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Investigating Electrotactile Feedback on The Hand

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***Abstract*— Electrotactile feedback can be used as a novel method to evoke different sensations on the skin. However, there is a lack of research exploring electrotactile feedback on the palm. This paper presents two experiments that investigate the effects of manipulating pulse width, amplitude and frequency of electrical stimulation on perceived sensations (urgency, annoyance, valence and arousal) on the palm. In the first study, we manipulated pulse width and frequency. The results showed that both parameters have a significant effect on the perceived sensations, except for frequency not having an effect on valence. Also, frequencies of 30Hz and above did not influence the perceived sensations. In the second study, we manipulated amplitude and frequency. The results showed that both parameters have a significant effect on perceived sensations, especially for frequencies lower than 30Hz. From both experiments, the increment of pulse width and amplitude led to a higher rating for urgency, annoyance and arousal. These results gives us a better understanding of the parameter space of electrotactile feedback to enable designers to create effective electrotactile feedback.**

Fig. 1. The placement of the electrodes on the hand and the functional electrical simulator (FES).

I. INTRODUCTION

Interacting with computing devices such as phones and smartwatches through touch is very common but creating good feedback for these interactions is difficult. One reason for this is the limited capabilities of actuators available, with most devices using vibrotactile motors to provide mechanical stimulation of the skin. In this paper, we investigate electrotactile feedback to study how it could be used to create a range of different sensations. Electrotactile feedback delivers cues to the skin by stimulating the nerves directly through the flow of electrical current. This is achieved through the manipulation of parameters such as pulse width, amplitude and frequency [1]. It has advantages over mechanical stimulation as the actuators can be small and thin, light, durable, free from mechanical resonance, with high responsiveness [2], [3], [4]. It has a high energy efficiency compared with mechanical stimulation, and can be small and dense in size [5].

Studies have investigated the perception of electrotactile stimulation on the fingers [6], forearms and wrists [7], [8] and have shown that people are very sensitive to the cues, making it suitable for delivering feedback. However, there is a lack of work investigating subjective experiences to the feedback which makes it difficult to use in interaction design.

In this paper, we present two experiments to investigate how electrotactile feedback influenced subjective perception of urgency, annoyance, valence and arousal through manipulating frequency, pulse width and amplitude of electrotactile cues on the palm. We wanted to explore the underlying parameter space of electrotactile feedback and understand the effects of the parameters on subjective responses to have a better idea of how to design effectively using it. Our results showed that frequency, pulse width and amplitude have significant effects on sensations and can be used to create a range of novel tactile cues.

A. Contribution

- We investigated the subjective perception of electrotactile feedback on the palm;
- We found that frequency, pulse width and amplitude had a significant effect on perceived urgency, annoyance, valence and arousal.

II. RELATED WORK

Electrotactile feedback can elicit sensations such as itch [8] and touch [1], or convey information, such as object shapes [9], [10] or verbal information [11] through electrical current generating an electrical field inside the skin to stimulate the nerves. Manipulating the parameters of electrotactile feedback, such as: amplitude, frequency, pulse width, type of electrical current and location of the electrodes, allows for the creation of different types of cues.

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To design electrotactile feedback, we need to understand what mechanoreceptors responds to it, and what sensations can be generated. Kajimoto *et al.* [12] developed an electrotactile display called "tactile primary colours" to elicit a wide range of sensations through stimulating the Meissner corpuscles (RA), Merkel cells (SAI) and Pacinian corpuscles (PC) separately. The amplitude they used for the stimuli was 2mA, pulse width 200 μs, and frequency of 200 Hz. When stimulating SAI, at 0.2 mA, users felt a tremble sensation; At 0.4 mA, they felt pressure: at 0.6 mA, they felt a vibration. When stimulating RA with a frequency less than 100 Hz, participants felt a vibration, when above 200 Hz it was uncomfortable.

In another study, Kajimoto *et al.* [4] constructed a mechanical and electrotactile stimulator to validate the selective stimulation of RA and PC. They presented participants with mechanical stimuli with a vibration amplitude 0.1 mA, duration 1 s and frequencies of 15, 30, 60, 120 Hz. For electrotactile stimuli, the amplitude was 2.4 mA, the pulse width was 0.2 ms and the same frequencies as the mechanical vibration with the addition of 45Hz. They assumed that the perception of electrical vibration would be the same as the mechanical vibration. After comparing the results, the vibration sensation was the same as electrotactile at 15 and 30 Hz. In electrotactile stimuli, participants could not distinguish frequencies at 45 Hz and above.

