The University Of Reading

Sensory Enhancement, A Pilot Perceptual Study of Subdermal Magnetic Implants

By

Ian Michael Harrison

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Declaration of Authorship

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged. All drawings not cited are original artwork created by the author.

Ian M. Harrison BSc.

Date

This work is lovingly dedicated to the late Angelina Olender,
who sadly passed away in the spring of 2011.

Gone but never forgotten.

Abstract

Subdermal magnetic implants originated as an art form in the world of body modification. To date an in depth scientific analysis of the benefits of this implant has yet to be established. This research explores the concept of sensory extension of the tactile sense utilising this form of implantation. This relatively simple procedure enables the tactile sense to respond to static and alternating magnetic fields. This is not to say that the underlying biology of the system has changed; i.e. the concept does not increase our tactile frequency response range or sensitivity to pressure, but now does invoke a perceptual response to a stimulus that is not innately available to humans.

Within this research two social surveys have been conducted in order to ascertain one, the social acceptance of the general notion of human enhancement, and two the perceptual experiences of individuals with the magnetic implants themselves. In terms of acceptance to the notion of sensory improvement (via implantation) ~39% of the general population questioned responded positively with a further ~25% of the respondents answering with the indecisive response. Thus with careful dissemination a large proportion of individuals may adopt this technology much like this if it were to become available for consumers. Interestingly of the responses collected from the magnetic implants survey ~60% of the respondents actually underwent the implant for magnetic vision purposes.

The main contribution of this research however comes from a series of psychophysical testing. In which 7 subjects with subdermal magnetic implants, were cross compared with 7 subjects that had similar magnets superficially attached to their dermis. The experimentation examined multiple psychometric thresholds of the candidates including intensity, frequency and temporal. Whilst relatively simple, the experimental setup for the perceptual experimentation conducted was novel in that custom hardware and protocols were created in order to determine the subjective thresholds of the individuals.

The overall purpose of this research is to utilise this concept in high stress scenarios, such as driving or piloting; whereby alerts and warnings could be relayed to an operator without intruding upon their other (typically overloaded) exterior senses (i.e. the auditory and visual senses). Hence each of the thresholding experiments were designed with the intention of utilising the results in the design of signals for information transfer.

The findings from the study show that the implanted group of subjects significantly outperformed the superficial group in the absolute intensity threshold experiment, i.e. the implanted group required significantly less force than the superficial group in order to perceive the stimulus. The results for the frequency difference threshold showed no significant difference in the two groups tested. Interestingly however at low frequencies, i.e. 20 and 50 Hz, the ability of the subjects tested to discriminate frequencies significantly increased with more complex waveforms i.e. square and sawtooth, when compared against the typically used sinewave.

Furthermore a novel protocol for establishing the temporal gap detection threshold during a temporal numerosity study has been established in this thesis. This experiment measured the subjects' capability to correctly determine the number of concatenated signals presented to them whilst the time between the signals, referred to as pulses, tended to zero. A significant finding was that when altering the length of, the frequency of, and the number of cycles of the pulses, the time between pulses for correct recognition altered. This finding will ultimately aid in the design of the tactile alerts for this method of information transfer.

Preliminary development work for the use of this method of input to the body, in an automotive scenario, is also presented within this thesis in the form of a driving simulation. The overall goal of which is to present warning alerts to a driver, such as rear-to-end collision, or excessive speeds on roads, in order to prevent incidents and penalties from occurring. Discussion on the broader utility of this implant has been presented, reflecting on its potential use as a basis for vibrotactile, and sensory substitution, devices. This discussion furthers with postulations on its use as a human machine interface, as well as how a similar implant could be used within the ear as a hearing aid device.

