First Steps Towards Designing *Electrotactons*: Investigating Intensity and Pulse Frequency as Parameters for Electrotactile Cues

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Figure 1: A participant interacting with the interface during the experiment. The electrodes used for the electrotactile display are on the left hand and the right controls the experiment using a mouse.

ABSTRACT

Electrotactile stimulation is a novel form of haptic feedback. There is little work investigating its basic design parameters and how they create effective tactile cues. This paper describes two experiments that extend our knowledge of two key parameters. The first investigated the combination of pulse width and amplitude (*Intensity*) on sensations of urgency, annoyance, valence and arousal. Results showed significant effects: increasing *Intensity* caused higher ratings of urgency, annoyance and arousal but reduced valence. We established clear levels for differentiating each sensation. A second study then investigated *Intensity* and *Pulse Frequency* to find out 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. 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.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

Electrotactile feedback, interaction design, pulse frequency, intensity

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1 INTRODUCTION

Tactile feedback is a common modality used for interaction in many different devices, from mobile phones to cars. Through the sense of touch, rich information can be delivered to the skin when visual interaction is limited or inappropriate, for example. The most commonly used form is vibrotactile, generated by actuators that mechanically stimulate the skin. However, they can only generate a range of tactile experiences. In this paper, we study a novel alternative tactile technology: electrotactile stimulation. Two studies that

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increase our knowledge of how to design effective electrotactile cues are presented to expand options for cutaneous tactile displays.

Electrotactile feedback uses the flow of electrical current to stimulate the receptors in the skin directly. Controlling this electrical flow is achieved by manipulating parameters such as pulse width, amplitude and frequency [11], which can evoke sensations. The actuators used for electrotactile display are thin and small, flexible, light, durable, highly energy efficient, have no mechanical resonance, and are highly responsive, giving it advantages over the mechanical actuators used for vibrotactile displays [19, 21, 35–37]. It can also present dynamic patterns with different intensities very rapidly [16]. Electrotactile feedback has been investigated for its perception on different parts of the body [9, 20, 29]. Our previous work [2] has started to look at some of the basic parameters available to designers to begin to understand how they might be used in a more structured way. However, there is little research into how this feedback should be designed to communicate messages and the effects of the different parameters on users. This is important from an interaction design perspective, as without such knowledge, it cannot be used effectively.

We present two experiments to study key questions in the design of electrotactile feedback. In the first, we investigate the perception of electrotactile *Intensity*, controlled by manipulating pulse width and amplitude, in terms of subjective sensations of urgency, annoyance, valence and arousal. We also wanted to find out which of these two parameters had more influence on the perception of these sensations. Results showed that *Intensity* had a significant effect on the subjective sensations, with increased stimulation significantly increasing perceived urgency, annoyance and arousal, and decreasing valence. We identified the uniquely distinguishable levels for each of the sensations, which are important when designing with electrotactile cues. In addition, results showed that neither pulse width nor amplitude had a greater impact on perceived sensation than the other.

In the second study, we investigated the discriminability of *Intensity* to find out how many distinguishable levels were possible, vital for its use in interface design. This study also looked at the discriminability of *Pulse Frequency* to assess its potential as another useful design parameter. Our results showed that both *Intensity* and *Pulse Frequency* had a significant effect on perception, with four distinguishable levels of *Intensity* and two of *Pulse Frequency*.

This work presents the first steps towards creating *Electrotactons*, an alternative to the vibration-based Tactons [5] more commonly seen in the literature. Electrotactons use electrotactile stimulation to create structured, abstract, tactile messages for user interfaces. These have potential benefits over vibration based cues due to the greater flexibility of the actuators and could also be combined with them to create a rich set of tactile stimulation for Tacton design.

2 RELATED WORK

2.1 Electrotactile stimulation

To elicit a specific electrotactile sensation, it is important to understand the structure of the skin. There are four types of mechanoreceptors in the human skin [15], and each one is responsible for sensing a specific skin deformation. The four types (from the top of the skin) are Meissner corpuscles that react to low frequencies (20-70 [Hz]). Next comes the Merkel cells that react to pressure sensation, then Ruffini endings that react to shear deformation, and at the lowest level the Pacinian corpuscles that react to high frequencies (100-300[Hz]) [21]. When placing two electrodes on the skin, a weak current between them generates an electrical field, stimulating the afferent nerve fibres responsible for touch sensation [25]. Stimulating these mechanoreceptors under the skin with electrotactile stimulation elicits touch sensations that can be used for feedback and notifications in human-computer interaction.

