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Subdermal Magnetic Implants: An Experimental Study

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ABSTRACT

In this paper, we consider the use of permanent implanted magnets inserted into an individual's fingers as a form of human computer interface, the magnets being excited by an external coil. Tests involving amplitude detection, amplitude discrimination, frequency discrimination, temporal discrimination, and temporal gap detection were performed on implanted subjects. As a comparison the same tests were performed on individuals who had identical magnets attached to the outside of their skin. Results indicated that much smaller stimulation currents were required to achieve a sensitivity response in the implanted subjects. It is apparent that different corpuscles are affected by complex signals at different frequencies and this has a considerable effect on the results obtained and hence on the type of stimulation that can best be applied.

KEYWORDS

Amplitude detection; amplitude discrimination; frequency discrimination; psychometrics; psychophysics; quest; subdermal magnetic implants; temporal discrimination; temporal gap detection; temporal numerosity discrimination

Introduction

In terms of the interaction between technology and humans the usual interfaces used generally involve input to the human through the normal sensory route, especially visual, audio, and touch. It is however well worth considering alternative arrangements as the performance obtained might actually be somewhat better in different ways. Here we take a look at the possibility of enhancing or rerouting touch sensing through the use of implanted magnets, in doing so opening up an alternative pathway from the outside world through a technological instrument to the human brain.

Hameed et al. (2010) began preliminary scientific research in the area of subdermal magnetic implants, SMIs. The focus of this research was to utilize the implant as a human machine interface. Prior to this research, SMIs (subdermal magnetic implants) were mainly seen in the body modification world as an art form. The research presented in this paper involves the outcome of a study used to quantify the perceptual benefits of SMIs. The results presented are from five psychophysical thresholding experiments namely: amplitude detection; amplitude discrimination; frequency discrimination; temporal

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discrimination; and temporal numerosity discrimination with respect to temporal gap detection, TNDwrTGD.

The reason for conducting our experiments, was to gain empirical results for the creation of stimulation signals for high stress application scenarios such as driving or piloting, where the implant could be used as a sensory enhancement element. Essentially this is an assessment of the basic physical properties of a human–machine system that is formed through the use of magnets implanted in fingers.

What we report on here are a series of experiments in which a comparison was made between individuals who had been implanted with a small permanent magnet (subdermal magnetic implant) and other individuals who had the same permanent magnet attached to the outside of their skin (dermis) in an identical position. We wished to consider specifically the force required in order that the stimulation could be witnessed by the individual, in the presence of different amplitude and frequency constraints. This is the first time that such a comparative study has been performed.

For those who were implanted this consisted of a small scalpel incision in the finger pad, followed by the use of a metal rod to bore a hole. The magnet was simply inserted and typically sutured using butterfly stitches. Usually for a right-handed person their left hand is selected and typically the index and middle fingers are used with one implant in each. For further details of this procedure please refer to Hameed et al. (2010).

In the "Background Literature and Experimental Aims" section, we give an overview of the different methods that have previously been used for sensitivity stimulation, particularly of the tactile kind. In the "Method" section we describe the methods used in our experiments and show how they link with previous experimentation. In the "Results" section we present the results of our experiments and then in the "Discussion" section we discuss our results at length. We follow this in the final section with some conclusions.

Background Literature and Experimental Aims

Amplitude Detection

In terms of previous vibrotactile experimentation conducted using psychophysical methods, amplitude detection [amplitude Reiz Limen (RL)—the least amount of stimulation needed to trigger a sensation] has been examined at great length by several authors in relation to contact external to the body (i.e., not through implants). A wide variety of factors contributing to changes in amplitude RL have been explored, such as: glabrous versus nonglabrous skin (Verrillo 1966), gender (Verrillo 1979), menstrual cycle (Gescheider et al. 1984; Espritt et al. 1997), age (Bernstein, Schecter, and Goldstein 1986; Gescheider, Bolanowski, Hall, Hoffman, et al. 1994; Gescheider, Edwards, et al. 1996; Stuart et al. 2003), skin temperature (Bolanowski et al. 1988; Gescheider et al. 1997; Bolanowski et al. 2001), masking effects (Bolanowski et al. 1988; Gescheider, Verrillo, and Pelli 1991; Verrillo 1992; Gescheider, Hoffman, et al. 1994), various equipment (Maeda and Griffin 1994), temporal summation (Gescheider, Hoffman, et al. 1994), contactor effects (Verrillo 1992; Gescheider, Bolanowski, Hall, Hoffman, et al. 1994; Morioka, Whitehouse, and Griffin 2008), body location (Johansson and Vallbo 1979; Stuart et al. 2003; Morioka, Whitehouse, and Griffin 2008), Asperger's syndrome (Blakemore et al. 2006), erotic stimuli on males (Jiao et al. 2007), contact load (Soneda and Nakano 2010), dyslexia (Stoodley et al. 2000), and local anesthesia (Mahns et al. 2006).

A key factor examined in this paper with regard to vibrotactile amplitude RL is frequency. Within the literature this factor has also been explored extensively (Verrillo 1963, 1966, 1979; Gescheider and Verrillo 1979; Verrillo and Gescheider 1992), again through external stimulation. The most prominent relationship found was the U-shaped curve which describes changes in amplitude RL as a function of frequency change. This discovery was first described in Verrillo (1963) and shows that each of the four mechanoreceptor channels responds differently to amplitude, with the RA2 receptors responding to the least amount of force (Bolanowski et al. 1988).

In this paper one aim of our experiments described was to determine the minimum amplitude required for the participants to detect the signal by varying the signal frequency. The exact nature of the operational set up and the stimulation procedure is described later in the "Method" section.

Amplitude Discrimination

Exploration into the literature of vibrotactile amplitude discrimination [amplitude difference limen (DL)] has shown, much like amplitude RL, that results obtained are altered by a multitude of factors, such as: continuous versus gated pedestal trial paradigms (Knudsen 1928; Gescheider et al. 1990; Gescheider, Zwislocki, and Rasmussen 1996), masking effects (Craig 1972; Craig 1974; Verrillo 1985; Gescheider, Bolanowski, Hall, and Mascia 1994; Gescheider et al. 2004), skin temperature (Apkarian, Stea, and Bolanowski 1994; Gescheider et al. 1997), temporal summation (Craig 1972; Gescheider, Zwislocki, and Rasmussen 1996; Gescheider, Bolanowski, and Verrilo 2004), age (Verrillo 1992; Gescheider, Edwards, et al. 1996; Gescheider, Bolanowski, and Verrilo 2004), contactor size (Verrillo 1985; Verrillo 1992; Forta, Griffin, and Morioka 2012), transcranial magnetic stimulation (Morley et al. 2007), stimulation location (Verrillo 1992; Forta, Griffin, and Morioka 2012), fingertip size (Hatzfeld and Werthschutzky 2012) and reference stimulus intensity (Gescheider, Zwislocki, and Rasmussen 1996; Forta, Griffin, and Morioka 2012).

The key factor explored in this paper with regard to amplitude DL is again frequency (Knudsen 1928; Forta, Griffin, and Morioka 2012). Similarly to the literature on amplitude RL, an increase in frequency has been reported to significantly reduce the amplitude DL. Further observations obtained from the literature are that the Weber fraction (Weber's law states that, as the ratio between the magnitudes of two stimuli increases, the more easily the difference between the two stimuli will be perceived) is altered greatly for a multitude of reasons. Craig (1972) stated the Weber fractions of vibrations determined by Knudsen (1928), Sherrick (1950), Schiller (1953), as 0.3, 0.11, and 0.05, respectively. Craig (1972) posed that "the difference in these values of threshold may be due to the various techniques used to obtain these values."