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Abbreviations

2D	Two Dimensional
3D	Three Dimensional
5-PS	5-Point Scale
ABS	Acrylonitrile Butadiene Styrene
AMD	Age-related Macular Degeneration
AVSS	Auditory Visual Sensory Substitution
BVD	Bilateral Vestibular Disorder
CAD	Computer Aided Design
CFCs	Chlorofluorocarbon Compounds
CNS	Central Nervous System
DC	Direct Current
DL	Difference Limen
DNAQ	Did Not Answer Question
DoF	Degrees of Freedom
EMF	Electro-Magnetic Field
EMG	Electromyography
FDA	U.S. Food and Drug Administration
FEA	Finite Element Analysis
FPS	Frames Per Second
Gov	Government
GUI	Graphic User Interface
Lab	Laboratory
LCD	Liquid Crystal Display
LCP	Leadless Cardiac Pacemaker
LED	Light Emitting Diode
LON	Local Operating Network
MC	Mental Chronometry
MEMS	Micro-Electro Mechanical System
MGOe	Mass-Gauss Oersteds
MIVS	Magnetically Induced Vibrotactile Stimulation
MnAl	Manganese Aluminium
MMT	Magnetically Driven Microtool
NaCl	Sodium Chloride
NdFeB	Neodymium Magnet
NHS	National Health Service
PC	Personal Computer
PDF	Probability Density Function
PF	Psychometric Function
PSU	Power Supply Unit
PWM	Pulse Width Modulation
PTFE	Polytetrafluoroethylene
RFID	Radio Frequency Identification Device
RA	Rapidly Adapting

RL	Reiz Limen
RMS	Root Mean Square
RT	Reaction Time
SA	Slowly Adapting
SPSS	Statistical Package for the Social Sciences
SSD	Sensory Substitution Devices
SSE	School of Systems Engineering
SSUS	Single Subject Unique Study
STD	Standard Deviation
TASS	Tactile Auditory Sensory Substitution
TBSS	Tactile Balance Sensory Substitution
TGD	Temporal Gap Detection
TMD	Temporomandibular Disorders
TMS	Transcranial magnetic stimulation
TND	Temporal Numerosity Discrimination
TVSS	Tactile Visual Sensory Substitution
UoR	University of Reading
WSAIL	Wormald Sensory Aids International Ltd.

Chapter 1 – Introduction

"Knowledge or Science is Nothing but Perception" – Plato [1]

Perception is defined in the Oxford English dictionary (2014) as; "the ability to see, hear, or become aware of something through the senses". In agreement with Plato, the author poses that knowledge or science is somewhat limited by the physiological capabilities of the human sensory organs. In order to combat these limitations, multiple measurement equipment has been created within technology (e.g. UV sensors, sonar systems and magnetometers) in order to increase our perceptual range, and make huge advancements in multiple areas. Medical technologies such as Magnetic Resonance Imaging, MRI, have hugely improved 'our' knowledge of the human body, and ultimately have led to advancement in patient care.

Within the world of science, postulations of key theories have been shown to have originated from observations of the world around us. A somewhat cliché example comes from the conception of the theory of gravity, posed by Sir Isaac Newton. In William Stukeley's Memoirs of Newton's life (1752) [2], Stukeley accounts on the time when Newton told him about his thought trail which led to such a vital theory.

> *"After dinner, the weather being warm, we went into the garden, & drank tea under the shade of some apple trees, only he, & myself. Amidst other discourse, he told me, he was just in the same situation, as when formerly; the notion of gravitation came into his mind. Why should that apple always descend perpendicularly to the ground, thought he to himself, occasioned by the fall of an apple, as he sat in contemplative mood" [2].*

If theories as significant as gravity were postulated in situations outside of the experimental confinement of the laboratory, with 'our' standard sensory systems and an insightful mind; what possible postulations could arise with the use of sensory augmentation or extension technologies, in everyday observations?

1.1 Background and Motivation

In this thesis the concept of sensory extension is explored, which is the concept of extending ones perceptual range. This is achieved, within this thesis, through the use of subdermal magnetic implants, SMIs. This simple implant enables an individual the ability to perceive magnetic fields via the tactile sense; which in turn enables contactless tactile sensations to be perceived, which (focusing solely on touch) is not innate to humans. The work presented is in continuation from the works of Hameed in 2009 [3] (Masters Dissertation), of which the author of this research collaborated with in 2010 [4].

SMIs originated in the world of body modification in the 90's. Multiple body modification artists, such as the agreed pioneer of this implant, S. Haworth [5], surgically implanting themselves with magnets and noticed that they could perceive electromagnetic fields, EMFs. Time variant EMFs cause an implanted magnet to move with the field in accordance to magnetic attraction law. This in turn stimulates the cutaneous mechanoreceptors and ultimately causes vibrotactile stimulation; further referred to as magnetically induced vibrotactile stimulation, MIVS.

