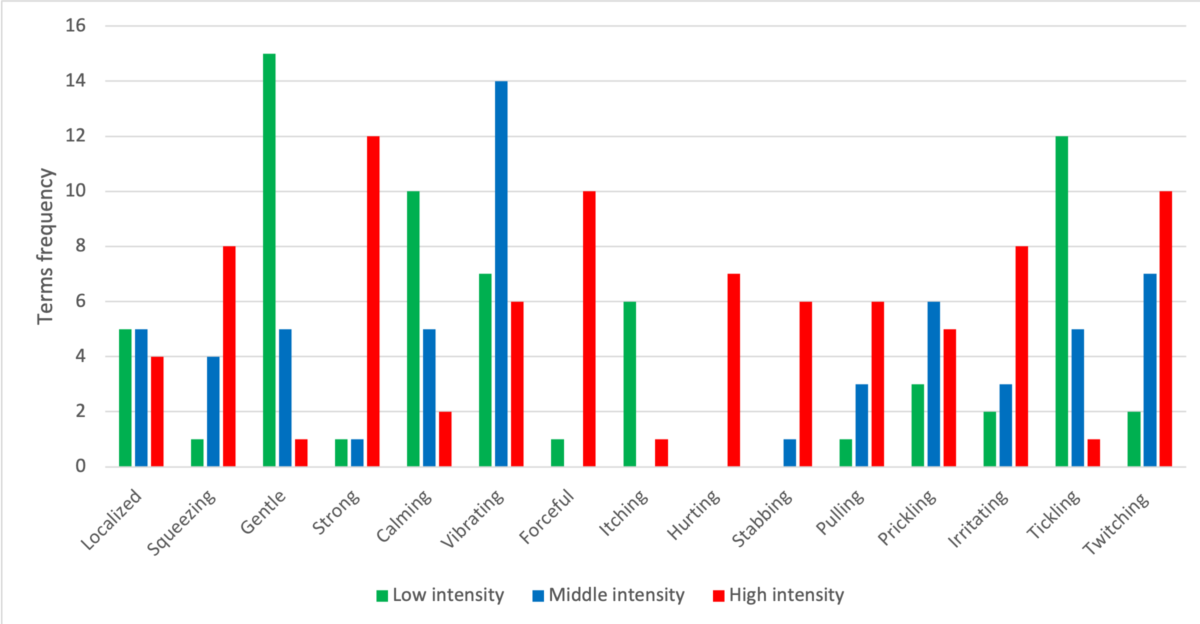

Figure 4.5: The 15 terms that participants can select from based on their intensity level perception for Experiment 5.

4.2.6 Calibration

The calibration phase for this experiment was the same as Experiment 3, but switching the order of the calibration was when increasing both pulse width and amplitude. First, the detection level was recorded, and then the discomfort level as mentioned in the procedure section. For amplitude, the average minimum value was 9.65 mA, SD= 2.64 mA and median= 9 mA, 18.91% less than Experiment 3. The average maximum value was 14.6 mA, SD= 3.54 mA and median= 13.5 mA, 17.28% less than Experiment 3. Figure 4.6 shows the distribution of amplitude values across participants. For pulse width, the average minimum value was 83.3 μs, SD= 5.02 μs, median= 84 μs, 1.24% less than Experiment 3. The average maximum value was 168.15 μs, SD= 19.26 μs, median= 175 μs, 2.04% less than Experiment 3. Figure 3.29 shows the distribution of pulse width values across participants. Calibrating the detection level for both parameters before the discomfort levels lead to having a lower minimum average. Amplitude was the most reduced parameter by 18.91%, whereas pulse width was reduced by only 1.24%. This was an indication that calibrating the detection threshold before the discomfort threshold made the participants more sensitive in detecting the lower values of the parameters, especially amplitude.

4.2.7 Experiment 5 Discussion

The aim of this experiment was to find how many levels of intensity and pulse width participants could discriminate using a force-choice method to see how many useful levels there would be for improving the design of *Electrotactons*. Results showed that inten-

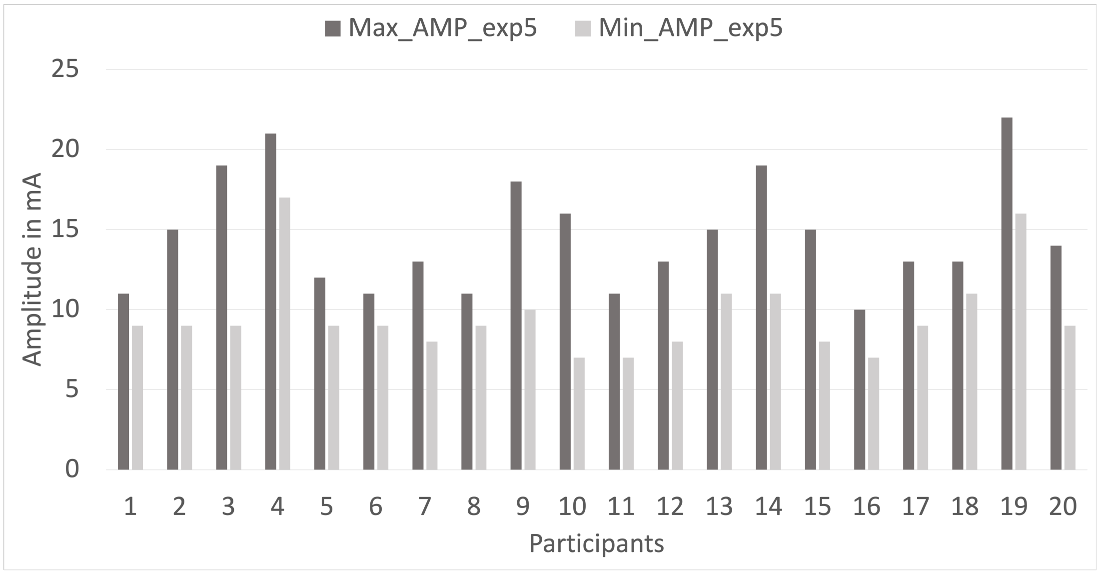

Figure 4.6: The distribution of maximum and minimum values for amplitude across participants for Experiment 5.

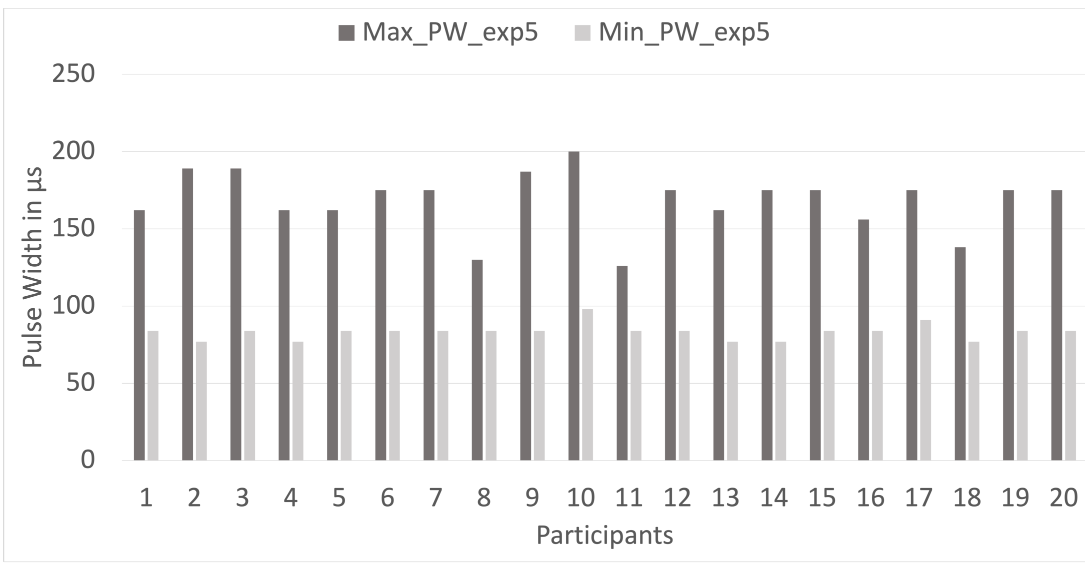

Figure 4.7: The distribution of maximum and minimum values for pulse width across participants for Experiment 5.

sity had a significant effect on perception with 4 unique levels (Figure 4.3). Therefore, *Hypothesis 1* is supported. From the same figure, it can be seen that as the strength of the stimulus increased, the count of intensity increased. This indicates the ability to control the perception of intensity by manipulating the strength of the stimulus. This is important for designing interfaces using electrotactile cues with a desired level of intensity. Therefore, *Hypothesis 2* is supported.

For pulse frequency, results showed only two unique levels that participants could discriminate (Figure 4.4). This makes it a more limited cue for the design than intensity but still has some potential. It also provides more insight into Yoshimoto *et al.*'s [54] findings where manipulating pulse frequency had an effect on roughness perception as it was shown that only two levels from the set of this experiment were distinguishable. Further work could investigate lower levels of pulse frequency below 10 PPS to see if other levels are discriminable. Therefore, *Hypothesis 3* is partially supported.

From Figure 4.4, it can be seen that there were no significant differences between pulse frequencies 30 PPS and above, which suggests that above that level cues are no longer distinguishable. This provides more evidence in line with [54, 80] where participants could not discriminate between stimuli with higher pulse frequencies as these are above the threshold of sensation. Therefore, *Hypothesis 4* is only partially supported.

4.3 Summary

The aim of this experiment was to investigate the perception of the complex electrotactile parameters' intensity comparing two stimuli in terms of which one was more intense, and the parameter pulse frequency in terms of which one was rougher using a force-choice method. Furthermore, measuring how many distinguishable levels each parameter can produce to be used in the improved design in the next experiment. This aim help to contribute an answer to Research Question 2 of this thesis:

- *How can the parameters of electrotactile feedback be used to encode information in Electrotactons?*

Looking back at the findings from experiments 1, 2, and 4 from Chapter 3, it showed that pulse width, pulse frequency, amplitude, and intensity all had a significant effect on the subjective perception of electrotactile feedback and that different levels of these parameters could evoke desired levels of sensations. For example, increasing pulse width and amplitude generally led to higher ratings of urgency, annoyance, and arousal and lower ratings of valence, while increasing pulse frequency had little effect on valence but affected urgency, annoyance, and arousal. Combining pulse width and amplitude into intensity also had a significant effect on all subjective perceptions.

In contrast, this experiment focused on the ability of participants to discriminate between different levels of intensity and pulse frequency. The results showed that participants could distinguish four levels of intensity but only two levels of pulse frequency. These results have implications for the design of *Electrotactons* design space, which can be optimized to convey information based on these perceptual characteristics.

4.4 Experiment 6 (Electrotactons with Complex Parameters)

Chapter 3 showed the possibility of encoding information to create *Electrotactons* using basic parameters, even though the overall recognition rate was low (38.19%), which showed that participants struggled to identify the whole cues. In addition, further analysis showed that using pulse width and amplitude individually was not efficient and that combining them into one parameter called intensity worked better. Experiment 5 investigated how many levels of the complex parameter (intensity) and pulse frequency were distinguishable using the force-choice method to improve the design of *Electrotactons* and achieve a higher recognition rate when conveying information.

This experiment investigated the levels of both intensity and pulse frequency discovered in Experiment 5 to improve the recognition performance of the initial design of *Electrotactons* in Chapter 3. The absolute identification rates were tested for these levels to evaluate their suitability to convey information, similar to Experiment 3. Furthermore, looking into additional parameters that might affect recognition rates such as electrode size and different body locations. Section 2.2.4 described the relationship between the size of the electrodes and the stimulated area. The smaller the electrodes, the higher the current flow leading to a more pronounced sensation. In addition, the experiment aimed to explore how the size of the electrodes impacts the recognition rate of Electrotactons. The investigation will focus on two different sizes. Different body locations differ in their sensitivity as discussed in Section 2.3.5. When choosing the arm as a location for the electrotactile stimulation, the further the stimulated area is from the fingertips, spatial acuity will be lower as the innervation density is low. In addition to investigating the palm as in previous experiments, the wrist and the upper arm were also investigated and their recognition rate of *Electrotactons* was measured. Choosing these locations will add significant knowledge to design novel, distinguishable notifications and messages in wearable devices. The results of this experiment will continue to contribute to answering Research Question 3.

4.4.1 Experimental Design

The design of this experiment used the same appointment task as Experiment 3 but encoded two dimensions of data (*Type* of appointment and *Importance* of appointment) in each stimulus using the parameters: intensity and pulse frequency. Three intensity levels were chosen from Experiment 5: H-H as high, M-M as medium and M-L as low. The reason for picking M-L was that it had the most intensity count of the lower intensity levels to ensure that participants could feel the stimuli. Two levels of pulse frequency were chosen from Experiment 5, 10 PPS and 90 PPS, and the third level was 2 PPS chosen from Experiment 3 as it had a 68.75% recognition rate and felt different than 10 PPS. A pilot study was conducted to test the design and ensure participants could recognise the stimuli.

This experiment used a 3x3 within-subject design, consisting of three phases: calibration, training and experiment. The independent variables were: intensity to convey the *Importance* of the appointment (high -> high importance, medium -> medium importance and low -> low importance) and pulse frequency to convey the *Type* of the appointment (90 PPS -> meeting, 10 PPS -> lecture and 2 PPS -> tutorial). From the two parameters, the total number of stimuli was 9. The dependent variables were the overall recognition rate of the combined cues (when all two parts are correct) and the recognition rates of the individual component parameters.

These 9 stimuli were delivered to the palm of the hand, the wrist and the upper arm, as this experiment aims to investigate if body location and electrode size affect the cues' recognition rate. Two different electrode sizes were used only on the palm of the hand. The first size was the same as in the previous experiments, which was 60x30mm (Figure 3.3)(large electrodes), and the second size was a circular shape with a 32mm diameter as seen in Figure 4.8 (small electrodes). Only the circular electrodes were used for the wrist and the upper arm because the bigger ones could stimulate the muscles. The electrode placement on the palm was the same as in the previous experiments. For the wrist, the placement was right beneath the Pisiform bone on top of the Ulnar bone, where there was no muscle as seen in Figure 4.9. The electrode placement on the upper arm was on the area between the deltoid muscle and the lateral head muscle to avoid muscle stimulation, as seen in Figure 4.10.