Electrotactile feedback has been investigated to: elicit itchiness [29], render stereo smell by stimulating the trigeminal nerve [6], integrate the sense of touch into a prosthetic device [11], present object shapes [16], and to present verbal information [23]. This has been done by manipulating pulse frequency, pulse width amplitude, and type of electrical current. The electrical current can be biphasic which is a positive current (anodic) followed by an equal negative current (cathodic) to maintain the current balance, or monophasic which is either positive or negative current [26]. When a higher current intensity is used, it becomes electrical muscle stimulation (EMS) which has also been used for interaction [27].

Electrotactile feedback has many potential benefits as it can potentially elicit different kinds of sensations to the more common vibrotactile form. The electrodes required also have benefits over vibrotactile actuators as they are much more flexible, allowing them to be mounted in different ways on mobile phones, steering wheels, etc., offering new opportunities for haptics. However, there has been little work in HCI on how it can be used to create useful messages and notifications. To do this, we need to understand the perception of the basic parameters of stimulation.

Figure 2 shows the basic structure of the electrotactile signal, and the parameters that can be manipulated to encode information in an electrotactile cue. The intensity of the electrical stimulation is controlled by the amplitude (mA) and pulse width (μs). Pulse Frequency is the number of pulse per second (PPS) which can potentially generate different feelings of roughness [38]. These basic parameters could be then built into more complex cues, for example rhythmic pulses of different durations and intensities. However, to use these more complex cues, we need to understand the perception of the basic parameters first, which is our aim in this paper.

2.2 Electrotactile Feedback

Kajimoto *et al.* [22] developed a tactile vision substitution system [4] for people with visual impairments called HamsaTouch that used an electrotactile display on the palm to present images. The system 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, 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 rate for the horizontal and vertical bar were 90%, the circle 65% and the cross-shape 35%. This suggests that we can use the skin of the palm to create uniquely identified electrotactile cues for handheld devices. However, their

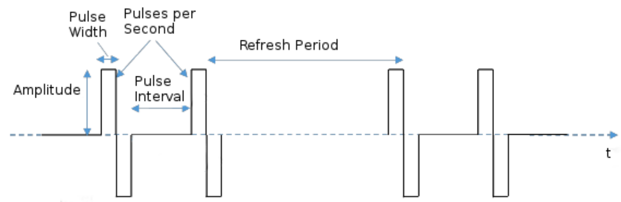

Figure 2: The structure of a biphasic electrotactile stimulus. The X axis is time, the Y axis is amplitude. The electrotactile stimulus increases from 0 (mA) to a specific value for some time and returns to 0. That time is the *pulse width.* The time between each stimulus is the *pulse interval.* The number of electrotactile pulses in a second is the*pulse frequency (pulses per second, PPS).*

electrotactile array would not be possible to use in many standard interaction scenarios. Our aim in this paper was to trial a much simpler setup with just 1 pair of electrodes on the palm (similar to the single vibration motor in a mobile phone) to see how we could use the basic electrotactile parameters.

Saito *et al.* [32] 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 [20]. In each trial, they randomly applied one type of the stimulations to one of the electrodes, 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 pressure and vibration sensations. We used a similar method of measuring subjective perception of different sensations in our study.

2.3 Electrotactile Intensity

To understand how the intensity (amplitude (mA) and pulse width (μs)) level of electrotactile stimulation affected perception, Kaczmarek *et al.* [17] conducted two experiments using a 7x7 49-point fingertip electrotactile display. In the first, they used eight intensity levels to present four patterns, and the stimulation range was from just below the sensation threshold to just below the discomfort threshold. The results showed that the recognition rate 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 useful cue design.