Djozic *et al.* [7] investigated the effect of changing 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, 50 and 100Hz), 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 frequency, but there was an interaction between PT and frequency. As frequency increased, the JND decreased despite which pulse width was used. This suggests that 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 JND and pulse width were low, and the value of frequency was high.

Okpara *et al.* [13] investigated the perceptual effect of manipulating electrotactile current and frequency. The electrodes were placed at the middle finger on the left hand. Four levels of both current and frequency were tested. The study consist of two sessions and each had three phases. The first was a calibration phase where minimum current I_s and maximum current I_m were recorded. Ten current measurements (five at 10 Hz and five at 100 Hz) were taken and the average calculated I_s at 10 Hz, and the average I_m at 100 Hz. The frequencies were 10, 15, 35, and 100 Hz. In the second phase, participants were given 120 pairs of stimuli, and were asked to rate each pair as "same" of "different". The third phase was the same as the second, but the order of the pairs was reversed. The finding was that the higher one of the parameters, the greater the sensitivity to the other parameter variations.

Pohl *et al.* [8] 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 of the functional electric stimulation devices did't have the level of flexibility of controlling the parameters. They restricted the frequency to around 50 Hz, amplitude to be under 1 mA and the pulse width to 2-5 ms to ensure minimal discomfort.

The study had two phases, a short stimuli phase and a long stimuli phase. The electrodes were placed on the hairy skin of the left forearm, just below the wrist. Before the first phase, they performed a calibration test to set up suitable feedback parameters. In the first phase, participants were presented with 40 stimuli for 4s. They were asked to choose any number of words out of a 21 term list that would describe how it felt, without asking about the itch sensation. In the second phase, participants were presented with 50 stimuli.

For each stimulus, a dialogue popped on the screen every 4s asking to then rate how itchy and pulsating it was. They also asked participants to rate their comfort level, how natural the stimulus felt, and sensation location. The results for the first phase showed that the most used word was 'vibration'. The words that been used to describe the lower-intensity stimuli were gentle and faint, and for the higher intensity were 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 signal was 60 Hz frequency, 3.8 ms pulse width and 0.2 mA, but there was a wide variation between participants.

The design of our electrotactile feedback was influenced by these experiments. We chose amplitude, pulse width and frequency to evoke sensations through the manipulation of parameters. Most of these earlier experiments did not look at the subjective experience of electrotactile feedback, which is vital for user interface design. Our experiments focused on the subjective reception of different sensations on the palm.

III. EXPERIMENT 1

At first experiment was conducted to provide an initial evaluation of electrotactile feedback and how people would react to it on the palm. Our research question was: do frequency and pulse width influence people's sense of urgency, annoyance, valence and arousal?.

A. Hypotheses

In accordance with the results of the study made by Kajimoto *et al.* [4], we expect that participants will not be able to discriminate between frequencies above 30 Hz. On the other hand, a low pulse width and high frequency should make participants rate valence higher based on Djozic *et al.* [7]. Furthermore, knowing that pulse width and amplitude influence sensation intensity perception [8], a higher rating of urgency is expected with high pulse width. With that, a higher urgency will induce a higher arousal and annoyance based on Russell's Circumflex Model of Affect [14].

Therefore, the hypotheses for this experiment were:

- ***Hypothesis 1:*** *Frequencies above 30 Hz will not have a significant effect on perception;*
- ***Hypothesis 2:*** *When pulse width is low and 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.*

B. Apparatus

We used two 60x30mm self-adhesive electrodes with 2mm jack connection made by Axion. The functional electrical stimulator (FES) was the MOTIONSTIM 8 made by Medel Medicine Electronics that produce a biphasic voltage pulse (Figure 1). It was connected to a PC through USB. A python script was written to control the parameters for the stimuli and the interface.

The experiment was conducted in a lab where participants sat in front a 23.6-inch HannsG HE247 monitor connected to a MacBook Air laptop running Windows 10. A mouse was used in the participant's dominant hand to interact with the interface.

C. Experimental Design

The experiment used a within-subjects design, consisting of three phases: calibration, training and experiment. The Stimulation parameters (frequency and pulse width) were the independent variables. We used six equally spaced frequencies (10Hz, 30Hz, 50 Hz, 70 Hz, 90 Hz and 110Hz), and three values for pulse width. 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, We cannot use the same pulse width across all participants: what might be a weak stimulus for one participant could be strong for others. In addition, if the electrodes are removed, 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: the perceived urgency, annoyance, valence and arousal. We wanted to measure the effectiveness of the electrotactile cues from the functional aspect of alertness (urgency and annoyance) [15] and the emotional aspect (valence and arousal) [14].