Using electrodes of different sizes, where one was larger than the other, is expected to have an impact on the recognition rate. As mentioned in the literature review subsection 2.2.4, there is an inverse relationship between the amount of electrical current (current density) and the size of the electrodes. The smaller the electrodes, the higher the electrical current that leads to a stronger stimulation. The palm skin is glabrous, which has a higher density of innervation than the hairy skin in the wrist and upper arm, making it more sensitive [9]. Therefore it is expected to have a higher recognition rate. From the pilot study, pulse frequency had a higher recognition rate than intensity, which is to be expected in the experiment. Therefore, the following hypotheses were made for this experiment:

- ***Hypothesis 1:*** *Pulse frequency will have a higher recognition rate than intensity;*
- ***Hypothesis 2:*** *The smaller electrodes will have a higher recognition rate than the large ones on the palm;*

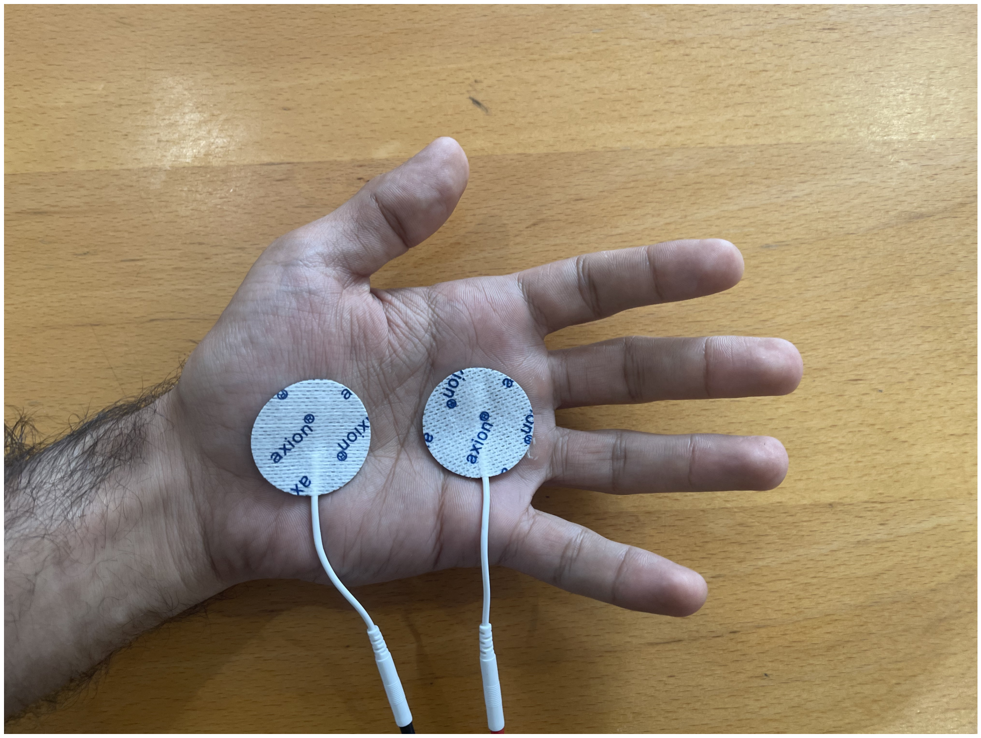

Figure 4.8: The small electrodes placement on the palm in Experiment 6.

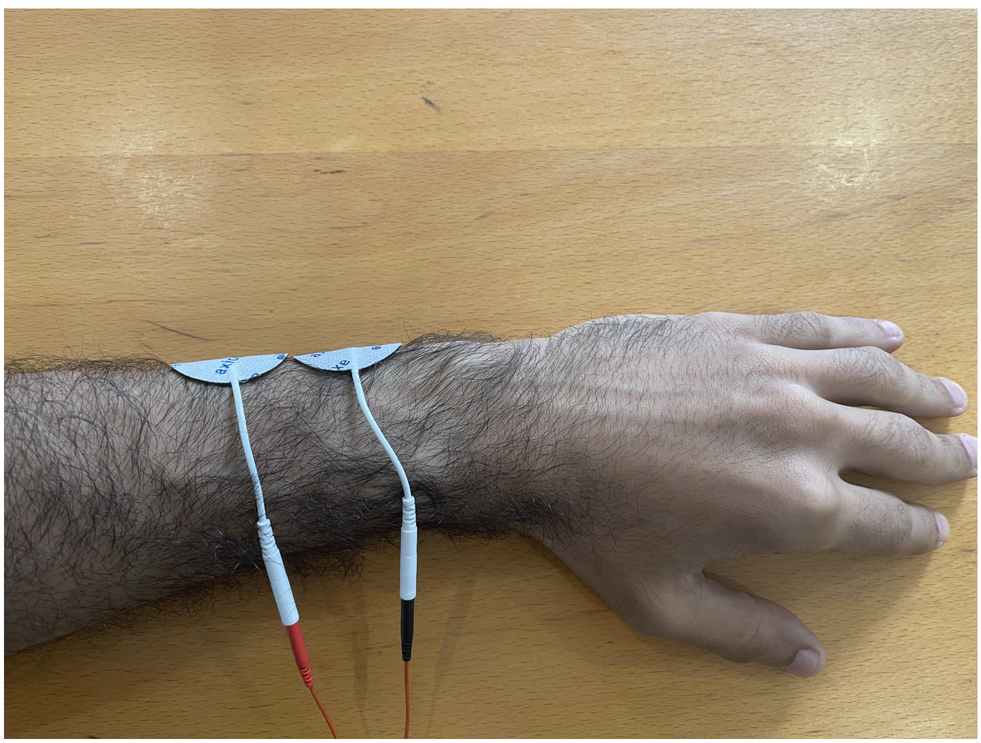

Figure 4.9: The electrodes placement on the wrist in Experiment 6.

- ***Hypothesis 3:*** *The palm of the hand will have a higher recognition rate than the other locations.*

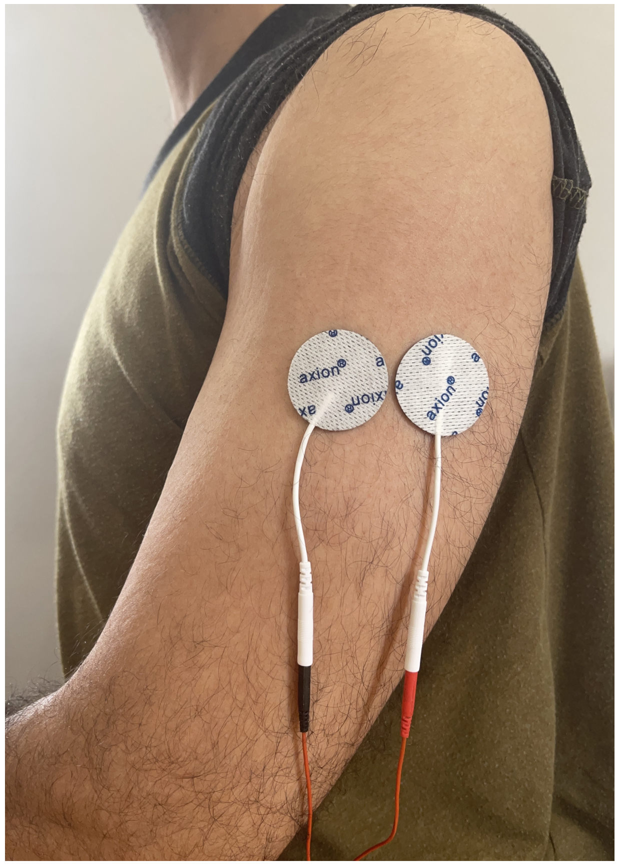

Figure 4.10: The electrodes placement on the upper arm in Experiment 6.

4.4.2 Participants

Twenty new participants (9 female, 11 male) between the ages of 20 and 40 (Mean=28.2, SD=6, Median=27.5), most were students, took part in this experiment. None had dermatitis or other skin conditions, or cardiovascular issues. Each participant read an information sheet and signed a consent form before the start of the experiment and was compensated £10 Amazon voucher for participating.

4.4.3 Procedure

The experiment setup and the number of phases are the same as in Experiment 3. The calibration steps were the same as in Experiment 5 for calibrating detection and discomfort thresholds. After the calibration phase, participants did the training phase. A 3x3 grid of buttons representing all possible stimuli were presented to the participants in the training phase (Figure 4.11). To complete the training, they were instructed to experience each stimulus at least twice or until they could distinguish between the different stimuli. Each stimulus lasted for 2 seconds on the skin. On the training interface, once a button is clicked twice, it will light green, and once all buttons are green, the quit button will light red, suggesting that they can exit the training phase if they wish.

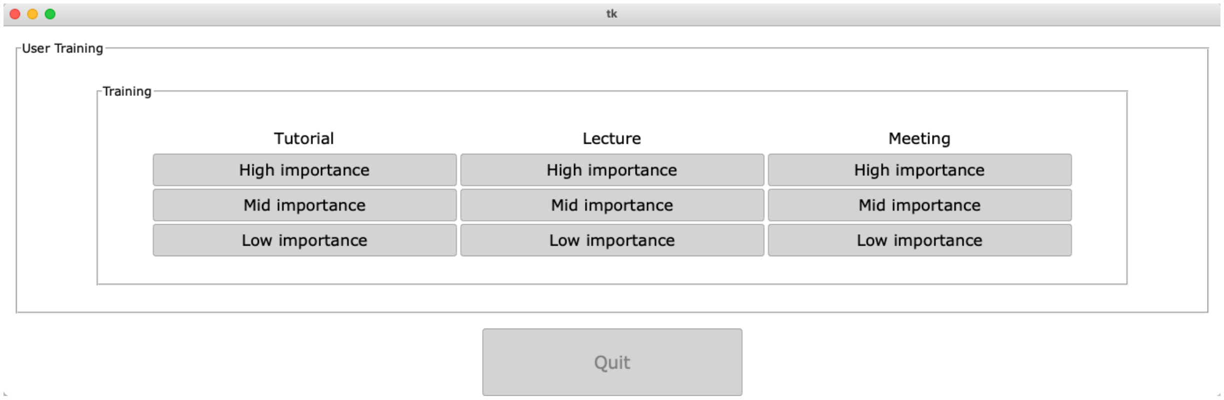

Figure 4.11: The training interface for Experiment 6.

In the experiment phase, participants did two blocks. In each block, the 9 stimuli were presented twice randomly. The total number of trials in the experiment phase for each participant was 36. To avoid fatigue, there was a 5-minute break between blocks. In each trial, after the participant received the stimulus, they were asked to identify the type and the importance of the meeting and save their answers using the interface seen in Figure 4.12.

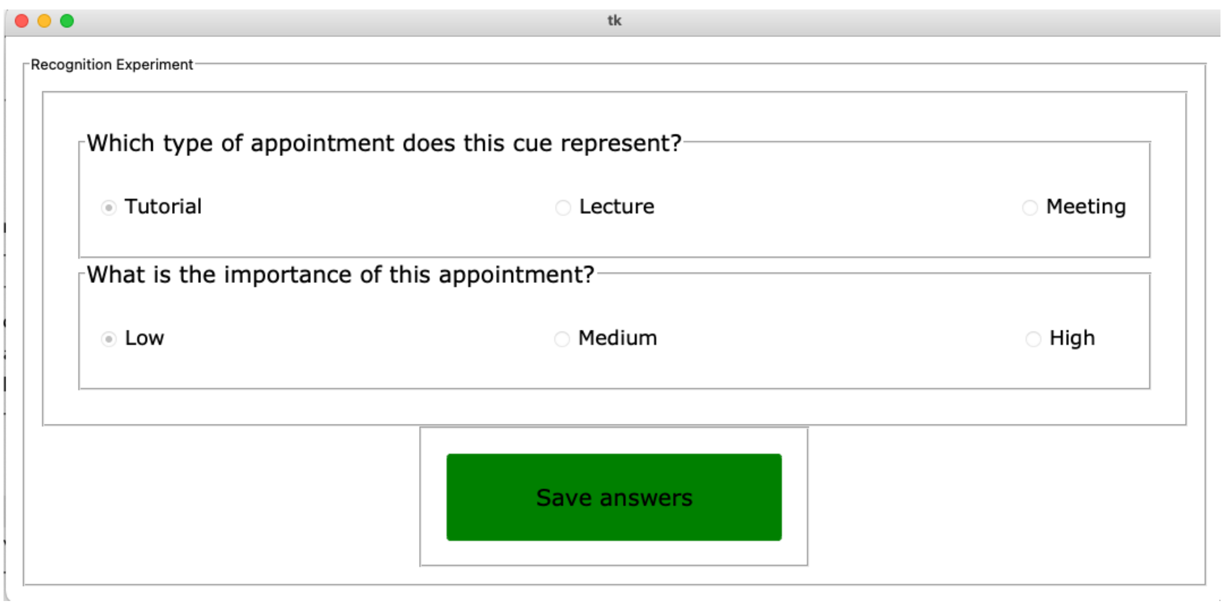

Figure 4.12: The experiment interface for Experiment 6.

This procedure and its steps were done four times. Twice on the palm, once using the large electrodes, and the other using the small electrodes. For the wrist and the upper arm, the procedure was done once at each location using the small electrodes. The total number of procedures was four, yielding 72 trials. The order of these procedures was randomized. For the qualitative data, after the end of the experiment phase in each procedure, participants were asked to experience three different stimuli by clicking the stimulus button as seen in Figure 4.13 and rank them from rough to smooth on a piece of paper to provide information on how they perceive electrotactile roughness of three pulse frequencies. These pulse frequencies of the stimuli were 2 PPS, 10 PPS and 90 PPS and their order of them was randomized each time. The level of intensity for the three stimuli was the same at middle intensity. Choosing a lower intensity might not be felt by the participants, or a higher intensity might be uncomfortable. After completing all four procedures, participants were handed the same paper as in the previous experiments for circling terms, then were asked the following questions, and their answers were recorded:

1-How confident were you in distinguishing between different stimuli in general?
2-Was there a body location that you found easier to recognize the stimuli on than others?
3-How would you describe your sensitivity to the stimuli over the time of the experiment?
4-How would you compare the stimuli you just felt with the ones you usually feel from your phone?
5-How would you describe your experience with electrotactile feedback?