In our previous work [2], we conducted two studies to investigate how manipulating pulse frequency, pulse width and amplitude affected perceived sensations of urgency, annoyance, valence and arousal on the palm. In the first study, we manipulated pulse frequency and pulse width, keeping amplitude fixed. Six equally spaced frequencies in the range of 10Hz-110Hz and three levels (High, middle and low) of pulse width, based on individual calibration, were used. Results showed a significant effect of pulse frequency on urgency, annoyance and arousal, with a significant difference between 10Hz and the other frequencies, but with frequencies above 10Hz not clearly distinguishable from one another. Pulse width had a significant effect on all perceived sensations. The second study was identical to the first but manipulated pulse frequency and amplitude, keeping pulse width fixed. Nine equally spaced frequencies in the range 5Hz-45Hz and three levels (high, middle and low) of amplitude were used. Results showed that the range of frequencies between 5Hz - 25Hz had a significant effect on perceived sensations, but beyond 25Hz there were no further effects. In addition, the higher the level of amplitude, the higher the ratings of urgency, annoyance and arousal, and the lower the rating of valence. This work inspired the current studies. However, it did not establish the useful discriminable levels of the parameters investigated. It also did not investigate the combination of pulse width and amplitude, which Kaczmarek suggested was important for the intensity of an electrotactile cue and a key potential design parameter.

2.4 Electrotactile Roughness

In another study, Yoshimoto *et al.* [38] proposed and evaluated an electrotactile augmentation technique for roughness modulation of real materials. They confirmed that the perceived roughness at the finger pad can be altered using electrotactile augmentation through 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 finger tip when they explored the materials. Their results showed that pulse frequency had a significant effect on perceived roughness in the presence of the real materials. This experiment inspired us 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.

In a study into the quality of electrotactile stimulation, Graczyk *et al.* [12] 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. In each trial, participants were asked to rate perceived frequency 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. At higher pulse frequencies, perceived frequency flattened or decreased 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. In this paper, we will be evaluating a wider range of pulse frequencies and see how many levels can be discriminated to further examine this as a potential parameter for electrotacton design.

2.5 Tactons

Tactons, or tactile icons, are "structured, abstract, tactile messages which can be used to communicate information non-visually", Brown *et al.* [7]. There has been much work within HCI on vibrotactile Tactons (for example, [3, 10, 13, 14, 24]) using mechanical actuators for stimulation. Brown 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. Our aim is to create an electrotactile version of Tactons, *Electrotactons*, taking the same approach.

In a study investigating the perception of vibrotactile roughness, Brown *et al.* [7] 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. In each task, participants were presented with two stimuli in a row and asked which stimulus felt rougher. Their results showed significant differences between all pairs, except between 20Hz and 30Hz. We used the experimental methodology from Brown *et al.* in this paper.

Brown *et al.* [8] 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 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 existing research influenced our experimental designs and showed the potential for creating *Electrotactons* to deliver information, building up from simple cues.

This existing research has shown that there is great potential for electrotactile stimulation for the creation of useful haptic sensations

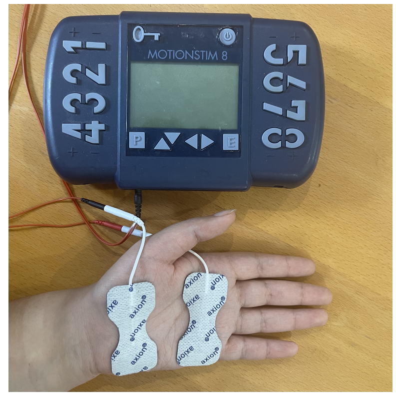

Figure 3: The placement of the electrodes on the hand and the MOTIONSTIM 8 functional electrical simulator (FES) used to generate the signals.

for interaction design. However, we are lacking knowledge of how the basic parameters can be used to create these electrotactile cues. The aim of the work in this paper is to gain an understanding of some of these parameters.

3 EXPERIMENTS

We conducted two experiments. In the first, we investigated how 9 levels of *Intensity* affected ratings of perceived urgency, annoyance, valence and arousal, using three levels of pulse width and amplitude, which govern the strength of the electrical current [29]. We wanted to evaluate what effects electrotactile cues had on the functional aspects of alertness (urgency and annoyance) and emotion (valence and arousal). In the second experiment, we investigated the same 9 levels of *Intensity* in terms of which stimulus felt more intense, and 6 levels of *Pulse Frequency* in terms of which stimulus felt rougher, looking at how many levels of each that participants could discriminate.