This observation is reinforced by Gescheider et al. (1990). Gescheider also observed that the lowest reported Weber fraction for amplitude DL was 0.05 (which corresponds to a 0.4dB change). Furthermore the highest Weber fraction reported was 0.3 by Sherrick (1950). Gescheider et al. (1990) reasoned the differences in observed values as follows: "Differences in methodology and stimulus conditions probably contributed to the different values of a differential sensitivity measured in these studies."

In this paper another aim of our experiments described was to determine the minimum amplitude difference required for the participants to detect the difference from the reference stimulus, by varying the signal frequency.

Frequency Discrimination

Examination of the literature regarding vibrotactile frequency DL shows that a vast quantity of factors affects the obtained values. For example, stimulus amplitude (Goff 1967; Morley and Rowe 1990); temporomandibular disorders (Hollins and Sigurdsson 1998); waveform of stimulation signal (Franzén and Nordmark 1975); gap time in two interval forced choice, 2IFC (Sinclair and Burton 1996); being congenitally deaf (Levänen and Hamdorf 2001); pretrial adaptation (Tommerdahl et al. 2005); glabrous vs. non glabrous skin (Mahns et al. 2006); blindness (various stages and congenitally) (Wan et al. 2010) and local anesthesia (Mahns et al. 2006).

The key points observed from the literature with regards to this research are the reference frequencies used by Goff (1967) and Mahns et al. (2006); the results of which are summarized in Table 1 In Goff (1967), he summarized the work of Sherrick (1950) stating " … that frequency discrimination is poor above 100 Hz and relatively good below 100 Hz."

In this paper yet another aim of our experiments described was to determine the minimum frequency change required such that the participant could distinguish it. Furthermore, this experiment not only altered the reference frequency but also the waveform of the signal, to determine interaction effects.

Table 1. Summary of frequency discrimination results presented by Goff (1967) and Mahns et al. (2006).

	Weber fractions		
Reference frequency (Hz)	Goff (35 dB above ARL)	Goff (20 dB above ARL)	Mahns et al.
20			0.32
25	~0.18*	~0.32*	
50	~0.19*	~0.21*	0.19
100	~0.3*	~0.48*	0.21
150	~0.28*	~0.38*	
200	~0.37*	~0.55*	0.14

ARL, amplitude Reiz limen.
*These values are interpolation estimates from Figure 4 in Goff (1967).

Temporal Discrimination

Within the literature specifically for temporal DL passing stimulation through the tactile sense, the concept of modality integration has been experimentally examined through multiple methods. Each of the following factors have been shown to alter the temporal DL: interval duration (comparing modalities: audio and tactile); interval duration (comparing modalities: audio, visual, tactile); reference stimulus interval length, stimuli duration (comparing modalities: audio, visual, tactile) (Jones and McAuley 2005); transcranial magnetic stimulation, TMS over the superior temporal gyrus; TMS (transcranial magnetic stimulation) over the somatosensory cortex in deaf people; and musical training on temporal DL (comparing modalities: audio, tactile) (Güçlü, Sevinc, and Canbeyli 2011).

Key findings in the literature with regards to this research are the Weber fractions recorded for tactile temporal DL measured at a reference stimulus length of 500 ms. Results from Güçlü, Sevinc, and Canbeyli (2011) reported a Weber fraction of 0.4 for tactile temporal DL measured with a reference stimuli length of 500 ms (250 Hz sine wave). However, in their experimental procedure the step size changes of the comparison stimulus were set to 25 ms. In this paper, they also reported a tactile temporal DL Weber fraction of ~0.29 when the reference stimulus was 3 s. Jones and McAuley (2005) reported a Weber fraction of 0.16 for a reference stimulus length of 1 s. The methods used to obtain this value were a transformed staircase method, with the minimum step size being 10 ms as opposed to the nonadaptive method of limits used by Güçlü, Sevinc, and Canbeyli (2011). This change in methodology perhaps could be reasonable for the difference in Weber fractions obtained by the two authors; which is similar to that seen in the amplitude DL by Gescheider et al. (1990).

Güçlü, Sevinc, and Canbeyli (2011) stated that this deviation from Weber's law has been reviewed in the literature. They said: "In the literature on timing, the proportionality between temporal variability of behavioral output and stimulus duration is called the scalar property, akin to Weber's law."

In this paper, a further aim of our experiments was to determine the minimum temporal difference required for the participants to detect the difference from the reference stimulus, by varying the signal frequency.

Temporal Gap Detection

Temporal gap detection (TGD) refers to an individual's ability to detect a silent gap between two or more concatenated pulses (the stimuli onset interval, SOI). TGD falls into the subject area of temporal resolution. Temporal numerosity discrimination, TND, explores the ability to count successive multiple stimuli. Lechelt (1975) described a study on how the number and rate of pulses presented per second affected an individuals' ability to count them; in which they varied modality. The study outcome showed that the auditory modality was best in this regard, individuals performing with very high accuracy under all tested conditions. For those concerned the tactile sense generally resulted in underestimation which increased linearly as the rate of stimuli presented per second increased. However, it was when the visual system was studied that individuals performed least accurately, typically underestimating the number of stimuli presented.

This result was commented on by Verrillo and Gescheider (1992) who concluded that "Lechelt's data indicated that numerosity judgements require short-term memory." Within the literature on temporal gap detection, whilst there is a large number of publications covering the auditory sense, the "literature concerning this measurement for the tactile sense is very scanty" as stated by Verrillo and Gescheider (1992). The factors found to affect tactile TGD are as follows: hemisphere (left hand versus right hand); audio-tactile integration; modality (audio, tactile, visual); age and frequency; sequential pulse number; and mechanical taps (Verrillo and Gescheider 1992).

Bresciani and Ernst (2007) interestingly reported on a reduction in TGD of two sequential stimuli as the frequency was increased; i.e., 65 and 72 ms to 60 and 50 ms, when the frequency was changed from 35 to 500 Hz.

Philippi, Van Erp, and Werkhoven (2008) conducted a numerosity study, the results reported an average of the tested individuals' responses to a particular number of stimuli with a number of set stimulus onset intervals (SOIs); hence the results stated (i.e., for 3, 4 and 5 pulses, SOI was ~20, 80–160, and 160–320 ms, respectively) are given in ranges of values and not the exact values. However, the only specific information given with regards to the tactile stimuli was that it was a pulse.

In this paper, we describe how a temporal numerosity discrimination task has been conducted, however, here the SOI was the main target variable. Essentially the task for the participants was to count the number of stimulation pulses (between 1 and 5) as the time between the pulses tended to zero.

Method

Participants

Two groups of individuals took part in the experimentation in order that we could evaluate the perceptual benefits of subdermal magnetic implants, an implanted group and a superficial group. Each group had six male subjects and one female subject (mean 28 years, SD 7 years). The superficial group members were chosen such that they each matched a member of the implanted group for age and gender. Whilst conducting the experimentation the superficial group members had the same magnets attached, through cyanoacrylate (superglue), to the same location of their counterpart, but these were positioned on the outside of their fingers, rather than being implanted. The participants are summarized in Table 2.

Experimental Setup

To induce stimulation to the magnets, a custom made electromagnetic coil was produced. This coil created varied electromagnetic fields to induce movement of the magnets, which could therefore be detected by cutaneous mechanoreceptors. This stimulation is further referred to as magnetically induced vibrotactile stimulation, MIVS. An IMG Stage Line, STA-235 1400 W Profession Power Amplifier was used to provide power to the created coil. This amplifier was then connected to a PC through standard audio cabling which enabled transmission of the stimulation signals. The created coil's inner diameter was 18 mm which was chosen such that the subject's fingertips could be positioned in the coil's center as shown in Figure 1. Positioning of both the fingertip and palm participants are shown in Figure 1.