D. 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 the information sheet and signed a consent form before the start of the experiment, and was compensated £8 for participating.

E. Procedure

For all three phases, participants were sat at a desk with a monitor, PC and mouse, which they controlled with their dominant hand. The two electrodes were attached to the palm of their non-dominant hand. One placed across the thenar and hypothenar eminences, the other on the distal palmar (Figure 1). The calibration phase was used set up the amplitude and the pulse width for each participant. 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 200 μs to avoid any pain sensation [2].

In the training phase, participants were briefed on how to interact with the interface and what are the meaning of all sensations measured. Once ready, they clicked 'next' to receive the first stimulus. Participants went through one block consisting of 10 randomly ordered stimuli that lasted for 1s. After the stimulation, participants rated how they felt for each dependent variable on a 7-point Likert scale. The next button was not activated until all ratings been given. The goal from this phase was to allow participants to get used to the stimuli before the main experiment phase.

The experiment phase had the same setup and steps, but was longer. It had four blocks, and each consisted of 18 stimuli, making the total trials for the experiment 72 trials in total. There was a 5 minute break between each block to avoid any fatigue. For the qualitative assessment, we asked participants how the stimuli felt and recorded their answers.

F. Results

We used the Aligned Rank Transform [16] to transform our data from non-parametric to parametric. Then a two-factor (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 frequency ($F(5,323) = 7.41$, $p < 0.001$) had a significant main effect, with no interaction. For annoyance, both pulse width ($F(2,323) = 279.6$, $p < 0.001$) and frequency ($F(5,323) = 14.42$, $p < 0.001$) had a significant main effect. There was an interaction ($F(10,323) = 3.28$, $p < 0.001$), and *post hoc* Tukey test showed that the difference between low and high pulse width with 10 Hz was significantly different when with 50 Hz, 70 Hz and 90 Hz.

For valence, only pulse width ($F(2,323) = 13.7$, $p < 0.001$) had a significant main effect, with no interaction. For arousal, both pulse width ($F(2,323) = 391.39$, $p < 0.001$) and

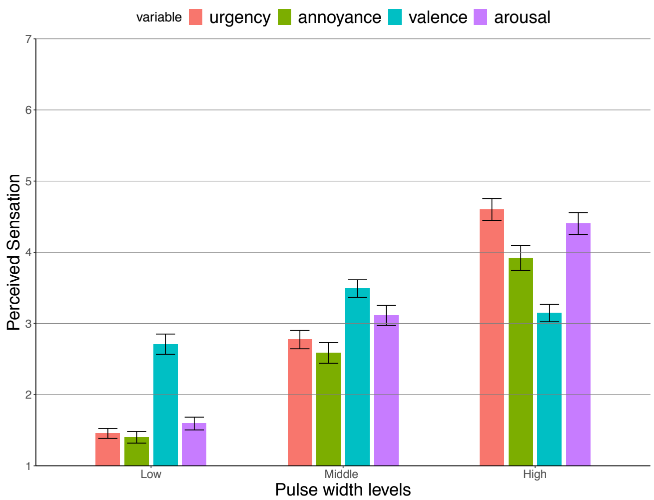

Fig. 2. The effect of pulse width on all dependent variables (the error bar in all graphs represent confidence intervals).

frequency (F(5,323) = 6.28, p < 0.001) had a significant main effect, with no interaction. After performing *post hoc* Tukey tests on all significant effects, we made some observations. For the effect of pulse width on all dependent variables, there were significant differences between all levels, except between high and low levels in valence, as shown in figure 2. For frequency (figure 3), the significant effect was between 10 Hz and all other frequencies, except between 10 Hz and 110 Hz in arousal. For annoyance, there was an additional significance between 30 Hz and 90 Hz. Participants performance was the same for all parameters across blocks indicating no learning effects.

Qualitative feedback showed that 16 out of 20 of participants reported that their sensitivity changed over time and that they got use to the stimuli in distinguishing different intensities. P02 reported that he *"was able to detect better later than the beginning. I was supervised at the be 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 hand. 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 wouldn't buy a device that uses it "*.

G. Discussion

The results showed that the significant effect of frequency on perception was between 10 Hz and higher. One possible reason for not finding significance between the rest of the frequencies could be that, at above 30 Hz, both the Meissner and Pacinian corpuscles were activated at the same time. This may have caused participants to have problems distinguishing between higher frequencies as found in [4]. Therefore, *Hypothesis 1* is supported.