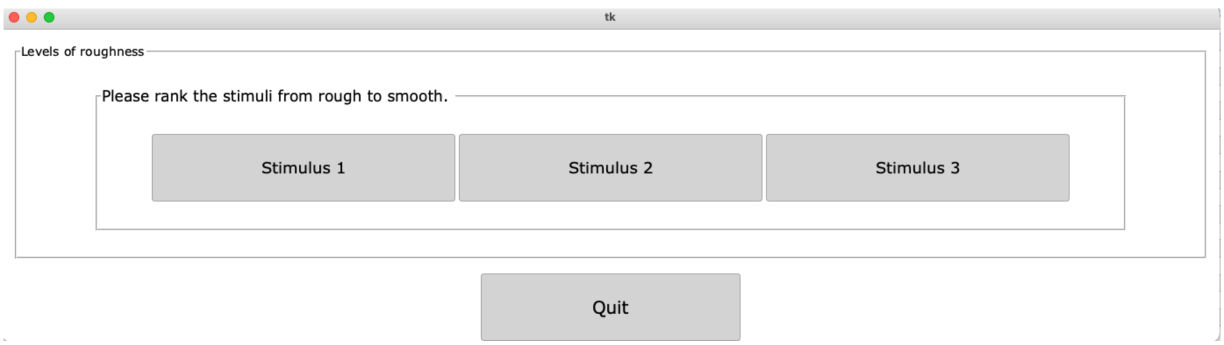

Figure 4.13: The three stimuli participants were asked to rank from rough to smooth in Experiment 6.

4.4.4 Results

The calculation of the recognition rate was done for the complete *Electrotactons* and for each component parameter. The mean overall recognition rate for the complete *Electrotactons* was 65.31%, which is a 27.12% improvement compared to the recognition rate of the initial *Electrotactons* design in Experiment 3. For the 9 *Electrotactons*, the recognition rates varied. From Figure 4.14 and Figure 4.15, it can be seen that (Type:meeting, Importance:high) and (Type:tutorial, Importance:low) had the highest overall recognition rates (86.88%) and (85.62%) respectively. These two *Electrotactons* represent the two ends of the intensity and pulse frequency levels. The lowest recognition rate (Type:tutorial, Importance:medium) had a rate of (39.06%).

For the individual component parameter, intensity had a recognition rate of 68.68% and pulse frequency had 94.41% (Figure 4.16). Within intensity (*Importance* of appointment), the high level had a recognition rate of 64.9%, medium had 54.37% and low had 86.77%

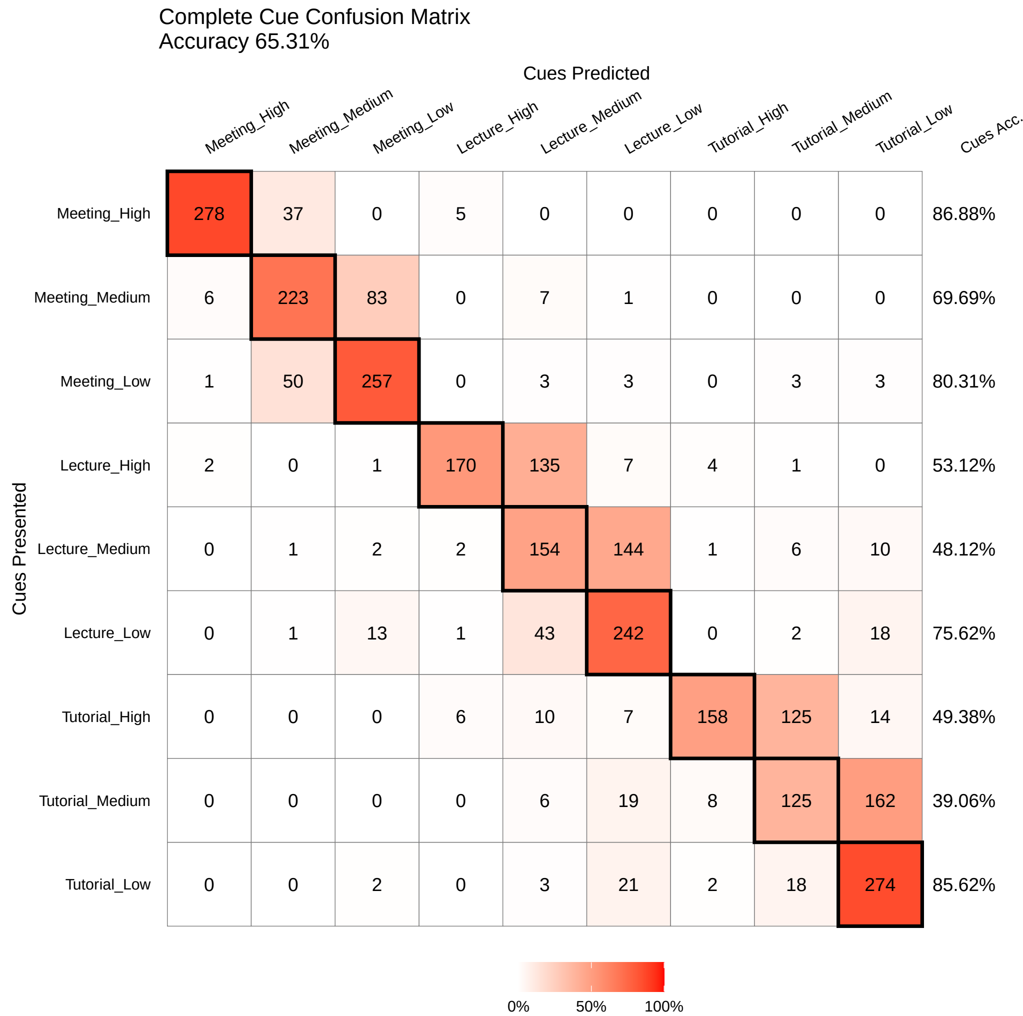

Figure 4.14: Heatmap for the recognition rate for all Electrotactons in Experiment 6.

(Figure 4.17). Within pulse frequency (*Type* of appointment), 90 PPS (meeting) had a recognition rate of 97.4%, 10 PPS (lecture) had 93.54% and 2 PPS (tutorial) 92.29% (Figure 4.19). For the locations, palm with large electrodes had an overall recognition rate of 64.17%, palm with small electrodes had 67.22%, wrist had 63.89% and upper arm had 65.97% (Figure 4.20).

Statistical testing was used to see if electrode size (large or small) had the most significant effect on the recognition rate on the palm. Before that, ART was used to transform the data into a parametric form. A one-way (size of the electrodes on the palm) repeated-measure ANOVA was then performed to see if there was any difference in recognition rates between the different electrode sizes. The test showed no significant effect on the recognition rate ($F(1,19)=1.47$, $p=0.239$)), as shown in the first two bars from the left Figure 4.20. To see if there was any difference in recognition rates between the palm (small electrode size only) and other locations, a one-way (location of the stimulus) repeated-measure ANOVA was then performed. The test showed no significant effect on the recog-

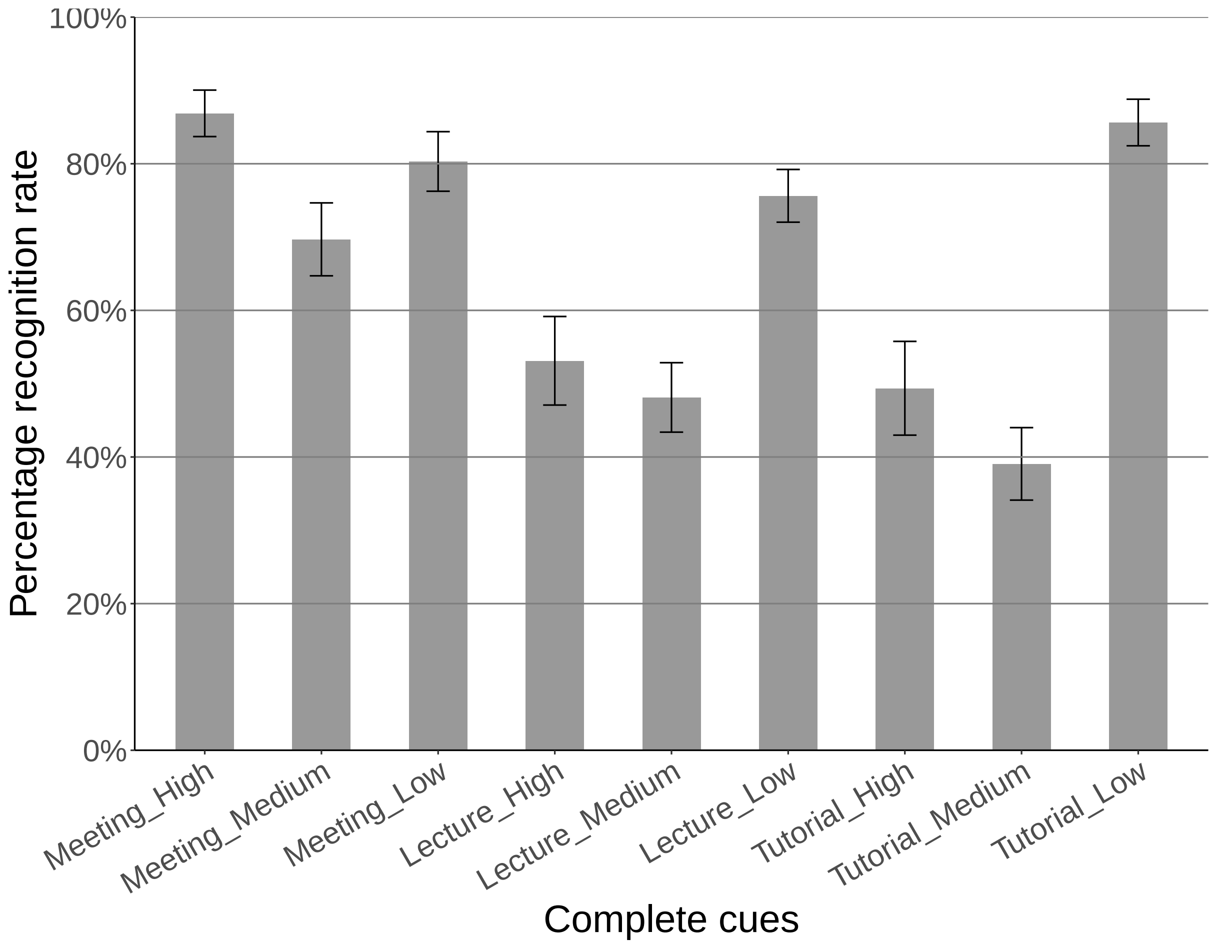

Figure 4.15: The recognition rate for all Electrotactons in Experiment 6.

nition rate ($F(1,19)=0.15$, $p=0.701$)) as shown in Figure 4.20. To see which parameter (intensity or pulse frequency) had the most significant effect on the recognition rate, a one-way (different parameters) repeated-measure ANOVA was then performed. The test showed a significant effect on the recognition rate ($F(1,19)=156.6$, $p<0.001$)) as shown in Figure 4.16.

4.4.5 Qualitative Results

Figure 4.21 shows that the most common sensation was gentle for low intensity, which was selected 20 times. The second most selected sensation was strong for high intensity, which was selected 18 times. Participants circled a total of 202 terms, where 93 counts for height intensity, 61 for middle intensity and 54 for low intensity. Compared to the total counts of Experiment 5, the total count of this experiment had 10 terms less, which was a small difference. Given that both Experiments 5 &6 used the same exact calibration steps, it can be assumed that the quality of the electrotactile stimulation in both was almost the same.

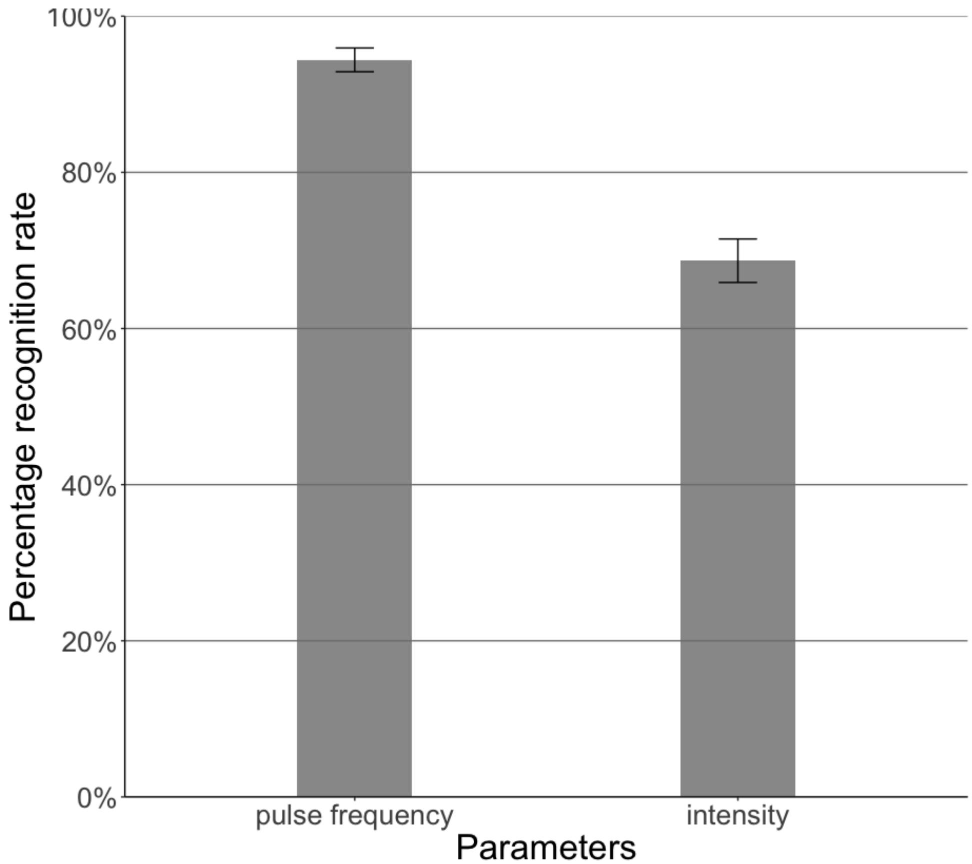

Figure 4.16: The recognition rate for each component parameter in Experiment 6.