A motivating factor behind this research is the overall goal to utilise this method of stimulation as a human machine interface for use within high stress scenarios. High stress scenarios such as driving or piloting put a major strain on the auditory and visual sense. This strain can cause the operator to have delayed reaction times, RTs, to potential incidents. Within driving specifically, stress levels inflicted upon drivers are often situational. Examples of such situations can be seen during the common occurrence of speed cameras on UK roads; which can be exacerbated by distractions such as the use of mobile phones.

Speed cameras are positioned in high accident prone areas [6], one of the criteria for which is 'number of personal injury collisions – 8 per Km in the last 3 years'. Areas such as these are where drivers should be entirely focused on the road and areas around the road e.g. pavements and pedestrian crossings, for potential hazards. However due to the penalty that could incur if the driver were to break the speed limit, it is quite common that drivers orientate the focus to their speedometer; ultimately leaving the drivers peripheral vision to observe any potential hazards. Furthermore if the hazard is too far out of the visual area the driver may not even perceive it, not react at all and ultimately

cause a road traffic incident. Relying solely on peripheral vision is also hazardous as multiple experimental results have shown that RTs to visual stimuli in the peripheral area are significantly increased when compared with that of the focal area [7, 8].

Experimental results presented by a number of authors [9, 10, 11] have shown that vibrotactile warning signals can significantly reducing driver RT's in breaking tasks. An application example for this research could be to provide speed information to the driver via MIVS. The driver could continuously be alerted at times where their speed is greater than the speed limit of their current position; enabling the driver to keep their visual focus on the road. Examples such as this coupled with information such as, rear-to-end collision alerts, have the potential to prevent incidents of collision from occurring

One of the overall goals of this research is thus to establish methods of converting information such as speed, or rear-to-end collision distances into MIVS. A specification for these alerts highly depends upon the application in question. However generic criteria for them would include the following: to be rapidly perceived, to be easily recognised, and to include an intensity weighting e.g. level of importance. In order to effectively produce these alerts certain perceptual thresholds must first be established when using MIVS. This along with determining any perceptual benefits to actually having the magnet implanted as opposed to superficially attached to the dermis are the main focuses of this research.

1.2 Contributions to Knowledge

1. A quantitative perceptual analysis of individuals whom possess an SMI. This analysis includes a cross comparison to individuals whom have magnets superficially attached via an adhesive. The perceptual analysis was conducted using a battery of psychophysics testing. Each experiment was conducted with the overall goal of determining variables that could eventually be used to create signals, to transfer information in situations such as high stress scenarios. In total there were six experiments conducted (each with a number of variables):
    - Simple Reaction Times
        - Comparing 4 different stimuli: auditory, MIVS, visual (focal area), visual (periphery)
    - Amplitude Detection

    - Varying signal frequency
  - Amplitude Discrimination
    - Varying signal frequency
  - Frequency Discrimination
    - Varying the standard frequencies and waveforms of signal
  - Temporal Discrimination
    - Varying signal frequency
  - Temporal Numerosity Discrimination With Respect To Temporal Gap Detection
    - Varying signal frequency, number of signals and signal length
2. A social survey which explores the personal views and experiences of individuals whom possess (or have possessed) SMIs. Furthermore a review of cases is presented where the explantation of SMIs was necessary.
3. A social survey which explores the views of individuals to questions regarding human enhancement.

1.3 Thesis Outline

This section presents the outline of the thesis by chapter number.

- **Chapter 1 – Introduction** – This chapter provides the overall introduction to the thesis discusses the background and motivation behind the research and outlines the contributions to knowledge.
- **Chapter 2 – Surveys Conducted** – This chapter presents the results of two surveys conducted in order to ascertain the views of the general public on human enhancement and the personal views of individuals whom possess (or have possessed) an SMI.
- **Chapter 3 – Literature Review** – This chapter reviews literature surrounding this area of study covering two proposed areas for application, i.e. sensory substitution, vibrotactile devices and haptics. Furthering with two areas of key consideration for this research, i.e. the limitations of human perception and finally restorative & experimental implants technologies.