3.1 Apparatus

We used two Axion 60x30mm self-adhesive electrodes (https://axion.shop/en/ electrodes/stimulation-current-electrode-pads -for-fingers -and-wrists) with 2mm jack connections placed on the palm of the non-dominant hand for both experiments. The functional electrical stimulator (FES) used was the MOTIONSTIM 8 (Figure 3) made by Medel Medicine Electronics (https://www.medel-hamburg.de/). It produces a biphasic voltage pulse . It was connected to a PC through USB. A python script was written to control the parameters for the stimuli and the user interface for the experiment. The experiments were conducted in a lab where participants sat in front of a 27-inch monitor connected to a laptop. A Bluetooth mouse was used in the participant's dominant hand to interact with the experiment interface (see Figure 1).

3.2 Experiment 1

3.2.1 Experimental Design. The experiment used a within-subjects repeated measures design investigating 9 levels of *Intensity*, consisting of three phases: calibration, training and experiment. The independent variable was the *strength 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 ones of three levels of pulse width and the second amplitude. The Low level for pulse width used a baseline value of 70 μs [2], 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 study, Pulse Frequency was kept constant at 20PPS to ensure participants could detect the stimulus [2].

The dependent variables were: perceived urgency, annoyance, valence and arousal. These variables give information about a range of different subjective aspects of cues [30] 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 we were interested to know more about this. Valence and arousal are part of the Circumplex model of emotion [31] Valence is the emotional pleasantness of a signal (higher valence meaning more pleasant, lower valence less pleasant) and arousal the physiological activation (low arousal meaning calmer emotions, high arousal more excited). Others have begun to look at the emotional experiences of vibrotactile cues [33] but there is little work on this in the electrotactile domain. Investigating emotional responses is important to ensure the creation of acceptable cues.

3.2.2 Hypotheses. From Kaczmarek *et al.* [18], we expected that the perception of *Intensity* would be influenced by the strength of the stimulus. Previous work, e.g. [2], had not compared amplitude and pulse width directly to assess their relative effects on perceived sensation. Pohl *et al.* [29] has stated that amplitude produced to 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.*

3.2.3 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 for participating.

3.2.4 Procedure. Participants sat at a desk with a monitor and a Bluetooth mouse. Two electrodes were placed on the palm of their non-dominant hand. The first was placed across the thenar and hypothenar eminences, and the second on the distal palmar region [15] (Figure 3). A calibration phase was then undertaken to set the amplitude and the pulse width for each participant. For amplitude, we increased from 0 mA until participants felt a sensation, while keeping pulse width at the lower limit of 70 μs. This amplitude value was recorded as the detection threshold and saved as the individual's low level value. Then the pulse width was slowly increased from 70 μs until participants felt uncomfortable and saved as high

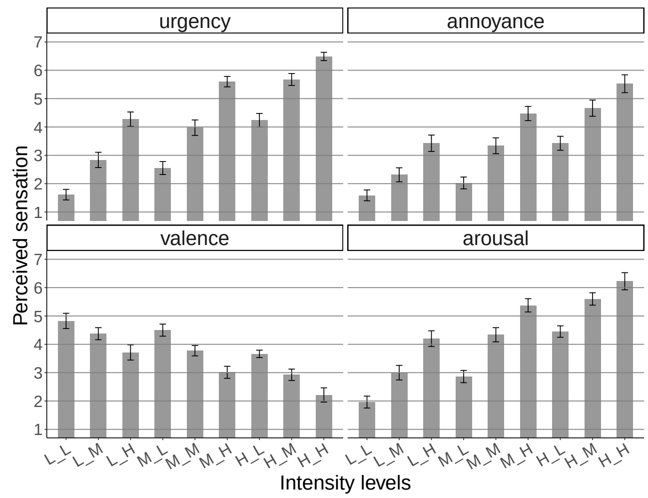

Figure 4: Effect of intensity on all dependent variables in Experiment 1 (the error bars in all graphs represent standard error). The first letter of intensity level (L,M,H) is the level of the pulse width, the second letter (L,M,H) is the level of the amplitude of the stimulus.

level value. Then pulse width was set to the mean of these two values, and amplitude increased until participants felt uncomfortable and saved as the high level. The maximum value used for the pulse width was 200 μs, and for amplitude was 20 mA to prevent any pain sensation [35]. We avoided signals strong enough to cause muscle contractions, as we were interested in electrotactile feedback only, rather than muscle stimulation.