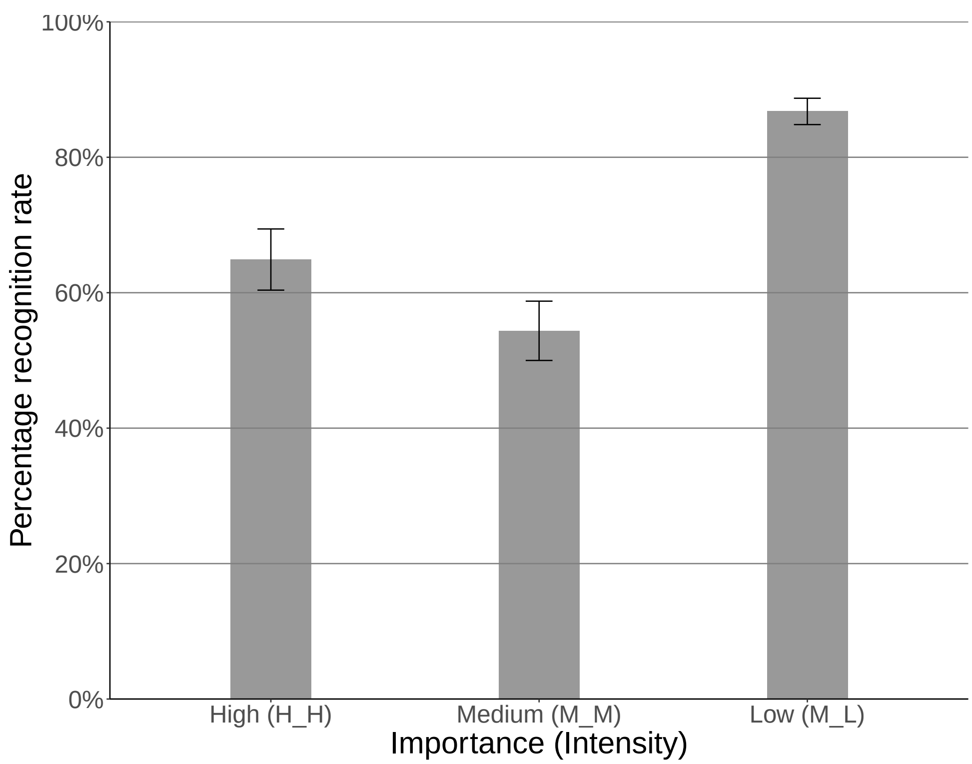

Figure 4.17: The recognition rate for the intensity levels in Experiment 6.

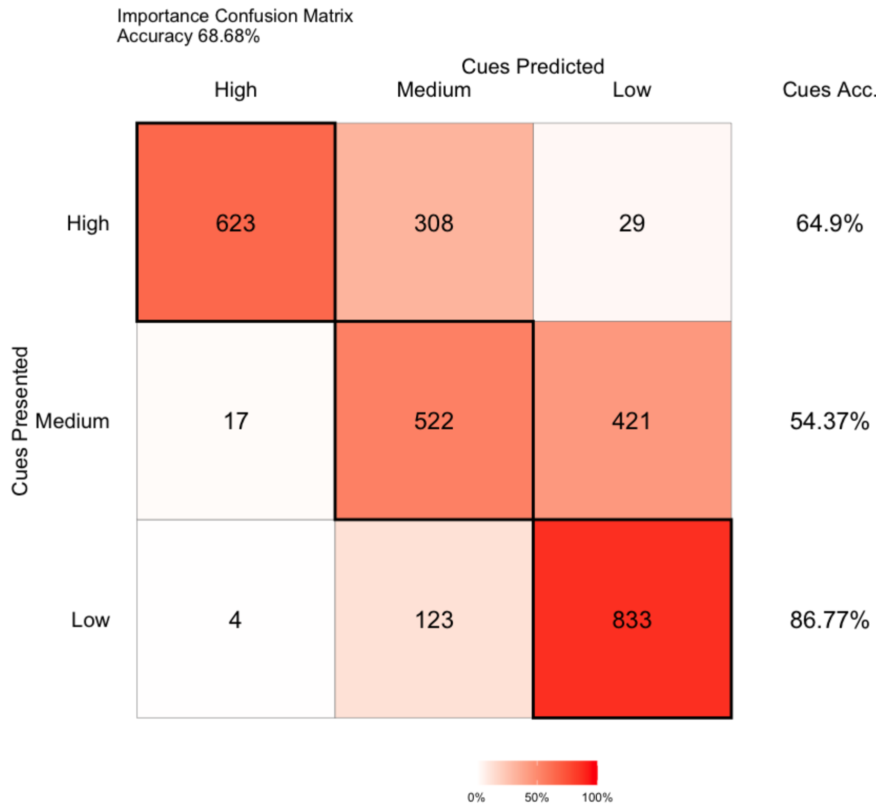

Figure 4.18: Heatmap for the intensity levels in Experiment 6.

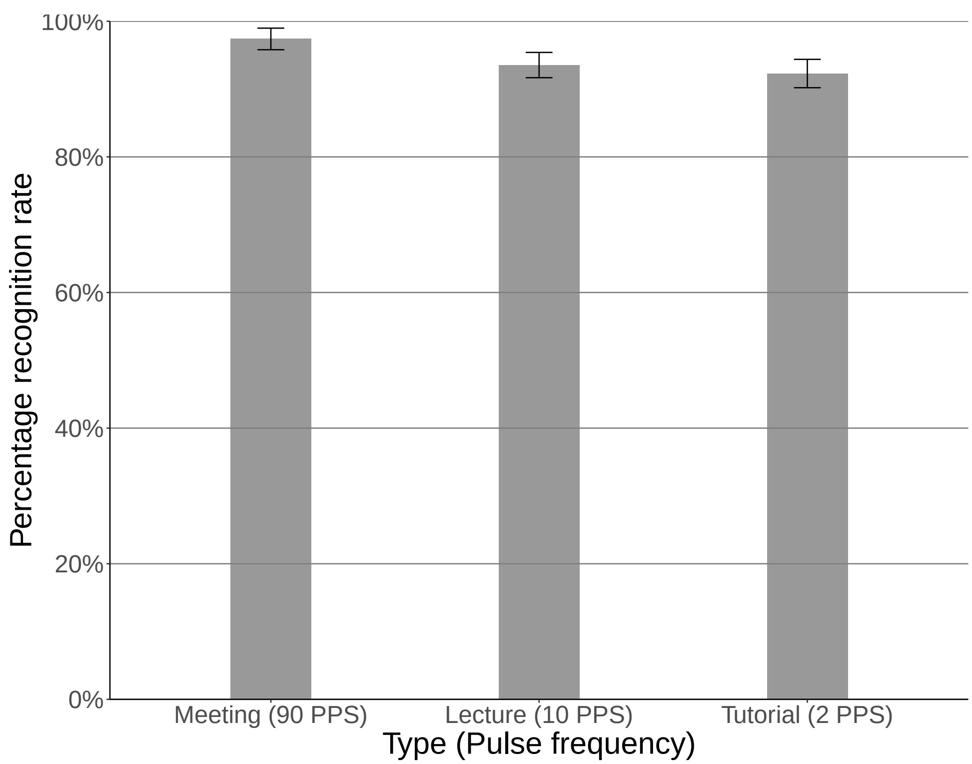

Figure 4.19: The recognition rate for the pulse frequency levels in Experiment 6.

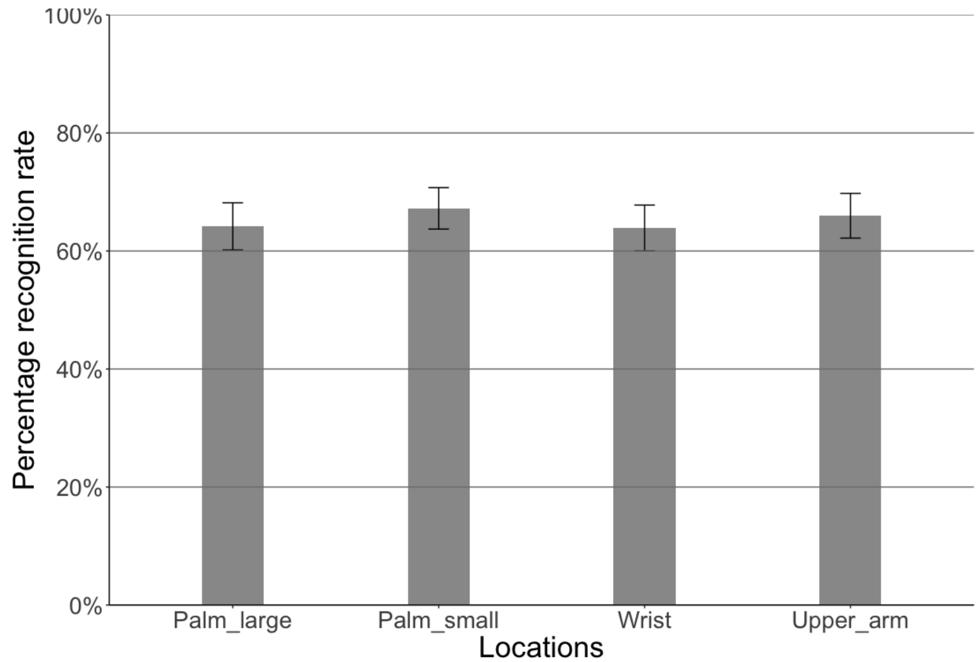

Figure 4.20: The recognition rate for all locations in Experiment 6.

For ranking stimuli from rough to smooth, Figure 4.22 and Table 4.2 show how participants rank the three stimuli at the end of each procedure. These results showed that half of the participants perceived 90 PPS to be rough, and the other half perceived it to be smooth. The same thing was observed with 2 PPS, but participants ranked it to be a bit smoother than rougher. This indicates that interface designers should be careful when mapping pulse frequencies to the perception of rough or smooth.

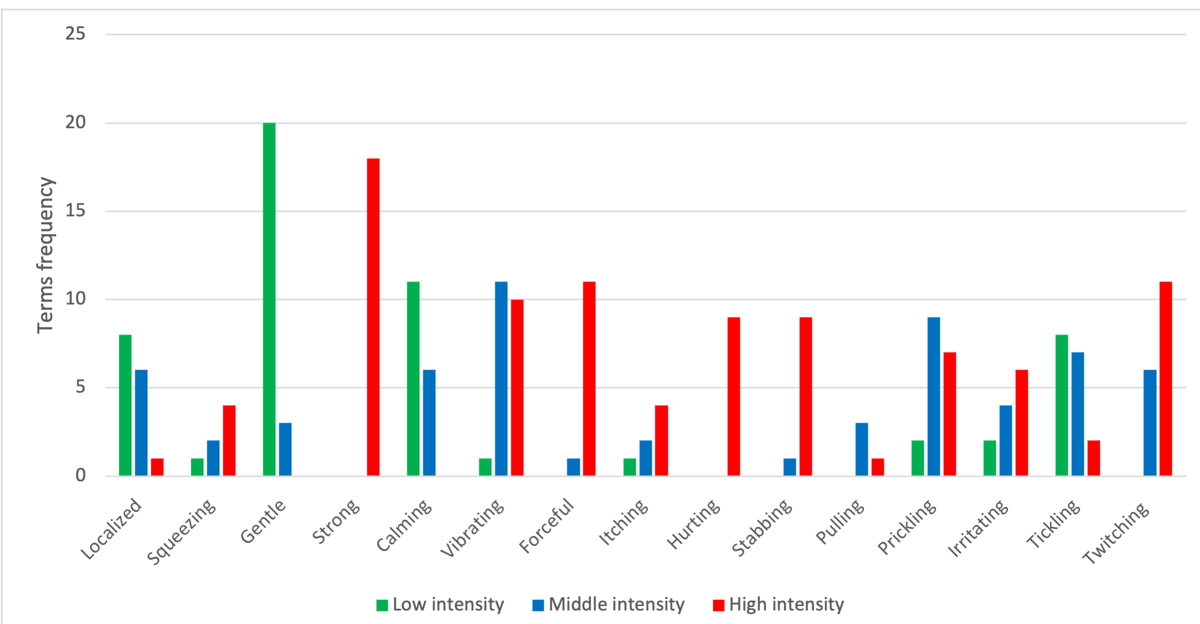

Figure 4.21: The 15 terms that participants can select from based on their intensity level perception for Experiment 6.

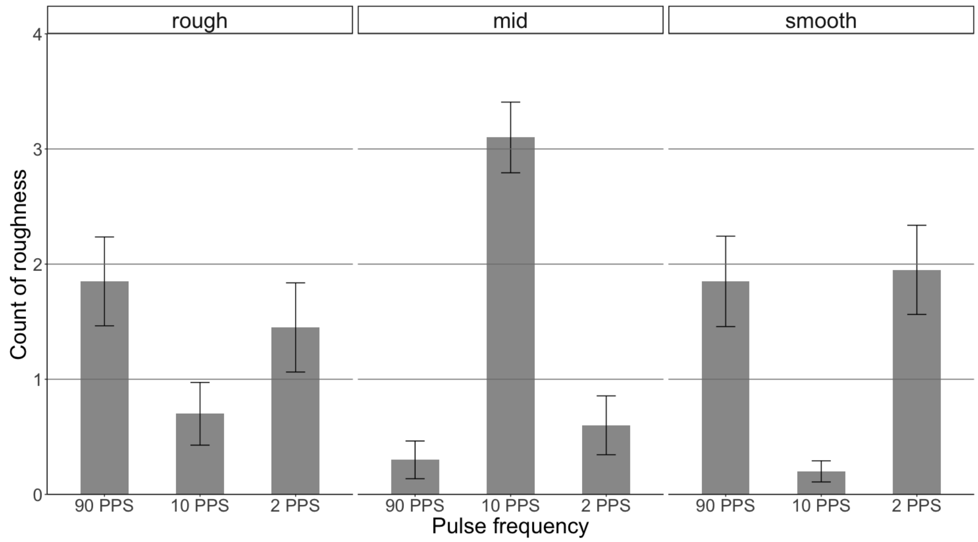

Figure 4.22: The ranking of the three stimuli from rough to smooth in Experiment 6.

Stimulus/Perception	Rough	Mid	Smooth
90 PPS	37	6	37
10 PPS	14	62	4
2 PPS	29	12	39

Table 4.2: The number of times each stimulus was ranked rough, mid or smooth in Experiment 6.