- **Chapter 4 – Somatosensory Sensory Perception and Psychophysics** – This chapter provides a review of the key areas relating to this research which reviews the following:
  - The biological and neuronal structures which are part of the somatosensory system.
  - The doctrine psychophysics is presented which provides the reader with knowledge of the specific methodologies used within the perceptual experimentation.
  - The literature regarding each of the perceptual experiments conducted within this research; i.e. RTs, Amplitude Detection, Amplitude Discrimination, Frequency Discrimination, Temporal Discrimination and Temporal Numerosity Discrimination with respect to Temporal Gap Detection.
- **Chapter 5 – The Magnet, Implantation and Stimulation Coil** – This chapter provides covers a wide range of areas regarding SMIs which includes the following;
  - The properties of the author's SMIs.
  - The methodology of the implantation of the author's SMIs.
  - Personal accounts of individuals who have undergone the explantation procedure.
  - The creation of a custom made electromagnetic 'stimulation' coil (accompanied with experimentation ascertaining its B field properties).
  - The empirically determined surface magnetism of the author's index fingertip (conducted to approximate the orientation of the implanted magnet)
  - Empirically determined approximation of the force applied to the magnets from the created 'stimulation' coil.
- **Chapter 6 – Initial Investigation** – This chapter discusses the methodologies, experimental setup as well as presenting the results and discussion of two preliminary psychometric thresholding experiments (i.e. frequency discrimination and temporal numerosity discrimination with respect to temporal gap detection) self-conducted upon the author.
- **Chapter 7 – Participant Perceptual Experimentation** – This chapter introduces and describes the participant perceptual experimentation, which includes;
  - The ethical approval process.
  - The participant selection process.

  - The definition of the multiple studies conducted.
  - The experimental setup used.
  - Introductions and methodology of each of the experiments conducted per participant.
- **Chapter 8 – Results & Discussion** – This chapter presents and discusses the results from each of the experiments conducted within the participant experimentation.
- **Chapter 9 – Application – VDrift** – This chapter outlines the initial development work conducted on an open source driving simulator in order to simulate an automotive rear to end collision scenario and test the effects of pre-warning tones presented via MIVS.
- **Chapter 10 – Conclusions & Future Work** – This chapter summarises the findings of this thesis, examines the contributions to knowledge, describes the limitations of the research and finally presents the proposed future work for this research.

Chapter 2 – Surveys Conducted

2.1 Introduction

For this research to be utilised on a global scale, the population would have to be willing to at least accept the general notion of human enhancement. In order to ascertain the social awareness, willingness and acceptance of human enhancement requires a social study. Within this chapter two online surveys are presented. The first survey aimed to determine the global view on human enhancement. The second survey aimed to grasp perceptual experiences of those individuals whom have or have had magnetic implants.

Within the presentation of each of the two surveys the questions and rationale for each question is detailed along with the proposed analysis of the responses. The human enhancement survey was conducted to determine the willingness of the population to undergo a variety of possible enhancements. The magnetic implant survey was conducted to not only grasp the perceptual experiences of individuals with magnetic implants, but also to obtain more information about the specifics of their implant. Things such as implant location and the specifics of the magnet implanted. To the author's knowledge there is no literature in the academic world which deals with these subject matters.

The two surveys were conducted anonymously online and were hosted on a website called FluidSurveys™. The strategies for distribution of each the surveys varied and hence are discussed individually in each of the survey sections. Design considerations for both surveys in terms of style and layout was aided with the use of the University of Reading's, UoR's, statistical services centres' document entitled, guidelines for planning affective surveys [12]. FluidSurveys™ also provide video tutorials as to how to design an effective survey which proved very useful when considering question structure and its benefits with regards to engagement of respondents.

Ethical considerations were taken into account as to the implementation and use of personal data from respondents. Both surveys were granted ethical approval by the

University of Readings Research Ethics Committee, as supplement to the participant experimentation described in Chapter 7. The documentation for this is provided in Appendix A.

2.2 The Global View on Human Enhancement

2.2.1 Introduction

As stated in the introduction, the purpose of the global view on human enhancement survey was to determine the awareness, willingness and acceptance of the population with regards to human enhancement. Furthermore certain questions within the survey were inserted within the aim to determine factors which may affect individuals in pursuing enhancement. These questions will aid with decisions made upon the dissemination of this research.