Psychometric Procedure

The adaptive psychometric procedure chosen for the experimentation was QUEST, developed by Watson and Pelli (1983). This was implemented using

Table 2. Participants summary. Unique ID: I/S implanted or superficial, 1–7 pair number, L/R left or right hand, P/I/M/R—lateral palm or index, middle, or ring finger pad. Sex, male/female. Age, the age of the participant on the test day. Implant Type. 1—NdFeB (48 MGO), 3.4 mm diameter and 0.73 mm thick, coated with Parylene C. 2—NdFeB (48MGO), 3.19 mm in diameter and 6.45 mm length, coated with Parylene C. 3—NdFeB (48MGO), 3 mm diameter 1 mm thick with a silicone coating (to the knowledge of the participant).

Unique ID	Sex	Age	Implant type
I1LI	M	36	1
I2LP	M	39	2
I3LI	M	24	1
I4RM	M	25	1
I5RM	M	23	1
I6LR	M	28	1
I7LR	F	21	3
S1LI	M	36	1
S2LP	M	39	1
S3LI	M	24	1
S4RM	M	25	1
S5RM	M	24	1
S6LR	M	28	1
S7LR	F	22	1

Figure 1. Fingertip location in coil (left) and palmside hand location above the coil (right).

the psychophysics toolbox created for Matlab and the settings used were standard QUEST parameters as given in the toolbox.

The parameters for each of the five experiments are given in Table 3. For each of the four 2IFC experiments, 44 trials were used per test, for the five alternative forced choice experiments 220 trials were used per test. After each trial the participant was able to repeat the trial once to avoid acquiescent data.

Visual representations of example stimulation signals are given in Figure 2. To avoid over stimulating the participants and to ensure participant comfort, the amplitude for each participant was subjectively set prior to the experimentation. This was found by the participant adjusting the amplitude of the amplifier output while being subjected to 10 s, 200 Hz, sine wave stimulation signal.

In each of the three DL experiments the threshold above the reference stimuli was measured, for example, in the amplitude DL experiment the difference above 0.5 times the participant dependent amplitude was measured. Furthermore, the results of these three experiments are expressed as Weber fractions, defined as the change in stimulus intensity over the reference intensity. For example, in the frequency DL experiment, if the participant was able to detect a 4 Hz change at 20 Hz (i.e., reference frequency 20 Hz, and target stimulus 24 Hz), the Weber fraction would be 0.2.

Each of the experiments had a different number of tests within them. These tests along with further details are described individually as follows.

Table 3. Summary of experimental parameters.

	Amplitude	Signal length (ms)	Separation time (ms)	Frequency (Hz)	Waveform	CRR (%)	Paradigm
Amplitude RL	*	1000	WT	20, 200	Sine	95	2IFC
Amplitude DL	$0.5 \times$ PD*	1000	1000	20, 200	Sine	95	2IFC
Frequency DL	PD	1000	1000	20*, 50*, 100*, 200*	Sine, Sq, Saw	82	2IFC
Temporal DL	PD	500*	1000	20, 200	Sine	95	2IFC
TNDwrTGD	PD	25, 250	*	20, 200	Sine	95	5AFC

PD, participant dependent; Sine, sinewave; Sq, square; Saw, sawtooth; CRR, correct response rate; WT, warning tones.
*Refers to the target variables. 2IFC—two interval forced choice, 5AFC—five alternative force choice.

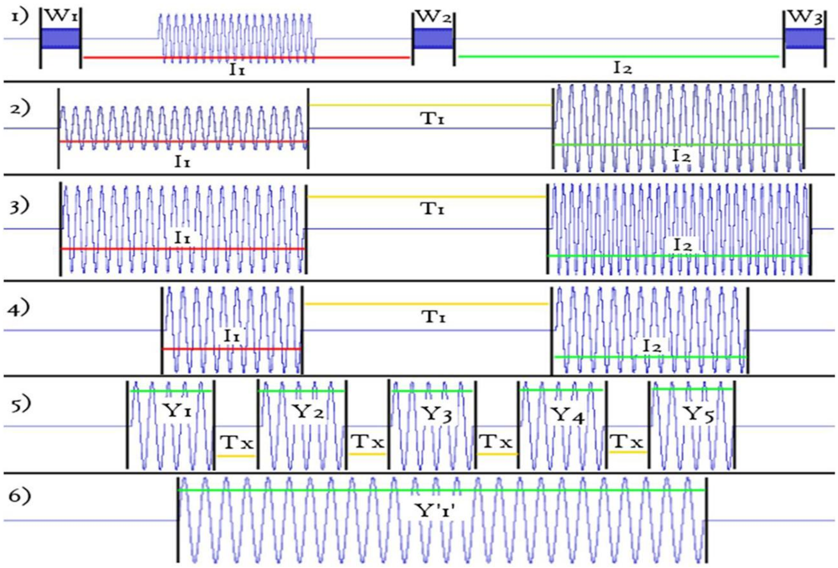

Figure 2. Experiment signals 1, amplitude RL. 2, amplitude DL. 3, frequency DL. 4, temporal DL. 5, TNDwrTGD, five signals example. 6, TNDwrTGD, five signals represented as "1."

Amplitude Detection

There were two tests conducted as part of this experiment, varying the stimulation signal's frequency between 20 and 200 Hz.

For each trial within each test the amplitude RL stimulation signal [Figure 2 (1)] comprised of two intervals, I1 and I2, separated by three warning tones W1-3, (200 Hz, 25 ms, sine wave). The 1 s stimulation signal was randomly placed in the center of one of the intervals per trial meanwhile the other interval was kept silent. After each trial the participant was asked "which interval has the highest amplitude?"

Amplitude Discrimination

Once more two tests were conducted as part of this experiment, varying the stimulation signal's frequency between 20 and 200 Hz.

For each trial within each test the amplitude DL signal [Figure 2 (2)] comprised of two intervals, I1 and I2, which were separated by a 1 s silent gap, T1. The reference stimulation signal was randomly placed into one of the intervals and the target was placed in the other. Both the reference and target stimulation signals were 1 s in length. After each trial the participant was asked "which interval has the highest amplitude?" In this case the reference stimulation signal was a silent gap (a signal with no amplitude) and the target was the threshold, i.e., The reference was what they were attempting to recognize and the target was the level of their threshold, in this case their minimum amplitude threshold.

Frequency Discrimination

There were 12 tests conducted as part of this experiment, varying the stimulation signal's frequency and waveform at 20, 50, 100, and 200 Hz, this being cross examined with sine, square and saw tooth waveforms. The waveform was postulated as a possible factor that could be altered to achieve varying tactile signals by Goff (1967). The multiple waveforms that were examined here were based on the hypothesis that the more complex waveforms (square and saw tooth) would enable a greater frequency DL at lower frequencies (20 and 50 Hz) due to their harmonic properties.

For each trial within each test the frequency DL signal [Figure 2 (3)] comprised of two intervals, I1 and I2, which were separated by a 1 s silent gap, T1. The reference stimulation signal was randomly placed into one of the intervals and the target is placed in the other. Both the reference and target stimulation signals were 1 s in length. After each trial the participant was asked "which interval has the highest frequency?"

Temporal Discrimination

Two tests were conducted as part of this experiment, varying the stimulation signal's frequency between 20 and 200 Hz.

For each trial within each test the temporal stimulation signal [Figure 2 (4)] comprised of two intervals, I1 and I2, which were separated by 1 s silent gap, T1. The 1 s stimulation signal was randomly placed in the center of one of the intervals per trial meanwhile the other interval was kept silent. After each trial the participant was asked "which interval was the longest in time?"

Temporal Numerosity Discrimination with Respect to Temporal Gap Detection

There were three tests conducted as part of this experiment, in which were varied signal length, frequency and therefore the cycle number per pulse. A pulse here refers to the short signal that is to be counted. The parameters for the three tests conducted simply altered the properties of the pulse, as summarized in Table 4.