From the record answers for Question 1: *"How confident were you in distinguishing between different stimuli in general?"*, 15 participants said that they were confident in distinguishing between different stimuli, while 5 said they were not confident. The majority of those who said they were confident elaborated that the *Type* of the appointment was easy to distinguish, but the *Importance* was not. P08 said *"I was quite confident. It was easy to distinguish between the types more than the importance"*. P11 added *"The high intensity stimuli were easy. Also, the types of the appointment were easy to distinguish. Low and medium importance were difficult to distinguish"*. P06 reported *"I was not confident. My main issue was between low and medium importance across all stimuli."*

For Question 2: *"Was there a body location that you found easier to recognize the stimuli on than others?"*, 7 participants said that the upper arm was the easiest to recognize the stimuli on, 5 participants said the wrist, 5 said the arm and 3 said they all felt the same. P01 reported *"On the palm of the hand for both sizes was the easiest"*. P05 said *"On the wrist, I could feel everything"*. P18 added *"Nothing stood out for the locations for me"*. For Question 3: *How would you describe your sensitivity to the stimuli over the time of the experiment?*, 13 participants reported that their sensitivity changed with time and that they got used to the stimuli and could recognize the type and the importance of the appointment. P01 reported *"I got used to the stimulation with time, especially for the wrist and the palm"*. P12 said *"I would not say it changed but I started to distinguish more with time."*. P14 added *"I would say I got used to them over time but by the end, it got hard to distinguish between"*. P16 reported *"With time, I got used to them, but at the end of the experiment, I could not distinguish between different cues"*.

Answering Question 4: *"How would you compare the stimuli you just felt with the ones you usually feel from your phone?"*, P03 reported *"I preferred electrotactile feedback more than vibration because the frequencies are more pronounced"*. P06 added *"It was stronger, more precise in delivering the meaning of the notification. It felt as if it was a part of my body"*. P16 said *"Medium intense ones were similar to the phone vibration but high and low or different"*. For Question 5: *How would you describe your experience with electrotactile feedback?*, P04 reported *"It's interesting and I can see the potential for it. Intensity can be sometimes high"*. P09 added *"I think it is interesting. It is not as subtle as a regular vibration and it needs training to be used in different applications"*. P17 said *"I think it can be usable in a video gaming console as feedback"*.

4.4.6 Calibration

For this experiment, the calibration phase was conducted four times, as mentioned in the procedure section, giving a calibration profile for each location. The table in Table 4.3 shows the average maximum and minimum values for both pulse width and amplitude for each location. Looking at the average values of the palm with large electrodes and comparing them to the calibration values of Experiment 5 (same placement and size electrodes), the amplitude average minimum value was 8.29% higher, and the average maximum value was 9.59% lower. For pulse width, the average minimum value was 1.32% higher, and the average maximum value was 14.39% lower. The reason for having lower maximum values was that in this experiment, the order of the locations was random, so some participants experienced electrotactile feedback before they did the palm with large electrodes. When looking at the averages for palm small, wrist and upper arm, there was not a big difference. Moreover, in the upper arm, the average min value for amplitude was 42.7% lower than other locations, suggesting that the upper arm was more sensitive to the electrotactile stimulation.

4.4.7 Experimental 6 Discussion

The overall recognition rate of the complete *Electrotactons* was 65.31%, which was an improvement compared to Experiment 3 (*Electrotactons with basic parameters*). Results showed that pulse frequency had a higher recognition rate (94.41%) than intensity

Parameter/Location	Palm Large	Palm Small	Wrist	Upper Arm
Maximum Pulse width	143.95 μs	149.7 μs	155.5 μs	172.05 μs
Minimum Pulse width	84.4 μs	85 μs	81.3 μs	85.15 μs
Maximum Amplitude	13.2 mA	11.65 mA	13.1 mA	10.4 mA
Minimum Amplitude	10.45 mA	8.85 mA	8.95 mA	5.1 mA

Table 4.3: The average maximum and minimum values of the parameters for each location in Experiment 6.

(68.68%), as can be seen in Figure 4.16. Therefore, *Hypothesis 1* is supported. When looking at Figure 4.15, participants performed well when pulse frequency (type) was 90 PPS (meeting) scoring 70% and above. From the same figure, when pulse frequency was 10 PPS (lecture) or 2 PPS (tutorial), participants struggled to distinguish the different intensity levels. In other words, when presenting an *Electrotacton* that was high importance lecture, participants confused it with medium importance lecture. The same happened with the following: medium importance lecture was confused with low importance lecture, high importance tutorial was confused with medium importance tutorial and medium importance tutorial with low importance tutorial. These results align with Kaczmarek *et al.* [57] as they found that the greater pulse frequency, the garter effect of intensity on perception. This suggests that having three levels of intensity may not be a good choice, especially when using it with 10 PPS and 2 PPS. The medium intensity seemed to be the level causing the confusion for participants, as it scored the lowest recognition rate from the intensity levels (Figure 4.15).

The heatmap in Figure 4.18 gives a clearer picture that intensity was the case of the confusion. When presenting high importance *Electrotacton*, it got confused with medium importance, and the same happened when presenting medium importance; it got confused with low importance. On the other hand, participants performed well when presenting *Electrotactons* that were low importance lecture or tutorial. Reducing the intensity levels to two by removing medium intensity could substantially improve recognition rate. When averaging high and low intensity levels, it suggests 75.83% could be achieved, improving the overall recognition rate for the complete *Electrotactons*. However, the size of the parameter space will be reduced. This mirrors the findings of Experiment 3 and Brown *et al.* [69], which had the same issue. For the different size electrodes on the palm, results showed no significant difference in recognition rate between the large (64.17%) and small (67.22%) sizes, as shown in the first two bar charts from the left in Figure 4.20. Therefore, *Hypothesis 2* is not supported. This suggests that having a higher current density in the small electrodes as described in Section 2.2.4 did not have a higher recognition rate compared to the large electrodes. The threshold in which the size of the electrodes would impact the recognition rate of *Electrotactons* needs to be explored in future work. Results showed no significant difference in recognition rate between palm small (67.22%), wrist (63.22%) and upper arm (65.97%) as shown in the first three bar charts from the right in Figure 4.20. Therefore, *Hypothesis 3* not supported. This indicates that *Electrotactons* can have a similar performance on different body locations which makes it suitable for different wearable applications.

4.5 Summary

This experiment investigated the improved design of *Electrotactons* using intensity and pulse frequency to encode multi-dimensional information. In addition, investigate the effect of using two different size electrodes on the palm, and the effect of delivering *Electrotactons* to different body locations on the recognition rate. The aim was to map these two parameters with two pieces of information to create *Electrotactons* and measure how well they perform. This aim contributed to answering Research Question 3:

- *What levels of performance can be achieved when these parameters are combined to create Electrotactons to present multidimensional information?*

The results of this experiment showed that reducing the dimension of information to two helped in improving the recognition rate of *Electrotactons* using the parameters intensity and pulse frequency to convey the information. The overall recognition rate for the complete *Electrotactons* was 65.31%, where intensity had 68.68% and pulse frequency had 94.41%. For the recognition rate on different body locations, palm with small electrodes had 67.17% and with large electrodes 64.17%, wrist had 63.89% and upper arm had 65.97%. Furthermore, the results showed that participants confused high intensity with middle intensity and middle intensity with low intensity. This suggests that removing the middle intensity level would significantly improve the recognition rate which will reduce the parameter space of *Electrotactons* even more. In future experiments, new parameters will be investigated to compensate for the reduction of the parameter space such as rhythm and body locations to encoding information in the pattern in which the electrodes are activated.

4.6 Conclusions and Research Questions

This experiment reported an experiment that aimed to answer Research Questions 2 & 3:

- *How can the parameters of electrotactile feedback be used to encode information?*

The results of this experiment gave useful insights into how to employ electrotactile parameters such as intensity and pulse frequency in designing *Electrotactons*. It was possible for participants to discriminate between four levels of intensity, the same number of distinguishable levels found by Brown *et al.* [69] in Tactons. For pulse frequency, participants were able to discriminate between two levels. These findings make both parameters useful cues and strong contributors to the *Electrotactons* design space to create effective cues where users can learn the mapping between the *Electrotactons* and their meanings.

- *What levels of performance can be achieved when these parameters are combined to create Electrotactons to present multidimensional information?*

The results of this experiment showed an improvement in the design of *Electrotactons* by reducing the information dimension from three to two by manipulating intensity and pulse frequency. Participants showed the ability to learn the mapping between *Electrotactons* and their meanings with 65.31% accuracy. Pulse frequency seems to be very successful as an *Electrotacton* parameter, performing better than it did in Experiment 3 for two reasons. First, the amount of information encoded into the *Electrotactons* in this experiment was reduced to two compared to three in Experiment 3, leading to less cognitive load on participants. Second, using the distinguishable levels from Experiment 5 and Experiment 3 made the range of pulse frequency used here wider than it was in Experiment 3, leading participants to distinguish between the different pulse frequencies easily.

The results also indicate that intensity could be a useful parameter for *Electrotactons*, as it achieved a recognition rate of 68.68%. However, participants confused high intensity with medium intensity and medium intensity with low intensity when using pulse frequencies 10 PPS and 2 PPS. In Experiment 5, intensity showed that it had four distinguishable levels when it was manipulated by itself, but when manipulated with pulse frequency to convey information, the cognitive load increased leading the participants to be less efficient in distinguishing between the intensity levels. Reducing the intensity levels to two by removing the medium level would eliminate the confusion. A future experiment will be designed and conducted to evaluate this in more detail.

Chapter 5

Conclusions

5.1 Introduction

This thesis investigated the subjective perception of electrotactile feedback to design cues with desired sensations and understand the parameter space, providing information on how to design *Electrotactons* to convey multidimensional information. The thesis statement in Introduction reads as follows:

> Electrotactile stimulation is a novel form of tactile feedback but has had little study in HCI. This research explores the parameters of electrotactile feedback to create a range of novel tactile cues and encode information in structured messages called *Electrotactons*. Results show that manipulating pulse width, amplitude and frequency can create effective cues and that users can learn the mappings between the *Electrotactons* and their meanings.

In the chapters that followed, experimental work was presented that supported this statement and sought to answer the thesis research questions. Chapter 3 investigated the subjective perception of electrotactile feedback through the manipulation of its basic parameters such as amplitude, pulse width and pulse frequency. The results showed that these parameters had an effect on perception, with each having distinguishable levels. In addition, the first design of *Electrotactons* using basic electrotactile parameters to convey information was investigated in terms of identification rates. The results showed the potential of *Electrotactons* in conveying information and provided insights into how to improve the design to achieve higher identification rates. However, rates were low, so other parameters were investigated to improve performance. Chapter 4 investigated the absolute identification of intensity and pulse frequency to see how many distinguishable levels each can produce to improve the design of *Electrotactons*. The second design of *Elec-*

trotactons using intensity and pulse frequency was investigated, and the results showed an improvement in the recognition rates compared to the first. The experiments in these chapters were designed and conducted to answer the three research questions outlined in Section 1.3, and their findings will be discussed and summarised in this chapter. Furthermore, the main contributions and limitations of this thesis will be discussed, followed by a description of future work.

5.2 Research Questions

5.2.1 Research Question 1

- *What parameters of electrotactile stimulation can be used to influence subjective perception (Experiments 1, 2 & 4)?*

Three experiments were conducted, described in Chapter 3, to answer this question. Each experiment manipulated a combination of two of the three basic electrotactile parameters, pulse width, amplitude and pulse frequency to create electrotactile stimuli and measure the subjective perception of the functional aspects of alertness (urgency and annoyance) and emotions (valence and arousal). The palm was the only body location stimulated in these experiments. The aim was to emulate the feedback someone would receive when holding a mobile device, steering wheel, etc. Experiment 1 investigated the effect of manipulating three levels of pulse width and six levels of pulse frequency on different sensations. Results showed that both parameters had a significant effect on subjective perception. Increasing pulse width increased the perception of urgency, annoyance and arousal and lowered the perception of valence. Pulse frequencies of 30 PPS and above were rated the same across all sensations, indicating that they evoked the same level of sensation.

Experiment 2 investigated the next combination of parameters: amplitude and pulse frequency. Three levels of amplitude and nine levels of pulse frequency (the range was informed by the results from Experiment 1) were manipulated, and their effect on subjective perception was measured on the different sensations. Results showed that both parameters had a significant effect on subjective perception. Increasing the level of amplitude caused higher ratings of urgency, annoyance and arousal with a lower rating of valence, indicating that the stronger sensation caused a less pleasant, more negative feeling. Pulse frequency evoked more clear levels of sensations than in Experiment 1, as it used a narrower range of values with smaller steps. Furthermore, pulse frequency had little effect on valence, as it does not contribute to the strength of the sensation as amplitude does. Experiment 4 investigated the effect of manipulating nine levels of the parameter intensity on different sensations. Intensity is the combination of the last pair of the electrotactile parameters:

pulse width and amplitude. Results showed that intensity had a significant effect on perceived sensation. The higher the level of intensity, the higher the rating of urgency, annoyance and arousal and the lower the valence. Looking at pulse width and amplitude separately, neither one had a greater impact on subjective perception than the other. To answer Research Question 1: electrotactile parameters such as pulse width, amplitude and pulse frequency can be used to influence subjective perception. This suggests that they can be used to create cues with a wide range of different levels of urgency and annoyance as they are important for their effective use in interface design. In addition, they can be used to create cues with positive and negative valences and three different levels of arousal, suggesting that they can be used to generate simple emotional experiences, especially for handheld devices that touch the palm.

A comparison of the effects of the parameters of electrotactile stimulation to that of mechanical stimulation would depend on various factors, such as the specific parameters being used, the individual's sensitivity to each type of stimulation, and the context in which the stimulus is being applied. However, electrotactile stimulation has generally been more precise and controllable than mechanical stimulation [112], which makes it more suitable for specific applications.

5.2.2 Research Question 2

- *How can the parameters of electrotactile feedback be used to encode information in Electrotactons (Experiments 1, 2, 4 & 5)?*

To answer this question, the clear levels of different sensations that were identified in Research Question 1 have been used to encode information into *Electrotactons* in a structured and abstract method. These levels can be mapped to whatever meaning depending on the application. Abstract mapping is a coding system where the cue used to represent information do not have an inherent connection to the meaning of the information they represent. Intuitive mapping, on the other hand, is a system where the cue used to represent information has a clear and direct connection to the meaning of the information they represent [113]. Users must learn and memorize the mapping in both methods to efficiently process and understand the information being conveyed.