Pulse width was the only independent variable with a significant effect on valence. As mentioned, there was no significance between high and low levels indicating that the valence threshold is somewhere between middle and high pulse width. Therefore, *Hypothesis 2* is not supported. The perceived intensity of an electrotactile stimulus is governed by pulse width and amplitude [8], 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.

We observed that there was a direct relationship between urgency, arousal and annoyance across both independent variables. Having a stimulus with higher urgency and arousal would induce a higher sense of alertness and reaction [17], [15]. 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 [18], and suggests that urgency had more impact on the rating more than annoyance. This is crucial since stimuli with a higher annoyance can be ineffective [19]. Therefore, *Hypothesis 4* is supported.

IV. EXPERIMENT 2

The aim of this experiment was to investigate how changes in frequency and amplitude affect perceived urgency, annoyance, valence and arousal. We investigated a wider range of frequencies from 5Hz to 45Hz, extending what we learned from the first experiment, using the same apparatus and set up as before.

A. Hypotheses

We extended the frequency range tested in Experiment 1 to find if participants could discriminate frequencies at lower levels below 30 Hz. Following the rational for H3 in Experiment 1, higher ratings of urgency, annoyance and arousal are expected with high amplitude. Pohl *et al.* [8] described that high amplitudes caused a stronger sensation, we expect amplitude to influence perception more than pulse

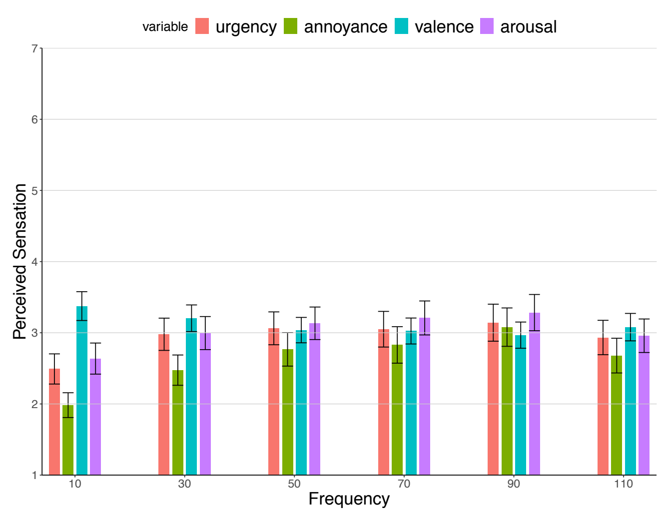

Fig. 3. The effect of frequencies on all dependent variables.

width.

The hypotheses of this experiment therefore were:

- ***Hypothesis 1:*** *Frequencies below 30 Hz will have a significant effect on perception;*
- ***Hypothesis 2:*** *When Amplitude increases, urgency, annoyance and arousal will increase;*
- ***Hypothesis 3:*** *Amplitude will have a bigger impact on perception than Pulse width.*

B. Experimental Design

The following changes were made compared to the first experiment. The stimulation parameters frequency and amplitude were independent variables. We used nine frequencies (5Hz, 10Hz, 15Hz, 20Hz, 25Hz, 30Hz, 35Hz, 40Hz, 45Hz), and three values for amplitude were defined during the calibration phase (see below). This gave 27 stimuli from both parameters.

C. Participants

Twenty new particepants (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.

D. Procedure

The procedure was the same as the first experiment with the following additions to 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 we increased the amplitude from the detection threshold until the participant felt uncomfortable and we saved it as the amplitude discomfort threshold. The maximum value for the amplitude was 20 mA to avoid any pain sensation. The total number of trials was 108 across the four blocks.

E. Results

We used the same method as the first experiment for two-factor (frequency and amplitude) repeated-measures ANOVA. For urgency, both amplitude ($F(2,494) = 476.4$, $p < 0.001$) and 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 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 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 frequency ($F(8,494) = 25.23$, $p < 0.001$) has a significant main effect, with no interaction. No learning effects across blocks were observed.