For each trial within each test, the participant was randomly presented with 1, 2, 3, 4, or 5 pulses, a total of 44 times. For the pulse numbers above 1, the threshold we were looking for was the minimum time gap (T_x) such that they could still tell what the correct number of pulses was. The "1" pulse was randomly created from 1, 2, 3, 4, or 5 pulses with no temporal gap [Figure 2 (6)]

Table 4. TNDwrTGD pulse type definitions and QUEST threshold summary, N.B. Number of cycles is in references to the number of complete cycles of the sinewave per pulse.

Test	Frequency (Hz)	Pulse length (ms)	Number of cycles	Threshold estimation (ms)
1	200	250	50	100
2	200	25	5	150
3	20	250	5	100

for an example of a 5 pulse length “1” pulse). This was done to avoid the participants easily being able to distinguish a single pulse. The remaining pulses (2, 3, 4, and 5) each had a QUEST stimulation estimating the minimum T_x value required, i.e., the temporal gap detection threshold. After each trial the participants answered the question “how many pulses did you feel (1, 2, 3, 4, or 5)?” The participants were also instructed to report 1 pulse if the pulse was perceived as being continuous (i.e., if no temporal gaps were felt).

Due to the large number of trials per test (220) there were three forced 2-min breaks after trial numbers 55, 110, and 165 to avoid participant fatigue. For clarification, four QUEST functions have been interleaved here to establish the threshold estimates for four separation times estimated per test; i.e., the fixed separation time between each pulse number (2, 3, 4, and 5).

Results

Amplitude Detection

Within the results for the amplitude detection experiment there are a number of outliers. As shown in Table 5 the results for I7LR and S2LP (20 Hz) and both thresholds for S7LR are far greater than the other participants. The I7LR and S7LR results have been omitted due to a failure in attaining their threshold, i.e., a failure in the experiment. An early mistake in the QUEST methodology makes the true threshold unattainable in a set number of trials due to its optimization technique. S2LP (20 Hz) is somewhat similar although here the participant was stimulated outside of the coil (Figure 1). As both S2LP and I2LP were stimulated in the same area (i.e., left lateral palm area) all of their results for this experiment have also been omitted due to the reduced number of cutaneous mechanoreceptors in the hand compared with the fingertip (Kaczmarek et al. 1991). Figure 3 presents these results without the mentioned outliers. A summary of these results are presented in Table 6.

Amplitude Discrimination

The only result in Table 7 suspected to be an outlier is S7LR 200 Hz, marked in red in Table 7. The results are assumed to be much higher than this

Table 5. Amplitude detection threshold as estimated coils B field (mT). UID—unique ID as presented in Table 2.

UID	20 Hz	200 Hz	UID	20 Hz	200 Hz
I1LI	0.38	0.36	S1LI	0.68	0.24
I2LP	1.07	0.06	S2LP	9.37	0.49
I3LI	0.31	0.02	S3LI	1.02	0.03
I4RM	0.73	0.03	S4RM	1.38	0.27
I5RM	0.43	0.03	S5RM	1.2	0.08
I6LR	1.02	0.02	S6LR	1.50	0.92
I7LR	12.05	0.03	S7LR	25.15	13.66

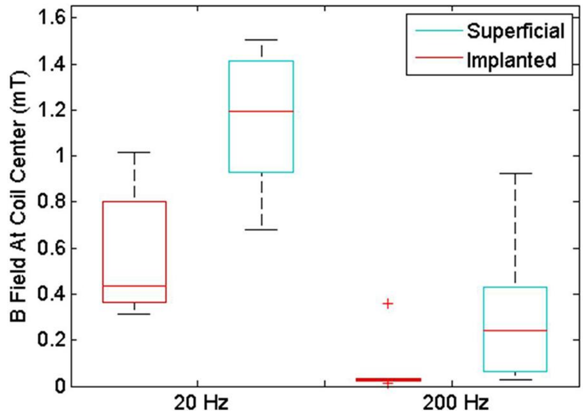

Figure 3. Amplitude RL results (without outliers) presented as the estimated coils B field (mT).

particular participant's actual threshold. This assumption is based on observation of the QUEST output from S7LR (Harrison 2015). Hence it has been removed.

A summary of these results are presented in Table 8 and Figure 4 in terms of Weber fractions.

Table 6. Amplitude detection threshold as estimated coils B field (mT).

Frequency	Group	Mean	STD	Median
20 Hz	Implanted	0.58	0.29	0.43
	Superficial	1.16	0.32	1.20
	Both	0.87	0.42	0.87
200 Hz	Implanted	0.08	0.14	0.03
	Superficial	0.31	0.36	0.24
	Both	0.18	0.27	0.03

Table 7. Weber fractions for amplitude discrimination experiment.

UID	20 Hz	200 Hz	UID	20 Hz	200 Hz
I1LI	0.06	0.09	S1LI	0.07	0.18
I2LP	0.09	0.20	S2LP	0.20	0.21
I3LI	0.11	0.11	S3LI	0.16	0.15
I4RM	0.33	0.25	S4RM	0.12	0.20
I5RM	0.13	0.22	S5RM	0.09	0.13
I6LR	0.10	0.24	S6LR	0.10	0.11
I7LR	0.20	0.30	S7LR	0.31	0.83

Table 8. Statistics summary of Weber fraction for amplitude DL.

Frequency	Group	Mean	STD	Median
20 Hz	Implanted	0.15	0.09	0.11
	Superficial	0.15	0.08	0.12
	Both	0.15	0.08	0.11
200 Hz	Implanted	0.20	0.08	0.22
	Superficial	0.16	0.04	0.17
	Both	0.18	0.06	0.20

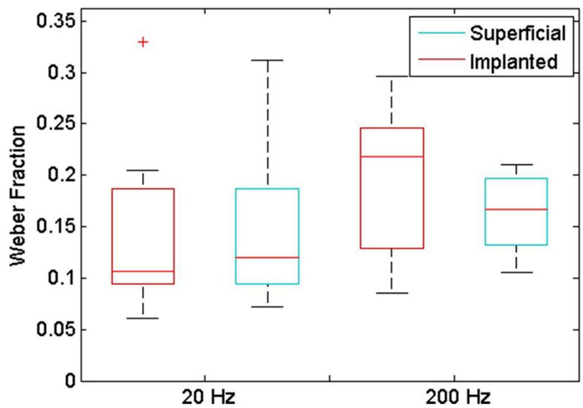

Figure 4. Amplitude DL results (without outlier) presented as Weber Fractions.

Frequency Discrimination

The results for the frequency DL experiment showed no real-world reason to remove any outliers, as such the entire participant data is presented in Figure 5. A statistical summary of the results is presented in Table 9.

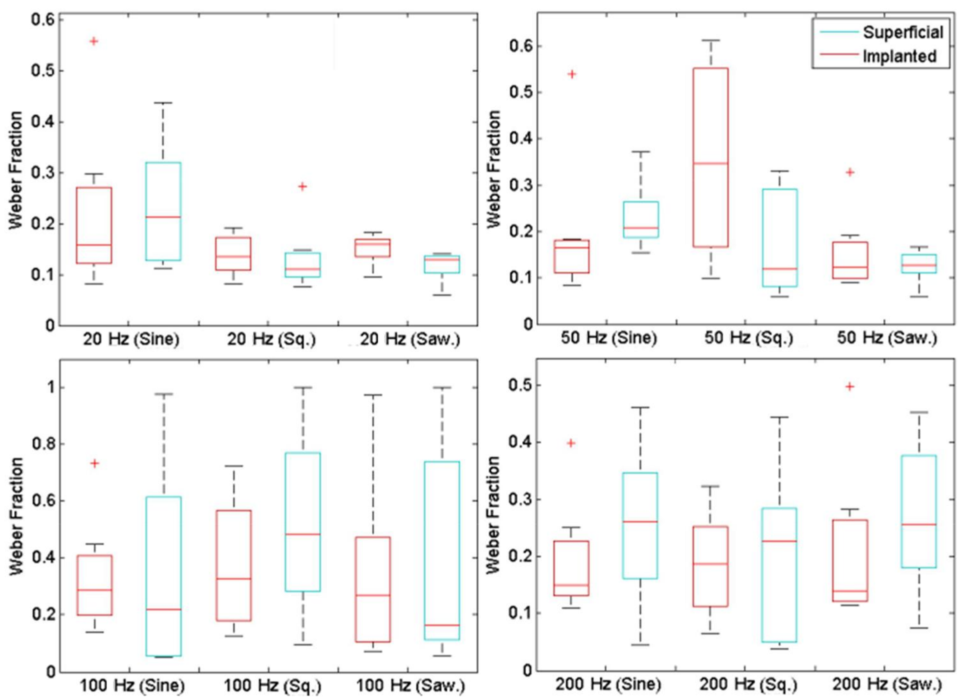

Figure 5. Frequency DL results presented as Weber Fractions. Sine—sinewave, Sq.—square wave, Saw.—sawtooth waveform.