In the training phase, we briefed participants on how to interact with the interface, explained the stimuli and the scale for the sensations measured. Participants received 9 randomly ordered stimuli that lasted for 1s each (which was one block of the experiment phase). After each stimulus, participants answered on a 7-point Likert scale how they perceived each of the dependent variables. The aim of this phase was to get participants used to the stimuli before the experiment phase. The experiment phase was the same as the training but with four blocks, giving 36 trials in total. To avoid fatigue, there was a 5 minute break between blocks.

3.2.5 Results. We used the Aligned Rank Transform (ART) [34] to transform our data to a parametric form for statistical testing. A one-factor (strength of the stimulus) repeated-measures ANOVA was then performed for each dependent variable (urgency, annoyance, valence and arousal). Strength of the stimulus had a significant effect on perceived urgency ($F(8,152)=98.08$, $p < 0.001$), with increasing values causing a greater sensation of urgency. Strength 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 4 shows the results in detail). The results of *Post hoc* Tukey tests can be seen in Table 1. From the table, for Urgency we therefore have 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 we have three unique levels: (H-H, H-M, M-H), (H-L, L-H, M-M), (L-L, L-M, M-L). For Valence we have two unique levels: (H-H, H-M, M-H), (H-L, L-H, L-M, M-M, M-L, L-L). For Arousal we have three unique levels: (H-H, H-M, M-H), (H-L, L-H, M-M), (L-L, L-M, M-L).

Table 1: *Post hoc* pairwise Tukey tests comparing stimulus levels for Experiment 1. As before, the first letter (L,M,H) is the level of pulse width, 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).

To see if either parameter of Intensity (amplitude or pulse width) 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 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.

3.2.6 *Discussion.*

Results showed that the strength of the *Intensity* stimulus had a significant effect on all perceived sensations. In Figure 4, when strength 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 that we can control the level of the perceived sensations by manipulating the strength of the stimulus. This is important for designing interfaces using electrotactile cues that need to elicit particular responses from users. The results also confirm Djozic *et al.*'s [9] findings where valence was rated higher when intensity was low, and, additionally, we showed the two unique levels of it. Therefore, *Hypothesis 1* is supported.

Looking at Figure 4, we can see that urgency spanned the range of ratings from low to high. This means we can create cues with a wide range of different urgencies, as required for designing messages. Annoyance also had a wide range. The interesting thing here is that it is possible to design electrotactile cues which do not annoy the receiver, key for their effective use in interface design. But as [30] found for his multimodal cues, urgency and annoyance are closely related, with the most urgent cues being the most annoying. This suggests that the most urgent messages should be used with care so as not to annoy users.

In terms of the Circumplex model of emotion [31], the electrotactile stimuli used give some coverage of the emotion space. We can create messages with both positive and negative valences, and we can create three different levels of arousal. This suggests electrotactile cues are capable of generating simple emotional experiences, which could be used for positive and negative messages/emojis, for example. This work is just a first step into the emotional aspects of electroactile cues, and further work is needed to explore the space further.

The detailed results showed how many unique levels of sensation could be identified for each dependent variable. For Urgency we have five levels, Annoyance three , Valence two, and Arousal three levels. This then gives us a range of different cues to communicate different meanings, with multiple similar cue choices at some of the levels. For example, if we wanted 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. If we wanted a cue to indicate a low priority event, we could choose (L-L, low pulse width, 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 greater impact on perceived sensation than the other. Therefore, *Hypothesis 2* is not supported. Combining them into the single *Intensity* parameter is the most effective way to use them. Overall, these results give a more detailed understanding of how we can manipulate perceived urgency, annoyance, valence and arousal by changing the intensity level of electrotactile stimulation.

3.3 Experiment 2

3.3.1 Experimental Design. This experiment again used a within-subjects design, and consisted of two parts. The first investigated the discriminability of the same 9 levels of *Intensity* from Experiment 1. The second part investigated the discriminabilty of 6 levels of *Pulse Frequency* as this had not been tested before in the literature. In both parts, we used the same method as Brown *et al.* [7] for testing the discriminability of roughness for vibrotactile cues.

For *Intensity*, the independent variable was: strength of 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 (eg. 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 (10PPS (Pulse Per Second, see Figure 2), 30PPS, 50PPS, 70PPS, 90PPS, 110PPS). In each trial, participants were presented with a pair of stimuli excluding pairs of 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). Previous research indicated a relationship between the Pulse Frequency of electrotactile stimulation and the sense of roughness [38]. As Pulse Frequency is quite abstract, participants rated the stimuli in terms of perceived roughness. 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.