The hypothesis was if the levels from Research Question 1 evoked different levels of sensations, it would convey different pieces of information, making it useful for the design of *Electrotactons*. From Experiment 1, pulse width had three clearly distinguishable levels for all sensations except two levels for valence, whereas pulse frequency had only two levels. From Experiment 2, amplitude had three clear distinguishable levels for all sensations, and pulse frequency had five clear distinguishable levels for all sensations except two for valence. The hypothesis was tested in Experiment 3, which showed that the use of pulse width and amplitude to encode information was not as clear as it was with sensations and that combining them into one parameter (intensity) might be a better choice to produce levels that can be used in *Electrotactons*.

Experiment 4 showed that intensity had five levels of urgency, three of annoyance and arousal and two for valence. Before using the levels of intensity and pulse frequency to test the improved design of *Electrotactons*, another method of evaluating parameters was used that was influenced by Brown *et al.* [69] where she tested the discriminability of roughness for vibrotactile feedback. In Chapter 4, Experiment 5 investigated intensity and pulse frequency in a force-choice method and measured how many distinguishable levels participants could discriminate in terms of intensity and roughness (pulse frequency). Results showed that both parameters had a significant effect on perception. Intensity showed to have four distinguishable levels, whereas pulse frequency only had two levels that can be used to improve the design of *Electrotactons*.

5.2.3 Research Question 3

- *What levels of performance can be achieved when these parameters are combined to create Electrotactons to present multi-dimensional information (Experiments 3 & 6)?*

This question was explored with two experiments in Chapters 3 & 4. These experiments investigated the performance levels achieved for absolute identification of *Electrotactons* encoding three and two dimensions of information. Experiment 3 investigated the combination of the three electrotactile basic parameters pulse width, amplitude and pulse frequency to create three-dimensional *Electrotactons* to convey information about appointments. Pulse width had two levels encoding the type of the appointment, amplitude had two levels encoding the importance of the appointment, and pulse frequency had three levels encoding the time until the appointment. Results showed that the overall recognition rate was 38.19%, the recognition rate for pulse width was 71.67%, amplitude 70.27% and pulse frequency 66.36%. Participants commented that they couldn't distinguish between cues containing high pulse width and low amplitude and cues containing low pulse width and high amplitude, causing confusion between both parameters. It is hard to consider this interaction between pulse width and amplitude to be temporal integration. As the electrical current goes through the shallow layer of the skin and reaches the deepest mechanoreceptor, it will also co-activate the shallower mechanoreceptors [17]. In comparison, it is possible to stimulate individual mechanoreceptors in vibrotactile selectively [114]. Furthermore, the two ends of were recognised more accurately for pulse frequency than the middle one, leading to a low recognition rate.

These results indicated that using pulse width and amplitude separately was ineffective in conveying information and that combining them into one parameter called intensity may improve performance. In addition, reducing the levels of pulse frequency from three to two may also improve performance and make cues easy to distinguish between, but at the cost of the parameter space. However, using a wider pulse frequency might maintain the number of levels. To investigate these suggestions, Experiment 6 was conducted. In Experiment 6, the combination of the two electrotactile parameters intensity and pulse frequency to create two-dimensional *Electrotactons* to convey information about an appointment was investigated. Intensity had three levels encoding the importance of the appointment, and pulse frequency had three levels encoding the type of the appointment. Results showed that the overall recognition rate was 65.31%, a 27% improvement compared to Experiment 3 due to reducing the dimension of information from three to two. For individual parameters, intensity had a 68.68% recognition rate and pulse frequency had 94.41%. The medium intensity level caused participants to confuse it with high and low levels and removing it would boost performance. However, this is at the cost of reducing the size of the design space. Whereas all levels of pulse frequency performed very well indicating that using a wider range was a better choice for the parameter when compared to the one used in Experiment 3.

5.3 Descriptive Words

As the calibrations phase improved over the subjective perception experiments 1, 2, & 4 in terms of detection and discomfort thresholds, the number of descriptive words circled by participants kept increasing from 217 to 264 words. However, in Experiment 5 which compared two cues if they were the same or different, and Experiment 6 where the improved *Electrotactons* design was tested, the number of descriptive words circled by participants was 212 and 202 words respectively. This could suggest that when measuring subjective perception, participants were evoked to circle more descriptive words compared to when recording recognition rates. Across all experiments, the word gentle was the most circled in three experiments associated with low strength cues. The word stronger was the most circled in two experiments associated with high strength cues.

5.4 Contributions and Recommendations

This thesis contributes novel insights into the design of electrotactile feedback. The main contributions are:

1- Design electrotactile cues that evoke desired sensations.

2- The first steps of designing and evaluating *Electrotactons* for conveying information.

Design recommendations have been extracted from the findings of the thesis and are summarised below. These recommendations are based on observations to aid designers who wish to use electrotactile feedback to create effective cues with clearly different levels of perceived sensation. Moreover, providing insights into how to construct *Electrotactons* in their interfaces.

5.4.1 Recommendations for calibrating electrotactile feedback (Chapters 3 & 4):

Calibrating detection and discomfort thresholds for electrotactile feedback: Calibration for electrotactile feedback should have two steps. The first step is calibrating the initial detection and discomfort values for individual parameters such as pulse width and amplitude. The second step is calibrating intensity (pulse width and amplitude together) by finding the detection threshold before the discomfort threshold to avoid masking effects and have a more accurate range for intensity. Pulse frequency is recommended to be kept at 20 PPS for the duration of the calibration process as it guarantees the detectability of both pulse width and amplitude.

5.4.2 Design recommendations for electrotactile cues with desired sensation (Chapter 3):

To create cues with a clear level of sensation through the manipulation of electrotactile feedback parameters, the following recommendations should be considered:

Pulse width: When manipulating pulse width to create effective cues based on the calibration values, designers can choose from three levels of urgency, annoyance and arousal, two for valence to create cues that elicit a particular response;

Amplitude: When manipulating amplitude to create effective cues based on the calibration values, designers can choose from three levels of urgency, annoyance, arousal and valence to create cues that elicit a particular response;

Intensity (Combining Pulse width and Amplitude): When manipulating intensity to create effective cues based on the calibration values, designers can choose from five levels of urgency, three for annoyance, two for valence and three for arousal, to create cues that elicit a particular response.

Pulse frequency: When manipulating pulse frequency to create effective cues based on the calibration values, designers can choose from five levels of urgency, annoyance and arousal, while valence had only three pairs of pulse frequencies to create cues that elicit a particular response. Moreover, designers should be aware that users can not distinguish between pulse frequencies above 30 PPS;

The difference in the number of levels between valence and other sensations, such as urgency, annoyance, and arousal in electrotactile feedback, may be attributed to the complexity of the valence dimension compared to the others. Valence is a more complex and nuanced sensation that involves a range of affective states, including positive and negative emotions [115]. In contrast, sensations such as urgency, annoyance, and arousal are more straightforward. Furthermore, while touch stimuli can have a strong emotional meaning and role in human-human communication, creating a clear and consistent rating scale for the valence dimension in electrotactile feedback may be more challenging. However, further research may be needed to understand the factors that contribute to this difference fully.

5.4.3 Design Recommendations for multi-Dimensional *Electrotactons* (Chapter 3 & 4):

When designing multi-dimensional *Electrotactons* using basic electrotactile parameters such as pulse width, amplitude and pulse frequency, the following recommendations should be considered:

Pulse width and Amplitude: Designers should be aware when encoding information into three levels of both pulse width and amplitude. Cues with a high level of pulse width and low level of amplitude will be confused with a low level of pulse width and high level of amplitude. It is recommended to manipulate one of the parameters or combine them into a single parameter called intensity, but this will reduce the number of dimensions. When using intensity, it is recommended to use two distinguishable levels. The levels are high intensity (high pulse width-high amplitude) and low intensity (middle pulse width-low amplitude), as using a middle level will hinder the performance, but this will be at cost of the number of information conveyed.

Pulse frequency: Designers should be aware when encoding information into three levels of pulse frequencies. When the levels are in a narrow range, such as 2 PPS, 8 PPS and 16 PPS, the 8 PPS will cause the performance to hinder as users can not distinguish it from the other two. It is recommended to use only the two ends, 2 PPS and 16 PPS, when using a narrow pulse frequency range, but at the cost of the amount of information conveyed. Using a range of pulse frequencies, such as 2 PPS, 10 PPS and 90 PPS will maintain the three levels of information conveyed with a better performance.

Electrode sizes: When designing two-dimensional *Electrotactons* to be delivered to the palm, designers can choose between two different size electrodes (60x30mm or 32mm diameter) that fit their application depending on the electrode-skin contact area without worrying about the performance.

Body locations: When conveying information, designers can choose between three different body locations, such as palm, wrist, and upper arm and maintain the same performance, especially when using the small electrode size mentioned above to make it suitable for wearable devices. It is recommended that the stimulated area should not be above the muscle to avoid activating it, as the purpose is to stimulate the skin, not the muscle.

5.5 Limitations and Future Work

The experiments reported in this thesis explored how manipulating electrotactile parameters can influence subjective perception of different sensations and encode information in electrotactile messages called *Electrotactons*. While these experiments added significant knowledge to the field of electrotactile feedback perception and established the basis of electrotactile icon design, this section discusses some general limitations, along with ideas for future work.

5.5.1 Duration of Electrotactile Cues

The electrotactile cues were presented for one second when measuring subjective perception in this thesis. The effect of a longer or shorter duration of electrotactile feedback on the same sensations measured in this thesis is unknown. For instance, shorter cues might be less urgent and more pleasant, while longer cues might be more urgent and less pleasant. Future work should investigate different durations and what effect they have on subjective perception. Furthermore, the combination of different durations and intensities defines the parameter rhythm as discussed in Section 2.3.7, and it has the potential to contribute to the design space of *Electrotactons*.

5.5.2 Multi Modality

The main focus of this thesis was one tactile modality; electrotactile. Combing electrotactile with other tactile modalities such as vibrotactile or audio and investigating its effect on subjective perception could be explored in future work. In addition, future work could also look into the combination of such modalities to create multimodal cues to convey information, but it needs to consider that multimodal feedback can cause sensory overload if combined without having a good understanding of each modality alone [116].

5.5.3 Electrode Size

This thesis used off-the-shelf self-adhesive electrodes that come in specific sizes. The two different electrode sizes used in the experiments were described in Section 3.3 and Section 4.4.1, and the findings reported may be specific to these electrodes. As discussed in Section 2.2.4, the size of the electrodes dictates the amount of the electrical current delivered to the skin, thus, changing the perception. Future work could investigate different size electrodes, especially smaller ones that allow for a high-resolution electrotactile display that can be placed on different body locations without muscle activation.

5.5.4 Calibration

The calibration set-up used in this thesis was based on the capability of the electrical stimulator. The detection and discomfort thresholds were measured manually for each participant at the start of each experiment and when removing and reapplying the electrodes at the same place or different places on the body as the skin impedance differs. Having an electrical circuit as a part of the stimulating machine that monitors skin impedance in real-time will ensure that the pulse width and amplitude values are always within the thresholds making the calibration phase more efficient [16] as the impedance depends on body location, the distance between the electrodes and the condition of the skin.

5.5.5 Body Location

The subjective perception in this thesis was investigated on the palm as the purpose was to emulate handheld devices, and the performance of *Electrotactons* was investigated on the palm, wrist and upper arm to add knowledge to design distinguishable notifications in wearable devices. The findings reported may be specific to these body locations as subjective perception may differ based on the sink type. Investigating other body locations might be limited as electrotactile feedback requires direct contact between the skin and the electrodes.

5.5.6 Participant Number and Demographic

The number of participants in the experiments of this thesis was small and similar in age and gender, as the experiments aim to establish an understanding of the effect of electrotactile feedback on subjective perception and create *Electrotactons*. Furthermore, most participants were recruited primarily within the university with no specific focus on diverse demographics or backgrounds. Having more participants from a more diverse group in the electrotactile perception investigation could yield important insights. For instance, as skin impedance increases with age [117], it could have an influence on perception.

5.6 Conclusion

Electrotactile stimulation is a novel form of haptic feedback that can be used to evoke different sensations and convey information. This thesis offers several insights into aspects of electrotactile feedback. The first is how manipulating electrotactile parameters influences the functional aspects of alertness and emotions. The findings provide a clear understanding of the parameter space for designing cues that elicit desired responses. The second is the first detailed investigation into the design of structured electrotactile cues called *Electrotactons*, which are electrotactile icons that can be used to encode information in a structured and abstract way. The findings provide a benchmark against which the results of future research on *Electrotactons* can be measured. Interface designers can use these novel cues in areas such as mobile and wearable devices to design distinguishable notifications and messages.

Appendix A

Appendix

A.1 Experiment 1

A.1.1 Experiment 1: Information Sheet

PARTICIPANT INFORMATION SHEET

Date: 11/06/2019

Title: Investigating Electrotactile Feedback on The Hand

You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Purpose of the study:

The purpose of the study is to investigate the perceived urgency, annoyance, arousal and valance from participants through electrotactile stimulations delivered to their palms.

Why have you been chosen:

You have been chosen because you are an adult, and your health is in good condition.

Do I have to take part?

Participation in the study is voluntary. You may decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

You will sit at a table, upon which is a PC. I will measure your hand by placing it on a piece of paper. Then, you will rest your non-dominant hand on a table, and I will spray a contact and cleansing water solution on your palm and dray it out with a tissue, then two electrodes will be placed on your palm to deliver the stimulus so that you can use your dominant hand to control the PC with the mouse.

In Task 1, I will calibrate the parameters for you that will be used to create gentle stimuli.

In Task 2, you will be presented with stimuli in a random order in four steps. The first step I will present ten stimuli, and after each stimulus, you will be presented pop-up window on the screen asking you how the stimulus made you feel. Once you finish, you will be presented with the next stimulus. After this, there will be a short break, and step two will start, which will be the same process as step one, but with 36 stimuli presented. This will be followed by a break, then step three and four will start, which are the same as step two.

Once you have completed both tasks, you will be asked some questions about your experience and your answers will be recorded. You will have the chance to ask any questions you may have before you finish.