Using *post hoc* Tukey tests on all significant effects, we made some observations. All levels of amplitude had a significant effect across all dependent variables, with valence decreasing as amplitude increased (Figure 4). For frequency's effect on urgency and arousal (Figure 5), the significant

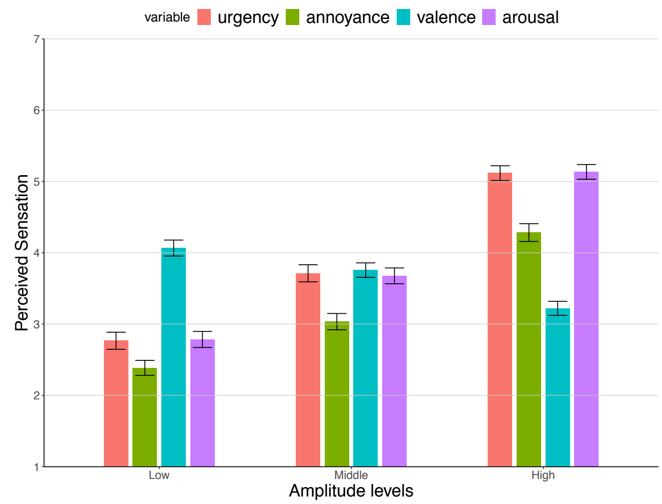

Fig. 4. The effect of amplitude on all dependent variables

effect is found when comparing the range 5Hz to 20Hz to higher frequencies, with some exceptions. For urgency, the difference between frequencies must be higher than 5Hz to have significance.

For arousal, when comparing 10Hz with other frequencies, the difference must be higher than 10Hz to have a significant effect. In the case of 15Hz and 20Hz, the difference must be 5Hz. For annoyance, a significant effect is found when comparing the range 5Hz to 25Hz to higher frequencies, with some exceptions. When comparing 5Hz to other frequencies, the difference must be higher than 5Hz. For the rest of the range, the difference must be higher than 10Hz. In valence, the significance was only found when comparing three pairs of frequencies 5Hz-40Hz, 15Hz-40Hz and 15Hz-45Hz.

Qualitative feedback showed that 15 out of 20 of participants reported that their sensitivity changed over time and that they got used to the stimuli and distinguishing different intensities. Similar to the first experiment, some participants reported that they felt the electrotactile feedback inside of their hand. P07 reported that *"The vibration from the phone feels flat, with no levels or dimensions. I feel more sensations from the electrotactile"*. P13 added *"The vibration from the phone is kind of one level and it is the same everything, where the electrotactile varies a lot more"*.

F. Discussion

Having smaller steps in the range frequencies compared to the first experiment, helped us locate what frequencies have significant effect on perception. We observed that the significant effect was between the range of 5Hz to 25HZ and the other frequencies. At that range, Only Meissner corpuscles are activated, leading participants to distinguish between different stimuli more reliably. Therefore, *Hypothesis 1* is supported.

In line of related work [8] and what we can see in figure 4, the higher the level of amplitude, the higher the urgency, annoyance and arousal. Therefore, *Hypothesis 2* is supported. Putting figure 4 alongside figure 5, we observed

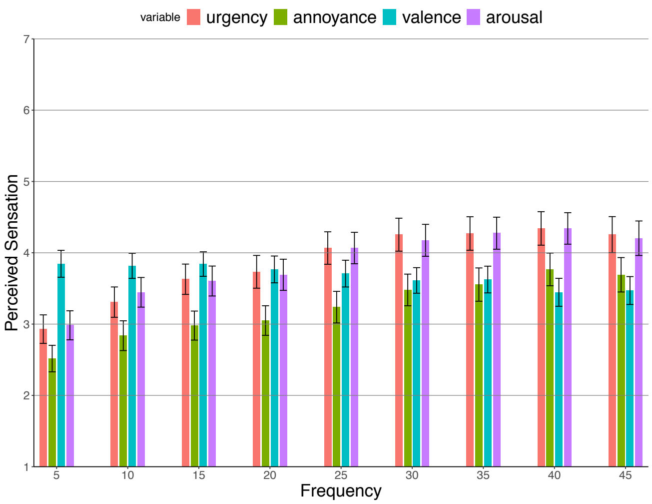

Fig. 5. The effect of frequency on all dependent variables

that amplitude has a higher impact on perception than pulse width across all levels. Therefore, *Hypothesis 3* is supported.

V. CONCLUSIONS

The studies in this paper investigated the effects of electrotactile feedback on urgency, annoyance, valence and arousal through the manipulation of frequency, pulse width and amplitude. The aim was to explore the design space of electrotactile feedback so that we can design effective cues and understand the relative importance of the different parameters. All of the parameters had a significant effect on subjective perception. Results showed perception of frequency peaked at 25-30Hz; above that, increases were not recognised. Frequency had generally little effect on valence but did affect the other sensations. However, there are only a few usable levels of the parameter. Increasing pulse width increased all of the perceived sensations, and gave three clear levels of the parameter. 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. These findings give us a clearer understanding of the parameter space for designing electrotactile cues to create desired sensations. We can design messages with clearly different levels of arousal and urgency, and can see the effects on annoyance; however, valence appears harder to manipulate using electrotactile cues.

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