The service provided by FluidSurveys™ enabled this survey to be readily available to any respondent willing to spend the few minutes which it took to give their views upon the subject. The survey was circulated through social media websites such as, Facebook, Twitter and LinkedIn, also to a number of online forums e.g. Reddit. Furthermore it was distributed throughout a number of Universities within the UK and US via email. In total 407 respondents answered the survey via these methods of distribution. This group is further referred to as the sample group.

It is widely known that survey respondents are more likely to complete a survey if they are interested in the surveys subject matter. Within the world there are communities such as the H+ and body modification enthusiasts that would be more likely to complete this particular survey; hence for comparative purposes this survey was not only run globally, but also has a focus group. The focus group was taken from first year students from the School of Systems Engineering within the UoR, whom each study science and technology based degrees. In total there were 44 respondents within the focus group.

Upon opening the survey respondents were given a brief introduction on the survey which outlines its aims and gives concise background information on the subject. The survey along with the introductory statement is shown in Appendix B. The average time taken by respondents to complete this survey was 3:22 minutes (as recorded by

FluidSurveys™). This length of time indicates that respondents did consider the questions put forth to them before answering.

2.2.2 Questions and Rationale

This section presents the questions and rationale for them used in the human enhancement survey. The first four questions were simply to ascertain the basic information of the respondents, i.e. age group, residency, ethnicity and gender. This information could indicate correlations such as the greater acceptance of human enhancement in (hypothetically speaking) in the younger population. The remaining questions all focused around the respondent's thoughts on human enhancement and factors which may affect their discussion upon undergoing such procedures.

Firstly the candidates were asked whether they were aware of any research being undertaken in human enhancement with the options of, 'yes', 'no' or 'a little'. This was followed up by asking the respondents how the general idea of human enhancement made them feel. Which was rated on a 5-Point Scale, 5-PS, this ranged from 'scared' too 'excited'. These two introductory questions were used in order to cross compare subsequent questions within the survey.

The next 3 questions were all based on a likelihood 5-PS ranging from 'definitely not' to 'definitely'. The questions revolved around how likely the respondent would be to undergo an implant procedure to; improve their senses, improve their physical capabilities and finally to implant a device which would enable their GPS location to be visible by friends and family or the emergency services. The response to the first question provides information as to whether this research could potentially become common use within the population. The GPS implant response to provide information as to whether an individual's privacy would deter them from undergoing an enhancement procedure. N.B. the respondents were specifically told 'assuming it remained private i.e. only people you want to see a position can'.

To follow these questions the respondents were asked two questions in an attempt to relate factors which may affect their decision upon getting an enhancement. Both questions were again based on a 5-PS ranging from 'not at all' too 'a lot'. The first question asked how the risk of the implantation would affect their decision. The second asked how social factors, i.e. friends, family and/or partners opinions would affect their decision.

The next 2 questions deal with two specific enhancements, namely thought communication and nanotechnology for medical use. Firstly the respondents were asked how the thought of these enhancements made them feel. This was again rated on a 5-PS ranging 'scared' too 'excited'. Secondly the respondents were asked 'how likely would you be to undergo these procedures', which was rated on a 5-PS from 'definitely not' too 'definitely'. The rationale for asking these questions in this particular style, was to determine if a correlation is present, e.g. if the candidate was excited about thought communication would they definitely undergo the procedure.

The final question was a dichotomous one which asked whether the respondents would ever have an artificial limb or organ if they ever hypothetically needed a transplant. The reason for asking this question along with the "nanotechnology for medical purposes" questions (see Appendix B) was to determine if a life-threatening scenario would cause the respondent to possibly opt for a technological solution.

2.2.3 Responses & Discussion

This section outlines and discusses the responses from the human enhancement survey. Tables within were generated using SPSS along with the Pearson chi squared (χ^2) and Pearson R correlation statistics. In order to simplify the data analysis process of this survey, respondents with missing answers were omitted from the analysis. The number of removals was 15 (~3.7%) and 0 from the sample and focus groups respectively.

Figure 2-1 is a graphical representation of the country of residence of the respondents. This graphic was created by FluidSurveys™ based upon the IP address of the respondents. The full count of individual countries can be found in Appendix B.