3.3.2 Hypotheses. Based on our first experiment, we hypothesised that the strength of the electrotactile stimulus would have a significant effect on the perception of intensity. Previous research indicated a relationship between the Pulse Frequency of electrotactile stimulation and the sense of roughness [38]. Our aim was to investigate this in more detail. We 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.*

3.3.3 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 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 for participating.

3.3.4 Procedure. The set up for this experiment and the calibration steps were the same as the first experiment. Additionally, for the calibration phase, we increased both pulse width and amplitude simultaneously from their low values until detection threshold to be sure participants could detect the stimulus and set it as minimum the value. We repeated the same step, but using middle values of pulse width and amplitude until the discomfort threshold was reached to avoid their combination causing additional discomfort and set it as the maximum value.

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?". They did 10 training trials. The experiment phase was the same as 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. We used the same calibrated values from the intensity part. 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" [7]; 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.

3.3.5 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 5). *Post hoc* Tukey test results can be seen in Table 2 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 5).

Pulse Frequency had a significant effect on 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 6). This suggests there are only two discriminable levels for this parameter.

3.3.6 Discussion. The aim of this experiment was to find how many levels of *Intensity* and *Pulse Frequency* participants could discriminate, to see how many useful levels there would be for designing electrotactile cues. Results showed that *Intensity* had a significant effect on perception with 4 unique levels (Figure 5). Therefore, *Hypothesis 1* is supported. From the same figure, we can see that as the strength of stimulus increased, the count of intensity increases. This indicates that we can control the perception of *Intensity* by manipulating the strength of stimulus. This is important for designing interfaces using electrotactile cues with a desired level of intensity. Therefore, *Hypothesis 2* is supported.

Table 2: *Post hoc* Tukey tests comparing intensity levels for Experiment 2-*Intensity*. As before, the first letter (L,M,H) is the level of pulse width, 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).

For Pulse Frequency, results showed only two unique levels that participants could discriminate (Figure 6). This makes it a more limited cue for design than Intensity but still has some potential. It also provides more insight into Yoshimoto *et al.*'s [38] findings where manipulating pulse frequency had an effect on roughness perception as we showed that only two levels from our set were distinguishable. Further work could investigate lower levels of pulse frequency below 10PPS to see if other levels are discriminable. Therefore, *Hypothesis 3* is partially supported.

From (Figure 6), we can see that there were no significance differences between pulse frequencies 30PPS and above, which suggests

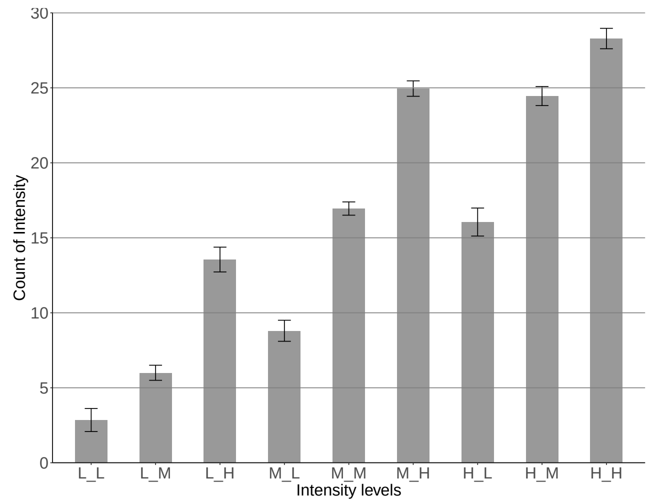

Figure 5: Effect of Intensity on perception in Experiment 2.

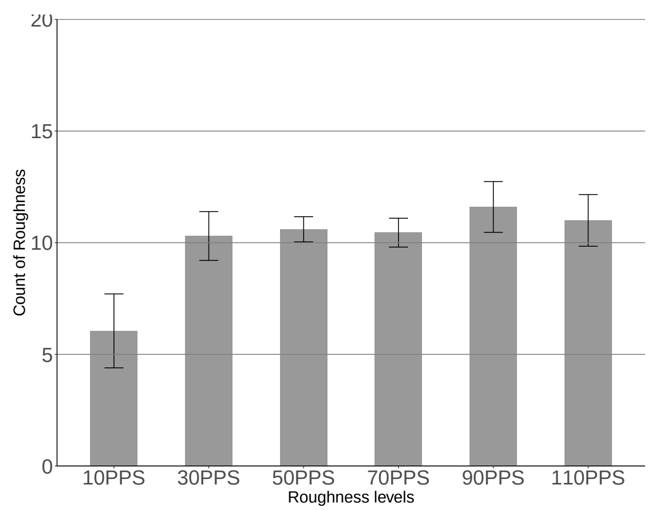

Figure 6: Effect of Pulse Frequency on perception in Experiment 2.