Table 9. Statistics summary of Weber fraction for frequency DL. Sine—Sine wave, Sq.—Square wave, Saw.—Saw tooth Waveform.

Test	Group	Mean	STD	Median	Test	Group	Mean	STD	Median
20 Hz (Sine)	Implanted	0.22	0.16	0.16	100 Hz (Sine)	Implanted	0.33	0.20	0.28
	Superficial	0.23	0.12	0.21		Superficial	0.36	0.36	0.22
	Both	0.22	0.14	0.17		Both	0.35	0.28	0.25
20 Hz (Sq.)	Implanted	0.14	0.04	0.13	100 Hz (Sq.)	Implanted	0.38	0.23	0.33
	Superficial	0.13	0.07	0.11		Superficial	0.50	0.32	0.48
	Both	0.13	0.05	0.12		Both	0.44	0.28	0.40
20 Hz (Saw.)	Implanted	0.15	0.03	0.16	100 Hz (Saw.)	Implanted	0.34	0.32	0.27
	Superficial	0.12	0.03	0.13		Superficial	0.38	0.40	0.17
	Both	0.13	0.03	0.14		Both	0.36	0.35	0.21
50 Hz (Sine)	Implanted	0.20	0.16	0.16	200 Hz (Sine)	Implanted	0.19	0.10	0.15
	Superficial	0.23	0.07	0.21		Superficial	0.26	0.14	0.26
	Both	0.22	0.12	0.18		Both	0.22	0.12	0.17
50 Hz (Sq.)	Implanted	0.35	0.21	0.35	200 Hz (Sq.)	Implanted	0.19	0.09	0.19
	Superficial	0.17	0.11	0.12		Superficial	0.19	0.15	0.23
	Both	0.26	0.19	0.19		Both	0.19	0.12	0.20
50 Hz (Saw.)	Implanted	0.15	0.08	0.12	200 Hz (Saw.)	Implanted	0.21	0.14	0.14
	Superficial	0.13	0.04	0.13		Superficial	0.27	0.13	0.26
	Both	0.14	0.06	0.13		Both	0.24	0.13	0.21

Temporal Discrimination

Similar to the previous experiment, the results for the temporal DL experiment showed no apparent reason to remove any outliers; as such the entire participant data is presented in Figure 6, meanwhile a statistical summary of the results is presented in Table 11.

Temporal Numerosity Discrimination with Respect to Temporal Gap Detection

Similar to the previous experiment, the results for the TNDwrTGD experiment showed no reason to remove any outliers; as such the entire

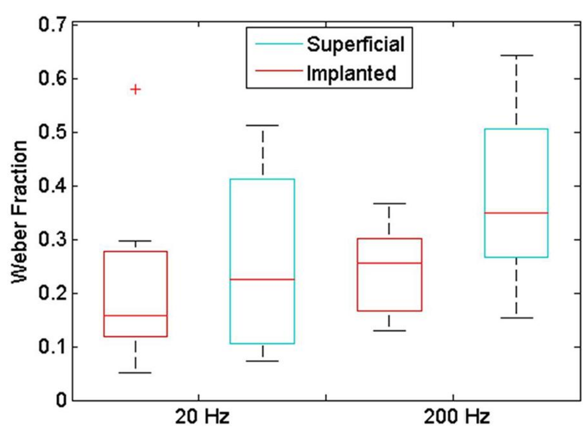

Figure 6. Temporal DL results presented as Weber fractions.

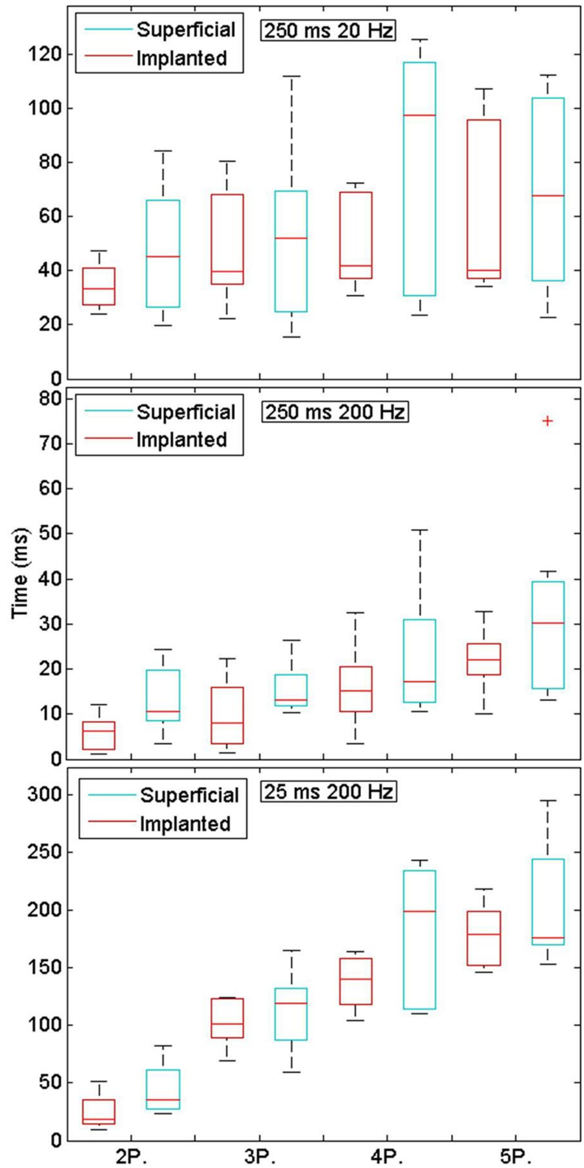

Figure 7. TNDwrTGD results presented as participants separation time. 2-5P. Refers to the pulse number.

participant data is presented in Figure 7 and a statistical summary of the results is presented in Table 10.

Discussion

The statistical models mentioned in this section were computed using IBM's SPSS.

Table 10. Statistics summary of TNDwrTGD results presented as participants separation time.