What are the possible disadvantages and risks of taking part?

You could experience mild discomfort from the gentle electrotactile stimulus. To help with this, you will be in control of when you receive each new stimulus and allowed to take breaks if you wish.

What are the benefits of taking part?

You will be paid £6 for one hour of your time, and you will have the chance to learn the outcomes of the following study.

Will my taking part in this study be kept confidential?

All information collected, or responses provided, during the course of the research will be kept strictly confidential. You will be identified by an ID number which in no way will be connected to you. Please note that assurances on confidentiality will be strictly adhered to unless evidence of serious harm, or risk of serious harm, is uncovered. In such cases, the University may be obliged to contact relevant statutory bodies/agencies.

What will happen to the results of the research study?

The results will be held and owned by the researcher and the University of Glasgow, and it might be used for publication. The results can be outlined to the participants whenever they become available. The participants won't be identified in any report or publication.

Who is organising and funding the research?

This research is funded by the School of Computing Science.

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee.

Contact for Further Information:

You can contact the researcher of this study Yosuef Alotaibi via the following methods:

Email: y.alotaibi.1@research.gla.ac.uk

Supervisor details: Professor Stephen Brewster (Stephen.Brewster@glasgow.ac.uk , 0141-330-4966)

Thank you for volunteering to take part in this study.

A.1.2 Experiment 1: Consent Form

Investigating Electrotactile Feedback On The Hand

CONSENT FORM

Before agreeing to this consent form, you should have been given an information sheet to read, which explains the general purpose of this study and the tasks it involves. If you did not receive this, please inform the experimenter. Throughout the study, the experimenter will explain in detail the different activities that you will be completing, but if you have any questions or require medical attention, please do not hesitate to ask.

In this study, you are required to receive gentle electrotactile stimuli on your non-dominant palm and record your reactions using a computer with your dominant hand. The systems you interact with will not ask personal information and all data are recorded anonymously. The data will be treated as confidential and kept in secure storage at all times. The material may be used in future academic research and publications, both print and online. The study will take appro**x**imately **60 minutes** to complete, and **£8** Amazon voucher will be sent to your email at the end. If you are a student, **no course credits** will be awarded for completing this study. You can withdraw from the study at any time. Lastly, to take part in this study, the following criteria must be met:

- I am at least 18 years old.
- I have no sensory impairments in any of my hands.

Experimenter details: Mr Yosuef Alotaibi **(**y.alotaibi.1@research.gla.ac.uk, xxxxxxxxxxx)

Supervisor details: Professor Stephen Brewster (Stephen.Brewster@glasgow.ac.uk, 0141-330-4966)

This study has been approved by the Ethics Committee (300180256).

By signing this form, you have read the conditions stated above and agree to take part in the study.

FULL NAME: ____

Age: _____

Gender: Male Female

SIGNATURE: ____

DATE: ____

EMAIL (if you want to be added to the participant's pool):

____

University of Glasgow | School of Computing Science

GIST Glasgow Interactive Systems Group

A.2 Experiment 2

A.2.1 Experiment 2: Information Sheet

PARTICIPANT INFORMATION SHEET

Date: 16/09/2019

Title: Investigating Electrotactile Feedback on the Hand

You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Purpose of the study:

The purpose of the study is to investigate the perceived urgency, annoyance, arousal and valence from participants through electrotactile stimulations delivered to their palms.

Why have you been chosen:

You have been chosen because you are an adult, and your health is in good condition.

Do I have to take part?

Participation in the study is voluntary. You may decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

You will sit at a table, upon which is a PC. You will rest your non-dominant hand on a table, and a spray of cleansing water solution will be used on your palm, then two electrodes will be placed on your palm to deliver the stimulus so that you can use your dominant hand to control the PC with the mouse.

In Task 1, I will calibrate the parameters for you that will be used to create gentle stimuli.

In Task 2, you will be presented with stimuli in a random order in five steps. In the first step I will present 15 stimuli, and after each stimulus, you will be presented with a pop-up window on the screen asking you how the stimulus made you feel. Once you finish, you will be presented with the next stimulus. After this, there will be a short break, and step two will start, which will be the same process as step one, but with 27 stimuli presented. This will be followed by a break, then step three and so on, which are the same as step two.

Once you have completed both tasks, you will be asked some questions about your experience and your answers will be recorded. You will have the chance to ask any questions you may have before you finish.

What are the possible disadvantages and risks of taking part?

You could experience mild discomfort from the gentle electrotactile stimulus. To help with this, you will be in control of when you receive each new stimulus and allowed to take breaks if you wish.

What are the benefits of taking part?

You will be paid £8 for one hour of your time, and you will have the chance to learn the outcomes of the following study.

Will my taking part in this study be kept confidential?

All information collected, or responses provided, during the course of the research will be kept strictly confidential. You will be identified by an ID number which in no way will be connected to you. Please note that assurances on confidentiality will be strictly adhered to unless evidence of serious harm, or risk of serious harm, is uncovered. In such cases, the University may be obliged to contact relevant statutory bodies/agencies.

What will happen to the results of the research study?

The results will be held and owned by the researcher and the University of Glasgow, and it might be used for publication. The results can be outlined to the participants whenever they become available. The participants won't be identified in any report or publication.

Who is organising and funding the research?

This research is funded by the School of Computing Science.

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee (Application Number 300190008).

Contact for Further Information:

You can contact the researcher of this study Yosuef Alotaibi via the following methods:

Email: y.alotaibi.1@research.gla.ac.uk

Supervisor details: Professor Stephen Brewster (Stephen.Brewster@glasgow.ac.uk , 0141-330-4966)

Thank you for volunteering to take part in this study.

A.2.2 Experiment 2: Consent Form

Investigating Electrotactile Feedback On The Hand

CONSENT FORM

Before agreeing to this consent form, you should have been given an information sheet to read, which explains the general purpose of this study and the tasks it involves. If you did not receive this, please inform the experimenter. Throughout the study, the experimenter will explain in detail the different activities that you will be completed, but if you have any questions or require medical attention, please do not hesitate to ask.

In this study, you are required to receive gentle electrotactile stimuli on your non-dominant palm and record your reactions using a computer with your dominant hand. The systems you interact with will not ask personal information and all data are recorded anonymously. The data will be treated as confidential and kept in secure storage at all times. The material may be used in future academic research and publications, both print and online. The study will take approximately **60 minutes** to complete, and **£8** Amazon voucher will be sent to your email at the end. If you are a student, **no course credits** will be awarded for completing this study. You can withdraw from the study at any time. Lastly, to take part in this study, the following criteria must be met:

- I am at least 18 years old.
- I have no sensory impairments in any of my hands.

Experimenter details: Mr Yosuef Alotaibi (y.alotaibi.1@research.gla.ac.uk, xxxxxxxxxxx)

Supervisor details: Professor Stephen Brewster (Stephen.Brewster@glasgow.ac.uk, 0141-330-4966)

This study has been approved by the Ethics Committee (300180256).

By signing this form, you have read the conditions stated above and agree to take part in the study.

FULL NAME: ______________________________

Age: _____

Gender: Male Female

SIGNATURE: ______________________________

DATE: ______________________________

EMAIL (if you want to be added to the participant's pool):

____

University of Glasgow | School of Computing Science

GIST GLASGOW INTERACTIVE SYSTEMS GROUP

A.3 Experiment 3

A.3.1 Experiment 3: Information Sheet

PARTICIPANT INFORMATION SHEET

Date: 05/09/2020

Title: Conveying Information using Electrotactile Stimuli.

You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Purpose of the study:

The purpose of the study is to investigate your perceived sensations and recognition rate of information through electrotactile stimulation delivered to your palm.

Why have you been chosen:

You have been chosen because you are an adult, and your health is in good condition.

Do I have to take part?

Participation in the study is voluntary. You may decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

You will be collected from outside the building by the experimenter to sign in and shown to the study location. 2m separation will be maintained. Once in the room, the experimenter and you will be >2m apart. If the experimenter need to be closer than 2m, he/she will wear a mask, visor and gloves. Then move back to >2m distance.

You will sit at a table, upon which is a PC. You will rest your non-dominant hand on the pad, and a spray of cleansing water solution will be used on your palm, then two electrodes will be placed on your palm to deliver the stimuli so that you can use your dominant hand to control the PC with the mouse.

In Task 1, I will calibrate the parameters for you that will be used to create gentle stimuli.

In Task 2, you will be presented with stimuli in a random order in five steps. In each step, I will present nine stimuli, and after each stimulus, you will be presented with a pop-up window on the screen asking you how the stimulus made you feel. Once you finish, you will be presented with the next stimulus. After this, there will be a short break, and step two will start, which will be the same process as step one. This will be followed by a break, then step three and so on.

Once you have completed the five steps, you will take a 5 min break and remove the electrodes from your palm.

In Task 3, I will calibrate the parameters for you again.

In task 4, you will be briefed about what kind of information I am trying to convey to you. After that, you will practice the stimuli through an interface having all possible combination of information. To complete the practice, you need to press each combination at least twice.

In Task 5, you will be presented with stimuli in a random order in 3 sessions. In each session, I will present 12 stimuli, and after each stimulus, you will be presented with a pop-up window on the screen asking you what kind of information was presented to you. Once you answered, you will be presented with the next stimulus and so on. Between the steps, there will be a short break.

Once you have completed all tasks, you will be asked some questions about your experience and your answers will be recorded. After that, you will be asked to circle or add some words based on the level of intensity of the stimuli. You will have the chance to ask any questions you may have before you finish.

What are the possible disadvantages and risks of taking part?

You could experience mild discomfort from the gentle electrotactile stimulus. To help with this, you will be in control of when you receive each new stimulus and allowed to take breaks if you wish.

What are the benefits of taking part?

You will be paid £10 for one hour of your time, and you will have the chance to learn the outcomes of the study.

Will my taking part in this study be kept confidential?

All information collected, or responses provided, during the course of the research will be kept strictly confidential. You will be identified by an ID number which in no way will be connected to you. Please note that assurances on confidentiality will be strictly adhered to unless evidence of serious harm, or risk of serious harm, is uncovered. In such cases, the University may be obliged to contact relevant statutory bodies/agencies.

What will happen to the results of the research study?

The results will be held by the researcher and the University of Glasgow and might be used for publication. The results can be outlined to the participants whenever they become available. The participants won’t be identified in any report or publication.

Who is organising and funding the research?

This research is funded by the School of Computing Science.

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee (Application Number 300190141).

Contact for Further Information:

You can contact the researcher of this study Yosuef Alotaibi via the following methods:

Email: y.alotaibi.1@research.gla.ac.uk

Supervisor details: Professor Stephen Brewster (Stephen.Brewster@glasgow.ac.uk , 0141-330-4966)

Thank you for volunteering to take part in this study.

A.3.2 Experiment 3: Consent Form

Conveying Information using Electrotactile Stimuli

CONSENT FORM

Before signing this consent form, you should have been given an Information Sheet to read, which explains the general purpose of this study and the tasks it involves. If you did not receive this, please inform the experimenter. Throughout the study, the experimenter will explain in detail the different activities that you will be completing, but if you have any questions or feel unwell, please do not hesitate to ask.

In this study, you will receive gentle electrotactile stimuli on your non-dominant palm, and record your reactions using a computer mouse with your dominant hand. The systems you interact with will not ask personal information and all data are recorded anonymously. All the equipment has been cleaned according to the University's COVID-19 protocols. The data will be treated as confidential and kept in secure storage. The material may be used in future academic research and publications, both print and online.

The study will take approximately **60 minutes** to complete, and an **£10** Amazon voucher will be sent to your email at the end. If you are a student, no course credits will be awarded for completing this study. You can withdraw from the study at any time. Lastly, to take part in this study, the following criteria must be met:

- I am at least 18 years old
- I have no sensory impairments in my hands

Please inform the experimenter if you have been diagnosed with, or in a close contact with someone who was diagnosed with, COVID-19 within the past two weeks, or for the next two weeks. This is required for the Government's Track and Trace procedures.

Experimenter details: Mr Yosuef Alotaibi (y.alotaibi.1@research.gla.ac.uk, xxxxxxxxxxx)

Supervisor details: Prof Stephen Brewster (Stephen.Brewster@glasgow.ac.uk, 0141 330 4966)

This study has been approved by the CoSE Ethics Committee (300190275).

By signing this form, you have read the conditions stated above and agree to take part in the study.

FULL NAME: ____

Age: _____

Gender: Male Female Non-binary Transgender Intersex Prefer not to say
Other : ……….

SIGNATURE: ___________________________DATE: ________________________

EMAIL (if you want to be added to our participant pool to take part in future studies):

____

University of Glasgow | School of Computing Science
GIST Glasgow Interactive Systems Group

A.4 Experiment 4

A.4.1 Experiment 4: Information Sheet

PARTICIPANT INFORMATION SHEET

Date: 05/09/2020

Title: Conveying Information using Electrotactile Stimuli.

You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Purpose of the study:

The purpose of the study is to investigate your perceived sensations and recognition rate of information through electrotactile stimulation delivered to your palm.

Why have you been chosen:

You have been chosen because you are an adult, and your health is in good condition.

Do I have to take part?

Participation in the study is voluntary. You may decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

You will be collected from outside the building by the experimenter to sign in and shown to the study location. 2m separation will be maintained. Once in the room, the experimenter and you will be >2m apart. If the experimenter need to be closer than 2m, he/she will wear a mask, visor and gloves. Then move back to >2m distance.

You will sit at a table, upon which is a PC. You will rest your non-dominant hand on the pad, and a spray of cleansing water solution will be used on your palm, then two electrodes will be placed on your palm to deliver the stimuli so that you can use your dominant hand to control the PC with the mouse.

In Task 1, I will calibrate the parameters for you that will be used to create gentle stimuli.

In Task 2, you will be presented with stimuli in a random order in five steps. In each step, I will present nine stimuli, and after each stimulus, you will be presented with a pop-up window on the screen asking you how the stimulus made you feel. Once you finish, you will be presented with the next stimulus. After this, there will be a short break, and step two will start, which will be the same process as step one. This will be followed by a break, then step three and so on.

Once you have completed the five steps, you will take a 5 min break and remove the electrodes from your palm.

In Task 3, I will calibrate the parameters for you again.

In task 4, you will be briefed about what kind of information I am trying to convey to you. After that, you will practice the stimuli through an interface having all possible combination of information. To complete the practice, you need to press each combination at least twice.