that above that level cues are no longer distinguishable. This provides more evidence in line with [2, 12, 38] 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 OVERALL DISCUSSION

The results of the two experiments give us useful insight into Intensity and Pulse Frequency as parameters for designing *Electrotactons*. From Experiment 1, we know that it can 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. From Experiment 2, we know that participants can discriminate four levels of Intensity, the same number of distinguishable levels found by Brown *et al.* [7] in Tactons. For Pulse frequency, participants can discriminate between two levels. These findings make both parameters useful cues and a strong contributors to the *Electrotacton* design space.

Our future work will carry out similar experiments on other potential parameters, such as rhythm, spatial location and waveform so that we can fully understand their properties. With distinguishable stimuli for each, we can then create effective cues where users can learn the mapping between the *Electrotactons* and their meanings, with a desired level of sensation.

4.1 Calibration

One aspect of electrotactile cue design that differs from vibrotactile is the issue of calibrating the signals. Calibration is key so that the cues are perceptible but do not cause muscle contractions or pain. In the calibration phase of each experiment, we collected the minimum and maximum values for Amplitude (mA) and Pulse width (μs). Each participant has their own dynamic range that is based on their skin impedance, the distance between the electrodes, and its size. These values allow us to see the ranges that were chosen by participants and gives us information on the variability between people.

Looking at Figures 7, 8, 9 and 10 we can see the distribution of values for both Amplitude and Pulse width across all participants where light grey bars represent the minimum values (detection threshold) and dark grey bars represent the the maximum values (discomfort threshold). From Figures 7 and 9 for Amplitude, we observed that the granularity in it is more distinguishable when increasing its value compared with Pulse width (Figures 8, 10). This is why the range of Pulse width values is wider than Amplitude. Based on the difference in ranges between Amplitude and Pulse width, we recommend when calibrating for electrotactile signals to increase the value of Amplitude by steps of 1 mA and for Pulse width by steps of 10 μs, as this would save some time in the calibration phase.

4.2 Limitations

The two studies had some limitations which potentially affect the generalisability of the results. We used only one size of electrodes, only tested on the palm of the hand, and used a fixed spacing of the electrode pair. Using the same size electrodes throughout both experiments prevents us from observing if size impacted the sensations and discrimination of electrotactile feedback. Different sized electrodes might have a higher current density, requiring different stimulation values [28]. In our next study, we will compare electrodes of different sizes to see if they change perception.

We only stimulated the palm. The aim was to simulate the feedback one would receive when holding a mobile device, steering wheel, etc. Different body locations have different numbers of mechanoreceptors [15] so this could potentially change the sensations elicited. The hand has a larger number of receptors than the bicep, for example if the user was wearing a device on their upper arm. Stimulating the palm's glabrous hairless skin would be different from hairy skin as it contains more mechanoreceptors, making it more sensitive and discriminative. Hairy skin contains

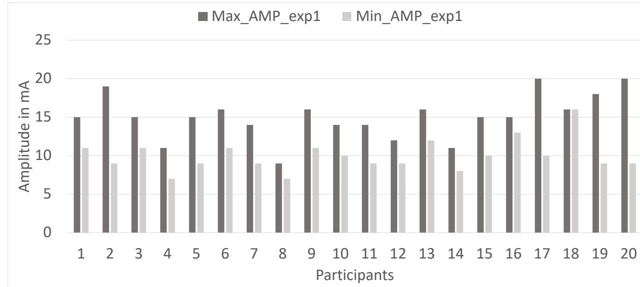

Figure 7: The distribution of min and max values for Amplitude from the calibration phase in Experiment 1. The light grey bars represent the min values, the dark grey represent the max values.