		200 Hz 250 ms (ms)			200 Hz 25 ms (ms)			20 Hz 250 ms (ms)		
Pulse no.	Group	Mean	STD	Median	Mean	STD	Median	Mean	STD	Median
2	Implanted	5.70	4.02	6.26	25.24	14.81	18.56	34.42	8.40	33.25
	Superficial	13.25	7.47	10.53	43.90	22.50	35.38	47.08	24.04	45.11
	Both	9.48	6.96	8.61	34.57	20.70	31.73	40.75	18.50	34.42
3	Implanted	10.41	7.82	7.95	103.51	21.34	101.44	48.80	21.41	39.67
	Superficial	15.81	5.66	13.17	113.91	35.10	119.36	52.98	33.25	52.15
	Both	13.11	7.13	12.91	108.71	28.42	113.53	50.89	26.96	45.91
4	Implanted	15.81	9.34	15.09	138.19	23.31	140.29	51.17	17.44	42.07
	Superficial	23.00	14.61	17.21	177.99	60.42	199.08	78.28	44.61	97.47
	Both	19.41	12.36	16.17	158.09	48.60	148.75	64.72	35.45	56.98
5	Implanted	21.94	7.11	22.16	178.80	27.15	179.37	63.48	32.82	40.11
	Superficial	32.09	21.76	30.20	206.38	52.21	175.86	71.88	37.08	67.89
	Both	27.02	16.42	23.42	192.59	42.47	177.62	67.68	33.92	66.68

Amplitude Detection

The data presented in Figure 3 suggest that a small amount of current was required to stimulate the individuals in both groups. However, the results clearly indicate that the implanted group required a smaller current than the superficial group. Furthermore, the results also indicate that as the frequency was changed from 20 to 200 Hz the current required for stimulation reduced in both groups.

To investigate this further, the results with outliers removed have been fitted to mixed models in SPSS. The results from the model showed that ~28% of variance was explained by the model. This result is unsurprising given the highly subjective nature of this measurement. The implanted group required a significantly lower magnitude of the B field for amplitude RL than the superficial group [$F(1,9.205) = 8.321$, $P = 0.018$]. The assumed reason for this reduction is that the skin's elasticity is greater than that of the mechanical resistance within the tissue; movement is therefore less restricted within the soft tissue compared to the skins surface.

The 200 Hz stimulation frequency significantly reduced intensity RL when compared with the 20 Hz stimulation frequency [$F(1,8.901) = 40.056$, $P < 0.001$]. This result is in agreement with the resultant U-shape response of amplitude RL described by Verrillo (1963). Within the context of this research the results suggest that for stimulation in high stress scenarios, it is more cost effective (in terms of power) to use a higher frequency for

Table 11. Statistics summary of weber fraction for temporal DL.

Frequency	Group	Mean	STD	Median
20 Hz	Implanted	0.22	0.18	0.16
	Superficial	0.25	0.18	0.22
	Both	0.24	0.17	0.20
200 Hz	Implanted	0.25	0.09	0.25
	Superficial	0.37	0.17	0.35
	Both	0.31	0.15	0.27

stimulation. There was no significant interaction between frequency and implant type found within this model.

For the implanted participants with magnet type 1 (Table 2), and their superficial counter parts, an approximate force estimation to perceive MIVS has been calculated in Table 12. These estimations have been established by utilizing the results of the "flipping experiment" described in Harrison (2015). These results are less than that obtained by Israr, Choi, and Tan (2006), who reported absolute amplitude thresholds of ~3.3E−2 N and ~2.7E−4 N for 20 and 200 Hz, respectively. However, the experiment used to calculate these force values is only an approximation.

It is evident that a 200 Hz stimulation signal is more favorable in comparison with a 20 Hz stimulation signal for the application of data transfer within high stress scenarios. The 200 Hz signal not only reduces the required power for stimulation but also has a more advantageous nature with regards to the perceived sensation. The 20 Hz sine wave stimulation signal is a less prominent stimuli, which is often described as a "flutter," whereas the 200 Hz sine wave stimulation signal feels more invasive, which the first (implanted) author describes as a buzz.

Amplitude Discrimination

The range of Weber fraction values (Table 8), 0.15–0.26, is in agreement with the literature. As previously discussed, Craig (1972) stated the Weber fractions of vibrations determined by Knudsen (1928), Sherrick (1950), and Schiller (1953), as 0.3, 0.11, and 0.05, respectively.

Figure 4 suggests that the 20 Hz stimulation frequency gave reduced Weber fractions in comparison to those at 200 Hz. In a similar fashion to the amplitude RL results, a mixed model was fitted to these results. As with the amplitude detection experiment a large number of personal factors can attribute to variations in the amplitude discrimination experiment. As anticipated the variance explained by the participant data for this model was rather large at ~66%. The implant type and interaction effects present no significant issue. The model does though provide evidence that the frequency of stimulation signal significantly increased the Weber fractions of the participants when changing from 20 to 200 Hz [$F(1, 10.09) = 5.102$, $P = 0.047$].

Table 12. Amplitude detection threshold as estimated force for participants of magnet type 1 (see Table 2).

Frequency	Group	Estimated force (N)
20 Hz	Implanted	1.56E−4
	Superficial	3.14E−4
	Both	2.35E−4
200 Hz	Implanted	2.50E−5
	Superficial	8.34E−5
	Both	5.42E−5

Whilst this result is in contrast to that presented by Forta, Griffin, and Morioka (2012) these authors did conduct their experimentation at different frequencies (10 and 125 Hz), and different contactor sizes (1 mm diameter and 10 mm diameter). Furthermore, the reference amplitude for their experiment was based on the decibel difference from their subjects' RL. Such differences can dramatically affect Weber fractions of this nature as discussed earlier in this document.

Bossomaier (2012) discussed the Meissner Corpuscles stating "Their primary role is sensing surface texture and properties by stroking or touching something which is now moving past or vibrating." This increase in ability to discriminate amplitudes (i.e., displacement of the skin) could have arisen from an evolutionary adaptation, as surface texture discrimination is one of the primary functions of the touch sense.

This experiment uses a gated pedestal trial paradigm. For application purposes the better solution would be to perhaps use a continuous pedestal method. This has also been shown to reduce amplitude DL (Knudsen 1928; Gescheider et al. 1990; Gescheider, Zwislocki, and Rasmussen 1996). However, the reason for using the methodology we did use was to eventually use adaptive amplitudes in collaboration with temporal numerosity, such that the information transfer signal would be constructed of a varied pulse number each with perhaps two levels of amplitude. This would increase the dimensions of the signal and overall increase the rate of transfer of information to the individual. While the 20 Hz stimulation frequency has shown empirically to be a better frequency for amplitude DL, overall the 200 Hz signal is still regarded as better for the reasons discussed in the previous section.

Frequency Discrimination

From the data presented for the 20 Hz reference (top left Figure 5) it is clear that the use of complex waveforms (square and saw tooth) increased the participant's ability to discriminate frequency. Once again individual participant variation is evident within this data particularly for the 20 Hz sine wave frequency discrimination task. The data presented from the 50 Hz reference suggests that the saw tooth waveform is the optimum choice for increasing frequency discrimination capabilities of the participants tested. Meanwhile the square waveform seemed to dramatically increase participant variation.

Figure 5 suggests there are differences between the implanted and superficial groups in particular results. For example, the 50 Hz sine wave results for the implanted group are overall reduced in terms of Weber fractions compared to the superficial group, i.e., the implanted group were more sensitive to the stimulation. However, by observing the 20 Hz saw tooth waveform the superficial group seemed to outperform (in terms of being more sensitive than) the implanted group. This coupled with the large subject variation indicates the implant type does not have an effect upon these two frequency references with regards to frequency discrimination.

The results from the 100 Hz trials show a remarkably high range of values. The standard deviation values for the 100 Hz tests, presented in Table 9, are almost double the majority of the other frequencies tested. This indicates that the task was certainly challenging for the participants. This observation has been previously commented on that frequency discrimination "is poor above 100 Hz" (Sherrick 1950; Sherrick and Cholewiak 1986). As discussed in Harrison (2015) between 100 and 200 Hz there is a crossover in frequency response range from the Meissner corpuscle and the Pacinian corpuscle. This crossover could be causing confusion in vibrotactile perception in this range, hence making this task difficult to complete.