Table 2-1 presents a breakdown of the respondent for age and gender. It is clear that the focus group is predominantly male; this is due to the popularity of the course that the focus group are studying (computer science). The sample group has a much more even split in regards to gender, which is expected seeing as the study was conducted openly online. The respondents' ages' are predominately in the range of 23 - 27 years old, possibly rationale for this comes from the nature of the main methods of survey distribution; i.e. through social networks and universities. Another may come from the idea posed in the introduction that the younger population may be more willing to accept the concept and thus have more positive thoughts towards human enhancement.

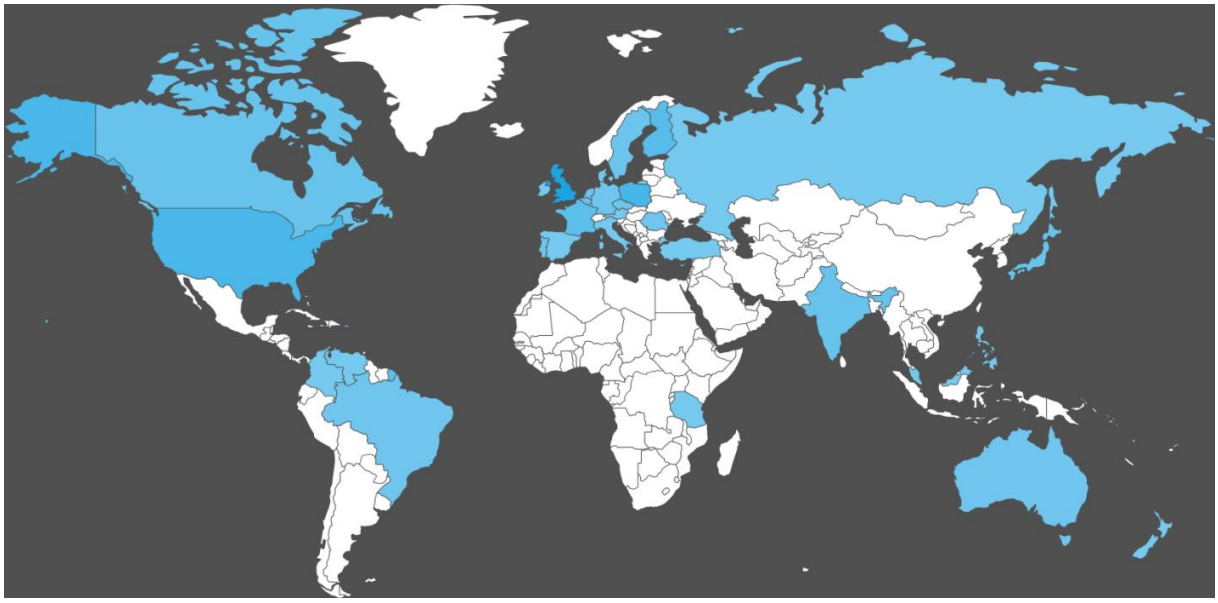


Figure 2-1: Geographical representation of the reach of the Human Enhancement survey from both groups

Group	How old are you?	What is your gender?		Total
		Female	Male	
Sample	Under 18	3	4	7
	18-22	28	37	65
	23-27	55	76	131
	28-32	23	39	62
	33-37	14	16	30
	38-42	12	9	21
	43-47	10	9	19
	48-52	15	4	19
	53-57	11	5	16
	58 or above	11	13	24
	Total	182	212	394
Focus	Under 18	1	0	1
	18-22	4	36	40
	23-27	0	2	2
	28-32	0	1	1
	Total	5	39	44

Table 2-1: Gender vs. Age Group for Human Enhancement Survey

Table 2-2 presents a cross tabulation of age group against the respondents general views towards human enhancement. From the sample group it seems there is a larger proportion of the younger sample (>18 – 32) that are more excited about the thought of human enhancement than the older sample (33 – 58≤). However, the age group with the most positive thoughts on the subject from this survey seems to be 38-42 with a positive response (positively and excited) of 71.4%.