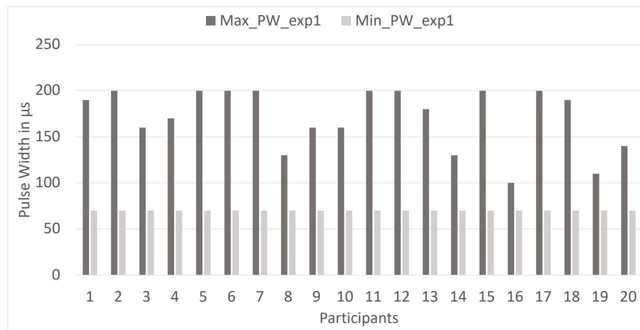

Figure 8: The distribution of min and max values for Pulse width from the calibration phase in Experiment 1.

C-tactile afferents that the glabrous skin does not have, which again may have an impact on affective sensation [1]. In our next study, we will compare the palm, wrist and upper arm to see how perception is affected.

We only tested one distance between the two electrodes. Changing the distance would change the depth that the current penetrates the skin, potentially changing perception. Further work is needed to investigate this and the other limitations to see what affects they would have on perception to give a deeper insight into the design space of electrotactile feedback.

5 CONCLUSIONS

This paper presented two studies investigating two different aspects of electrotactile cue design on the palm. It expanded upon previous work, exploring the design space of electrotactile feedback for creating effective cues and has provided new knowledge about the importance of different parameters. In the first study, we investigated the effect of manipulating intensity on the perceived sensations of urgency, annoyance, valence, and arousal. Results showed that intensity had a significant effect on subjective perception, giving clear different levels of each sensation. An increase in intensity increased perceived urgency, annoyance and arousal, but caused a decrease in perceived valence. We did not find a difference between amplitude and pulse width in the study, with results suggesting that both had similar effects. For user interface design,

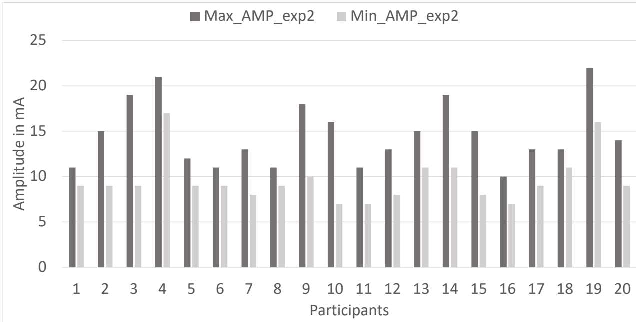

Figure 9: The distribution of min and max values for Amplitude from the calibration phase in Experiment 2.

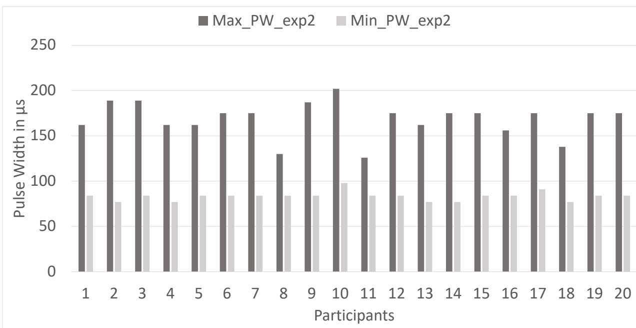

Figure 10: The distribution of min and max values for Pulse width from the calibration phase in Experiment 2.

this means we can generate cues with clearly different levels of perceived sensation by using intensity with greater number of discriminable levels.

The second study investigated how many distinguishable levels can be perceived from intensity and pulse frequency that would be useful for richer messages or notifications. Results showed that intensity and pulse frequency both had a significant effect on perception, giving clear four distinguishable levels for intensity and two for roughness from pulse frequency. An increase in intensity caused an increase in perception. For pulse frequencies 30Hz and above, roughness perception did not change. Two guidelines can be drawn from these studies:

Designing cues with desired sensations: 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;

Designing cues with desired levels of Intensity and Pulse Frequency: Designers can choose from four distinguishable levels of Intensity and two of Pulse frequency to create electrotactile cues. When going over 30PPS, cues are no longer distinguishable.

This research has provided an in-depth understanding of using intensity and roughness as parameters to create electrotactile cues with desired sensations. These give some initial insight into the design space for *Electrotactons*, opening up the opportunity for using them in areas such as mobile and wearable devices where visual interaction is limited. Designers could use the results to select suitable cues for designing novel, distinguishable notifications and messages.

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