The results of the participant's data for the 200 Hz reference frequency DL experiment seem consistent regardless of the stimuli's waveform. Overall the results seem to indicate that as previously hypothesized, the frequency discrimination thresholds measured at the lower frequencies (20 and 50 Hz) are affected by complex waveforms, whereas at higher frequencies (100 and 200 Hz) frequency thresholds are unaffected by complex waveforms. The postulated reason for increased discrimination capabilities at lower frequencies comes from the interaction of the harmonics of the complex waveforms upon the dermis. These harmonics predictably not only stimulate the Meissner corpuscles within their optimum range (20–40 Hz), but stimulate the Pacinian corpuscles also (optimum range 200–400 Hz) (Harrison 2015).

From Table 9, the results for sinewave stimuli are: 0.22, 0.22, 0.35, and 0.22, for the 20, 50, 100, and 200 Hz reference frequencies, respectively. Aside from the 100 Hz results, on average the participants' performance in this experiment does conform to Weber's law (Kingdom and Prins 2010). These results are largely in agreement with the results attained by Goff (1967), i.e., ~0.18, ~0.19, ~0.3, ~0.28, and ~0.37 for 25, 50, 100, 150, and 200 Hz. The difference in our results to Goff's could be due to differences in experimental methodology. For example, within Goff's experiments the amplitude of the stimuli were set with reference to the absolute threshold of intensity for each subject. Meanwhile in our experiments the amplitude was subjectively set to a comfortable level for each participant.

Five statistical models have been fitted to this data. The first four are aimed at individually examining the reference frequencies to determine the effects of waveform. The final model has been fitted to the entire dataset to determine if the 100 Hz results are statistically different to the other three. The model type used was mixed models for all of the models except for the 20 Hz reference, where a univariate model was used.

A summary of the results of models 1–4 is presented in Table 13. The largest variance explained by the participants' data was the 200 Hz, the fourth

Table 13. Summary of models 1–4 fitted to the frequency discrimination Weber fractions, individually examining each reference frequency for waveform effects.

	Model number			
Factors and effects	1 (20 Hz)	2 (50 Hz)	3 (100 Hz)	4 (200 Hz)
Participant's variance (%)	N/A	~20%	~49%	~64%
Waveform	$P = 0.017$*	$P = 0.027$**	$P = 0.457$	$P = 0.241$
Implant type	$P = 0.772$	$P = 0.252$	$P = 0.630$	$P = 0.487$
Implant type × waveform	$P = 0.832$	$P = 0.058$	$P = 0.843$	$P = 0.557$

*$F(2,36) = 4.540$, $P = 0.017$.
**$F(2,24) = 4.222$, $P = 0.027$.

model. This is interesting in that the range of values attained within the 100 Hz task was a lot larger than that with 200 Hz. This result suggests that the participants were slightly more consistent in their error per waveform whilst performing this task.

As anticipated from the previously explained hypothesis the waveform showed significance for the 20 and 50 Hz reference frequencies. Post hoc analysis with Šidák correction was conducted upon the waveform factor to ascertain which variables caused these significant values. A summary of this is presented in Table 14.

The results in Table 14 combined with Table 9 show that the complex waveforms for the 20 Hz reference both significantly improved the participants' ability to perform the frequency discrimination experiment. The pairwise comparison of the 50 Hz reference revealed that the only significant difference that is present is between the square and saw tooth waveforms. Exploring the mean results presented in Table 9 gives reasons for this, however it still indicates that on average the saw tooth wave increases the participants' ability to discriminate frequencies.

Unsurprisingly the output of model 5 showed that the 100 Hz reference frequency is statistically different to the other three reference frequencies. This is based on a Šidák pairwise comparison ($P < 0.001$) for each other reference frequency.

A proposed method for relaying information to an individual using frequency changing stimuli would be to use concatenate signals with no SOI (i.e., continuous pedestal). Sinclair and Burton (1996) (as previously discussed) have shown that as SOI increases so the ability to accurately discriminate frequency significantly decreases. From undocumented testing

Table 14. Pairwise comparison results for models 1–2 exploring the variables of waveform to determine underlying significance of the different waveforms (i.e., sine, square, and sawtooth).

		Square	Sawtooth
Model 1 (20 Hz)	Sine	$P = 0.04$*	$P = 0.038$*
	Square		$P > 0.999$
Model 2 (50 Hz)	Sine	$P = 0.657$	$P = 0.227$
	Square		$P = 0.025$*

*The mean difference is significant at the 0.05 level.

on the first author, the continuous pedestal method does indeed make the discrimination task easier to comprehend, which is essential for a high stress scenario.

Some anecdotal evidence was obtained in terms of remarks from various participants post completion of the tests. For lower frequencies (20–70 Hz) the saw tooth waveform can be recommended for two reasons. First, it was shown to increase one's ability to discriminate frequencies. Second the saw tooth waveform was felt to be more intrusive than the sine and square waveforms, which is essential for warning alerts in high stress scenarios. For higher frequencies (200–300 Hz) however the square waveform was recommended due to its intrusive nature.

A final point of interest was in terms of the frequency discrimination experiment. A number of participants from both groups, including the author, completed this experiment using a synesthetic like ability; in that rather than just perceiving the vibrotactile stimuli, some commented that they could hear the frequency change. The following quotes are from participants while undergoing the experiment (N.B. these were entirely unprompted):

"That's weird I'm sort of hearing it" - I4RM

"It kinda feels like when a motor goes buzz or hmmm" - S5RM

"I turn the signal into sound" - I1LI.

While further discussion of these comments is omitted from this paper as it did not fall immediately within the context of the research, its inclusion in this section was thought to complement the quantifiable results.

Temporal Discrimination

Through observation of the results in Figure 6 it appears that the 200 Hz stimulation frequency slightly increased the participants' temporal discrimination threshold. This observation is emphasized through examination of the mean results for both groups presented in Table 11; 0.24 and 0.31 for the 20 and 200 Hz stimulation frequencies, respectively.

The closest comparable result (due to the variables used) is that presented by Güçlü, Sevinc, and Canbeyli (2011), who examined temporal DL with a 500 ms reference (250 Hz sine wave) signal, and reported a Weber fraction of 0.4. While the result obtained by the experiment conducted in this research is smaller than this, i.e., 0.31 (Table 11, mean 200 Hz, from both groups), the difference can be attributed to the different methodologies used and a variation in stimulation signal (i.e., a 250 ms 200 Hz signal used for this experiment).

Statistical analysis of the results of this experiment has been once again done using a mixed model. The variance explained by the participants' data is ∼26%, however none of the factors examined have shown to be significant. This is unsurprising given the results presented in Figure 6 and Table 11.

The aim of this experiment was to empirically determine whether a change in frequency affected an individual's ability to perform a temporal discrimination task. Through qualitative and quantitative analysis this was found not to be the case for the participants. If changes in signal length were used to relay information, to be effective the stimuli would need to alter in another variable (e.g., frequency) as well. For instance a stimulus signal comprised of a 100 ms, 50 Hz saw tooth signal concatenated (with no SOI) with a 200 ms, 200 Hz square wave signal. Another possibility would be to use it in conjunction with temporal numerosity much like Morse code. For example, a long pulse then short pulse then long pulse could be used to relay a particular piece of information.

Temporal Numerosity Discrimination with Respect to Temporal Gap Detection

The results (Figure 7) for each of the three pulse types show that a similar somewhat linear increase in separation time is required for the participants to correctly identify the number of pulses. Table 12 presents a summary of the R^2 statistics and the fitted linear equations as generated by IBM's SPSS.

For example, the 200 Hz, 25 ms pulse type has a far greater gradient when compared to the other pulse types, which can be further observed in the regression statistics presented in Table 12. The assumed reason for this change required in gap time for the correct perception of pulse number, between these two pulse types is the effect of temporal summation. Another difference is found between the 200 Hz, 250 ms pulse type and that at 20 Hz, 250 ms. The gradient is similar between the two, however the intercept is much greater in the 20 Hz, 250 ms pulse.