In Task 5, you will be presented with stimuli in a random order in 3 sessions. In each session, I will present 12 stimuli, and after each stimulus, you will be presented with a pop-up window on the screen asking you what kind of information was presented to you. Once you answered, you will be presented with the next stimulus and so on. Between the steps, there will be a short break.

Once you have completed all tasks, you will be asked some questions about your experience and your answers will be recorded. After that, you will be asked to circle or add some words based on the level of intensity of the stimuli. You will have the chance to ask any questions you may have before you finish.

What are the possible disadvantages and risks of taking part?

You could experience mild discomfort from the gentle electrotactile stimulus. To help with this, you will be in control of when you receive each new stimulus and allowed to take breaks if you wish.

What are the benefits of taking part?

You will be paid £10 for one hour of your time, and you will have the chance to learn the outcomes of the study.

Will my taking part in this study be kept confidential?

All information collected, or responses provided, during the course of the research will be kept strictly confidential. You will be identified by an ID number which in no way will be connected to you. Please note that assurances on confidentiality will be strictly adhered to unless evidence of serious harm, or risk of serious harm, is uncovered. In such cases, the University may be obliged to contact relevant statutory bodies/agencies.

What will happen to the results of the research study?

The results will be held by the researcher and the University of Glasgow and might be used for publication. The results can be outlined to the participants whenever they become available. The participants won't be identified in any report or publication.

Who is organising and funding the research?

This research is funded by the School of Computing Science.

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee (Application Number 300190141).

Contact for Further Information:

You can contact the researcher of this study Yosuef Alotaibi via the following methods:

Email: y.alotaibi.1@research.gla.ac.uk

Supervisor details: Professor Stephen Brewster (Stephen.Brewster@glasgow.ac.uk , 0141-330-4966)

Thank you for volunteering to take part in this study.

A.4.2 Experiment 4: Consent Form

Conveying Information using Electrotactile Stimuli

CONSENT FORM

Before signing this consent form, you should have been given an Information Sheet to read, which explains the general purpose of this study and the tasks it involves. If you did not receive this, please inform the experimenter. Throughout the study, the experimenter will explain in detail the different activities that you will be completing, but if you have any questions or feel unwell, please do not hesitate to ask.

In this study, you will receive gentle electrotactile stimuli on your non-dominant palm, and record your reactions using a computer mouse with your dominant hand. The systems you interact with will not ask personal information and all data are recorded anonymously. All the equipment has been cleaned according to the University's COVID-19 protocols. The data will be treated as confidential and kept in secure storage. The material may be used in future academic research and publications, both print and online.

The study will take approximately **60 minutes** to complete, and an **£10** Amazon voucher will be sent to your email at the end. If you are a student, no course credits will be awarded for completing this study. You can withdraw from the study at any time. Lastly, to take part in this study, the following criteria must be met:

- I am at least 18 years old
- I have no sensory impairments in my hands

Please inform the experimenter if you have been diagnosed with, or in a close contact with someone who was diagnosed with, COVID-19 within the past two weeks, or for the next two weeks. This is required for the Government's Track and Trace procedures.

Experimenter details: Mr Yosuef Alotaibi (y.alotaibi.1@research.gla.ac.uk, xxxxxxxxxxx)

Supervisor details: Prof Stephen Brewster (Stephen.Brewster@glasgow.ac.uk, 0141 330 4966)

This study has been approved by the CoSE Ethics Committee (300190275).

By signing this form, you have read the conditions stated above and agree to take part in the study.

FULL NAME: ____

Age: _____

Gender: Male Female Non-binary Transgender Intersex Prefer not to say
Other : ……….

SIGNATURE: ____________________________ DATE: ________________________

EMAIL (if you want to be added to our participant pool to take part in future studies):

____

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A.5 Experiment 5

A.5.1 Experiment 5: Information Sheet

PARTICIPANT INFORMATION SHEET

Date: 09/08/2021

Title: Evaluating Electrotactile Parameters.

You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Purpose of the study:

The purpose of the study is to investigate if participants can distinguish between two electrotactile stimuli being delivered to their palms.

Why have you been chosen:

You have been chosen because you are an adult, and your health is in good condition.

Do I have to take part?

Participation in the study is voluntary. You may decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

You will sit at a table, upon which is a PC. Then, will rest your non-dominant hand on a table, and I will spray a contact and cleansing water solution on your palm and dry it out with a tissue, then two electrodes will be placed on your palm to deliver the stimulus so that you can use your dominant hand to control the PC with the mouse.

In Task 1, I will calibrate the parameters for you that will be used to create gentle stimuli.

In Task 2, you will be presented with a combination of two stimuli in three steps. In each step, I will present 72 pairs of stimuli in a random order, and after each pair, you will be presented with a pop-up window on the screen asking which stimulus feels more intense? After this step, there will be a short break, and step two will start, which will be the same process as step one. A break will follow this, then step three. Then a five-minute break.

Task 3 will be the same as Task 2, but Task 3 will have 30 pairs of stimuli, and the pop-up window will ask which stimulation feels the rougher?

Finally, task 4 will be asking you some questions and record your answers about the experiment. In addition, you will be given a paper that has words to choose from to describe the stimuli that you will experience. You will have the chance to ask any questions you may have before you finish.

What are the possible disadvantages and risks of taking part?

You could experience mild discomfort from the gentle electrotactile stimulus. To help with this, you will be in control of when you receive each new stimulus and allowed to take breaks if you wish.

What are the benefits of taking part?

You will be paid £10 in Amazon voucher for one hour of your time, and you will have the chance to learn the outcomes of the following study.

Will my taking part in this study be kept confidential?

All information collected, and responses provided, during the course of the research will be kept strictly confidential. You will be identified by an ID number which in no way will be connected to you. Please note that assurances on confidentiality will be strictly adhered to unless evidence of serious harm, or risk of serious harm, is uncovered. In such cases, the University may be obliged to contact relevant statutory bodies/agencies.

What will happen to the results of the research study?

The results will be held and owned by the researcher and the University of Glasgow, and they might be used for publication. The results can be outlined to the participants whenever they become available. The participants won't be identified in any report or publication.

Who is organising and funding the research?

This research is funded by the School of Computing Science.

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee.

Contact for Further Information:

You can contact the researcher of this study Yosuef Alotaibi via the following methods:

Email: y.alotaibi.1@research.gla.ac.uk

Supervisor details: Professor Stephen Brewster (Stephen.Brewster@glasgow.ac.uk , 0141-330-4966)

Thank you for volunteering to take part in this study.

A.5.2 Experiment 5: Consent Form

Evaluating Electrotactile Parameters

CONSENT FORM

Before signing this consent form, you should have been given an Information Sheet to read, which explains the general purpose of this study and the tasks it involves. If you did not receive this, please inform the experimenter. Throughout the study, the experimenter will explain in detail the different activities that you will be completing, but if you have any questions or feel unwell, please do not hesitate to ask.

In this study, you are required to receive gentle electrotactile stimuli on your non-dominant palm and record your reactions using a computer with your dominant hand. The systems you interact with will not ask personal information and all data are recorded anonymously. All the equipment has been cleaned according to the University's COVID-19 protocols. The data will be treated as confidential and kept in secure storage. The material may be used in future academic research and publications, both print and online.

The study will take approx**x**imately **60 minutes** to complete, and an **£10** Amazon voucher will be sent to your email at the end. If you are a student, no course credits will be awarded for completing this study. You can withdraw from the study at any time. Lastly, to take part in this study, the following criteria must be met:

- I am at least 18 years old
- I have no sensory impairments in my hands

Please inform the experimenter if you have been diagnosed with, or in a close contact with someone who was diagnosed with, COVID-19 within the past two weeks, or for the next two weeks. This is required for the Government's Track and Trace procedures.

Experimenter details: Mr Yosuef Alotaibi **(**y.alotaibi.1@research.gla.ac.uk, xxxxxxxxxxx)

Supervisor details: Prof Stephen Brewster (Stephen.Brewster@glasgow.ac.uk, 0141 330 4966)

This study has been approved by the CoSE Ethics Committee (300200268**).**

By signing this form, you have read the conditions stated above and agree to take part in the study.

FULL NAME: ____

Age: _____

Gender: Male Female Non-binary Transgender Intersex Prefer not to say
Other : ……….

SIGNATURE: ____________________________DATE: ________________________

I would like to add my email address to the participants pool to take part in future studies ☐

University of Glasgow | School of Computing Science

GIST GLASGOW INTERACTIVE SYSTEMS GROUP

A.6 Experiment 6

A.6.1 Experiment 6: Information Sheet

PARTICIPANT INFORMATION SHEET

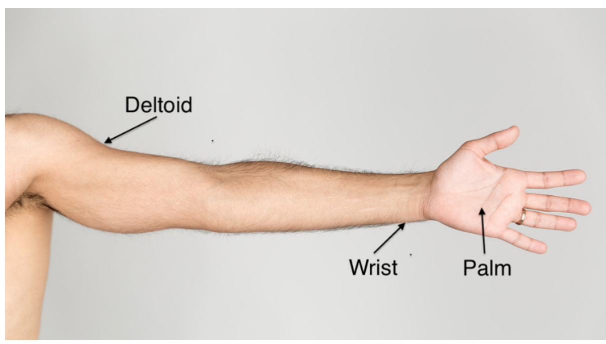
Date: 1/11/2021

Title: Evaluating two dimensional Electrotactons.

You are being invited to take part in a research study. Before you decide, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Purpose of the study:

The purpose of the study is to investigate if participants can recognize two pieces of information through electrotactile stimuli being delivered to three body locations: palm, wrist, and deltoid as shown in the picture below.



Why have you been chosen:

You have been chosen because you are an adult, and your health is in good condition.

Do I have to take part?

Participation in the study is voluntary. You may decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason.

What will happen to me if I take part?

You will sit at a table, upon which is a PC. Then, you will rest your non-dominant hand on a table, and I will spray a contact and cleansing water solution on your palm and dry it out with a tissue, then two electrodes will be placed on your palm to deliver the stimulus so that you can use your dominant hand to control the PC with the mouse.

In Task 1, I will calibrate the parameters for you that will be used to create gentle stimuli.

In Task 2, you will be briefed about what kind of information I am trying to convey to you. After that, you will practice the stimuli through an interface having all possible combinations of information until you feel confident distinguishing between them. To complete the practice, you need to press each combination at least twice.

In Task 3, you will be presented with stimuli in a random order in 2 sessions. In each session, I will present 18 stimuli, and after each stimulus, you will be presented with a pop-up window on the screen asking you what kind of information was presented to you. Once you answered, you will be presented with the next stimulus and so on. Between the sessions, there will be a short break.

After this, all Tasks will be repeat with smaller electrodes on the palm. Then, with the small electrodes, repeat all Tasks on the wrist, then the deltoid.

Finally, we will be asking you some questions and record your answers about the experiment. In addition, you will be given a paper that has words to choose from to describe the stimuli that you will experience. You will have the chance to ask any questions you may have before you finish.

What are the possible disadvantages and risks of taking part?

You could experience mild discomfort from the gentle electrotactile stimulus. To help with this, you will be in control of when you receive each new stimulus and allowed to take breaks if you wish.

What are the benefits of taking part?

You will be paid £10 in Amazon voucher for one hour of your time, and you will have the chance to learn the outcomes of the following study.

Will my taking part in this study be kept confidential?

All information collected, and responses provided, during the course of the research will be kept strictly confidential. You will be identified by an ID number which in no way will be connected to you. Please note that assurances on confidentiality will be strictly adhered to unless evidence of serious harm, or risk of serious harm, is uncovered. In such cases, the University may be obliged to contact relevant statutory bodies/agencies.

What will happen to the results of the research study?

The results will be held and owned by the researcher and the University of Glasgow, and they might be used for publication. The results can be outlined to the participants whenever they become available. The participants won't be identified in any report or publication.

Who is organising and funding the research?

This research is funded by the School of Computing Science.

Who has reviewed the study?

The project has been reviewed by the College Ethics Committee.

Contact for Further Information:

You can contact the researcher of this study Yosuef Alotaibi via the following methods:

Email: y.alotaibi.1@research.gla.ac.uk

Supervisor details: Professor Stephen Brewster (Stephen.Brewster@glasgow.ac.uk , 0141-330-4966)

Thank you for volunteering to take part in this study.

A.6.2 Experiment 6: Consent Form

Evaluating two dimensional Electrotactons

CONSENT FORM

Before signing this consent form, you should have been given an Information Sheet to read, which explains the general purpose of this study and the tasks it involves. If you did not receive this, please inform the experimenter. Throughout the study, the experimenter will explain in detail the different activities that you will be completing, but if you have any questions or feel unwell, please do not hesitate to ask.

In this study, you are required to receive gentle electrotactile stimuli on your non-dominant palm, wrist and deltoid and record your reactions using a computer with your dominant hand. The systems you interact with will not ask personal information and all data are recorded anonymously. All the equipment has been cleaned according to the University's COVID-19 protocols. The data will be treated as confidential and kept in secure storage. The material may be used in future academic research and publications, both print and online.

The study will take approximately **60 minutes** to complete, and an **£10** Amazon voucher will be sent to your email at the end. If you are a student, no course credits will be awarded for completing this study. You can withdraw from the study at any time. Lastly, to take part in this study, the following criteria must be met:

- I am at least 18 years old
- I have no sensory impairments in my hands

Please inform the experimenter if you have been diagnosed with, or in a close contact with someone who was diagnosed with, COVID-19 within the past two weeks, or for the next two weeks. This is required for the Government's Track and Trace procedures.

Experimenter details: Mr Yosuef Alotaibi (y.alotaibi.1@research.gla.ac.uk, xxxxxxxxxxx)

Supervisor details: Prof Stephen Brewster (Stephen.Brewster@glasgow.ac.uk, 0141 330 4966)

This study has been approved by the CoSE Ethics Committee (300210070).

By signing this form, you have read the conditions stated above and agree to take part in the study.

FULL NAME: ____

Age: _____

Gender: Male Female Non-binary Transgender Intersex Prefer not to say
Other : ……….

SIGNATURE: ______________________________DATE: __________________________

I would like to add my email address to the participants pool to take part in future studies ☐

University of Glasgow | School of Computing Science

GIST
Glasgow Interactive Systems Group

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