The regression statistics shown in Table 12 describe a strong linear correlation between pulse number and separation time for the 200 Hz, 25 ms pulse type ($R^2 = 0.717$). This can be observed numerically from the mean and standard deviation results presented in Table 10. However, for the 20 and 200 Hz, 250 ms pulse types the regression statistics presented suggests that only a week linear correlation is present, i.e., $R^2 = 0.121$ and 0.262, respectively (see Table 15).

This could be attributed to a number of factors. For example, the test methodology itself could have caused some confusion or fatigue effects, due to the length of each experiment, although this was attempted to be controlled, with mandatory breaks as discussed previously. Both of which could have caused estimation error on particular pulse numbers. An example of this error can be seen in mean results for the 20 Hz, 250 ms pulse type from the superficial group (presented in Table 12), 47.08, 52.98, 78.28, and 71.88 ms for the 2, 3, 4, and 5 pulse numbers, respectively. Here the 4-pulse result, 78.28, is assumed to be overestimated. Another possible factor could be that the underlying model that fits this data is not linear. Whilst these and other factors have been considered further discussion would require additional results.

Comparing the results obtained in this experiment to those presented in the literature, the closest comparable results are those achieved by Philippi, Van Erp, and Werkhoven (2008). Their results are based on a TND experiment with fixed SOIs for a given number of pulses. These results are the interpolated results from their presented results for 3, 4, and 5 pulses where the SOI was ~20, 80–160, and 160–320 ms, respectively. Their results show that a large increase in pulse separation time is required, for a "pulse" stimulus much like the 200 Hz, 25 ms pulse type used in this experiment. Another comparable result is that of Bresciani and Ernst (2007), who showed that separation time decreased as pulse frequency increased; i.e., 65–50 ms as frequency changed from 35 to 500 Hz. This result is similar to the comparison between the 250 ms, 20 and 200 Hz pulse types used in this experiment, i.e., 40.75–9.48 ms for the both group's 2-pulse TGD as shown in Table 10.

Three mixed models have been fitted to this data to cross examine the three test stimulation signals (Table 4):

- Model 1—compares the 200 Hz, 250 ms pulse type and the 20 Hz, 250 ms pulse type, examining frequency factor.
- Model 2—compares the 200 Hz, 25 ms pulse type and the 20 Hz, 250 ms pulse type, examining frequency factor.
- Model 3—compares the 200 Hz, 250 ms pulse type and the 200 Hz, 25 ms pulse type, examining the number of signal cycles factor.

A summary of each model is given in Table 10. Each of the factors of interest significantly affects the separation time required for these participants to correctly determine the number of pulses (see Table 16).

Model 1 results presented in Table 10 suggest that for a given pulse length, the higher frequency (200 Hz) significantly reduced the separation time required between pulses for correct pulse number perception when compared with the lower frequency (20 Hz).

Model 2 results presented in Table 10 suggest that for a given number of sinusoidal cycles, the lower frequency (20 Hz) significantly reduced the separation time required between pulses for correct pulse number perception when compared with the higher frequency (200 Hz).

Model 3 results presented in Table 10 suggest that for a given frequency, the larger number of sinusoidal cycles (50) significantly reduced the separation time required between pulses for correct pulse number perception when compared with the smaller number of sinusoidal cycles (5).

The overall aim of this experiment was to minimize the total signal length required to convey information to an individual through this method in a

Table 15. Regression statistics for the three stimulations signals within the TNDwrTGD experiment. Statistics and equations generated using IBM's SPSS.

Stimulation signal	Fitted linear equation	R^2 statistic
250 ms 20 Hz	$y = 9.46x + 8.42$	0.121
250 ms 200 Hz	$y = 5.89x + 8.42$	0.262
25 ms 200 Hz	$y = 52.34x + 44.98$	0.717

high stress scenario. A summary of the total signal lengths dependent upon the gap time required per pulse number is presented in Table 17. These are based on the estimated mean separation times for both groups given in Table 10, as there was no significant difference found in implant type (Table 10).

As the 200 Hz, 25 ms pulse type has the shortest total signal lengths (Table 17), from those tested; it would be the optimum for use in high stress scenario applications. However, to empirically determine if this is actually the case, a choice reaction time test would need to be conducted, which has been left open for future work.

Whilst the waveform tested within this experiment was a sine wave, a square waveform would be better suited for application as it is perceptually

Table 16. Summary of the three statistical models fitted to the participant's TGD data. Acronyms used: Par—participant's variability, IT—implant type (implanted or superficial), F—frequency (20 or 200 Hz), PN—pulse number (2, 3, 4, or 5 pulses), NoC—number of cycles (5 or 50 cycles). N.B. Green highlighted boxes highlight results where $P < 0.05$ and blacked out boxes do not apply to that particular model.

	Model number		
Factors and effects	1	2	3
Par	~43%	~45%	~38%
PN	[$F(3,84) = 9.85$, $P < 0.001$]	[$F(3,84) = 78.331$, $P < 0.001$]	[$F(3,84) = 93.686$, $P < 0.001$]
IT	[$F(1,12) = 1.497$, $P = 0.245$]	[$F(1,12) = 2.192$, $P = 0.164$]	[$F(1,12) = 2.79$, $P = 0.121$]
IT × PN	[$F(3,84) = 0.646$, $P = 0.588$]	[$F(3,84) = 1.425$, $P = 0.241$]	[$F(3,84) = 1.425$, $P = 0.241$]
F	[$F(1,84) = 148.7$, $P < 0.001$]	[$F(1,84) = 217.831$, $P < 0.001$]	
F × IT	[$F(1,84) = 0.753$, $P = 0.388$]	[$F(1,84) = 1.453$, $P = 0.231$]	
F × PN	[$F(3,84) = 0.854$, $P = 0.468$]	[$F(3,84) = 37.824$, $P < 0.001$]	
F × IT × PN	[$F(3,84) = 0.631$, $P = 0.597$]	[$F(3,84) = 0.117$, $P = 0.950$]	
NoC			[$F(1,84) = 734.352$, $P < 0.001$]
IT × NoC			[$F(1,84) = 4.448$, $P = 0.038$]
PN × NoC			[$F(3,84) = 61.11$, $P < 0.001$]
IT × PN × NoC			[$F(3,84) = 0.571$, $P = 0.635$]

Table 17. Summary of total signal lengths (ms) for the given pulse type and the TGD threshold determined per pulse number.

	Pulse number				
Pulse type	1	2	3	4	5
200 Hz, 250 ms	250	509	776	1058	1358
200 Hz, 25 ms	25	84	292	574	895
20 Hz, 250 ms	250	541	852	1194	1521

more intrusive than the sine waveform. Further testing in this area would involve altering factors such as waveform, frequency and pulse length.

Conclusion

The experiments conducted have proved to be very successful. For the first time a detailed study has been performed comparing the scientific response to stimuli of implanted magnets with the same magnets positioned externally. The advantages, in terms of increased sensitivity, can therefore be clearly witnessed. Anecdotal evidence was also useful in giving an idea of what such stimulation actually "feels" like.

This paper has presented the results from five psychometric thresholding experiments, to evaluate SMIs. Through examination of individuals with SMIs and those whom have had them superficially attached to the dermis, the results suggest that individuals with the implant require significantly less amplitude to detect a stimulus (amplitude RL). The results of the remaining experiments will aid in the construction of stimuli to convey information in high stress scenarios. For instance, the results obtained in the frequency DL experiment showed the importance of the waveform of the stimulus, as altering this allows for greater discrimination.

The results from the TGDwrTND experiment will aid in the creation of the shortest possible numerosity intensity based stimuli, enabling the fastest response by the operator. Future work in this experimental line would see a choice reaction time conducted in tandem with this experiment to check cognition time correlates with signal length. Clearly however the results have shown that such implants provide a realistic potential interface route between technology and humans for a variety of applications.

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