Group	How old are you?	How does the general idea of Human Enhancement make you feel?					Total
		Scared	Negatively	Okay/Not Sure	Positively	Excited	
Sample	> 18		14.3%	28.6%	14.3%	42.9%	100.0%
	18-22	3.1%	3.1%	35.4%	23.1%	35.4%	100.0%
	23-27	3.1%	5.3%	32.1%	32.8%	26.7%	100.0%
	28-32	1.6%	14.5%	24.2%	30.6%	29.0%	100.0%
	33-37	3.3%	6.7%	33.3%	36.7%	20.0%	100.0%
	38-42		9.5%	19.0%	47.6%	23.8%	100.0%
	43-47	10.5%	15.8%	21.1%	31.6%	21.1%	100.0%
	48-52	10.5%	21.1%	36.8%	21.1%	10.5%	100.0%
	53-57		12.5%	37.5%	43.8%	6.3%	100.0%
	58≤		16.7%	41.7%	29.2%	12.5%	100.0%
	Total	3.0%	9.1%	31.2%	31.2%	25.4%	100.0%
Focus	> 18	100.0%					100.0%
	18-22	2.5%	7.5%	30.0%	27.5%	32.5%	100.0%
	23-27			50.0%		50.0%	100.0%
	28-32				100.0%		100.0%
	Total	4.5%	6.8%	29.5%	27.3%	31.8%	100.0%

Table 2-2: Age of Respondent vs. their views on Human Enhancement

The high proportion of the younger sample being excited about human enhancement pose is reflected in the 18-22 age groups within the focus group. The other age groups unfortunately have a very limited response rate (4 in total), and thus are disregarded from this analysis.

Table 2-3 presents the relationship between the awareness of research being carried out in human enhancement and the general feelings towards the subject. Within the sample group, the response of the human enhancement research awareness and feelings on the general idea of human enhancement holds statistical evidence to reject the null hypothesis that they are independent; based on $\chi^2 = 89.376$ ($P < 0.001$). There exists a significant ($P < 0.001$) correlation weak linear ($R = 0.421$) between these two variables.

However this is not the case for the focus group, $\chi^2 = 7.114$ ($P = 0.524$), which shows very weak linear correlation ($R = 0.203$) and not significant ($P = 0.186$). This result is not surprising given that the students within the focus group are studying science based degrees and that new, upcoming technology is a common occurrence within science. Even with a low sample awareness of the subject matter (22.7%, for yes – awareness of human enhancement research), there is relatively high positive feeling towards the subject (59.1%, for positively + excited – general feelings towards human enhancement).

Table 2-4 presents the relationships between the likelihood of sensory enhancement and the general feeling on human enhancement for both the sample and focus group. In both cases there is statistical evidence to suggest that there is a relationship between these two questions for both the sample (χ^2 = 276.696, P < 0.001) and focus (χ^2 = 41.196, P = 0.001) group.

Group	Are you aware of research being carried out in Human Enhancement?	How does the general idea of Human Enhancement make you feel?					Total
		Scared	Negatively	Okay /Not Sure	Positively	Excited	
Sample	Yes	.8%	.8%	3.6%	11.9%	15.2%	32.2%
	A little	1.0%	3.6%	16.0%	14.5%	7.9%	42.9%
	No	1.3%	4.8%	11.7%	4.8%	2.3%	24.9%
	Total	3.0%	9.1%	31.2%	31.2%	25.4%	100.0%
Focus	Yes		2.3%	6.8%	2.3%	11.4%	22.7%
	A little		2.3%	11.4%	15.9%	11.4%	40.9%
	No	4.5%	2.3%	11.4%	9.1%	9.1%	36.4%
	Total	4.5%	6.8%	29.5%	27.3%	31.8%	100.0%

Table 2-3: Human Enhancement Research Awareness vs. Feelings on the general idea of Human Enhancement

Group	How likely would you undergo an implant/procedure to improve your senses, if it were to become available?	How does the general idea of Human Enhancement make you feel?					Total
		Scared	Negatively	Okay/Not Sure	Positively	Excited	
Sam.	Definitely Not	1.5%	5.3%	3.0%	1.0%	.8%	11.7%
	Unlikely	1.0%	2.5%	14.0%	5.6%	1.0%	24.1%
	Maybe/Not Sure	.5%	1.3%	10.2%	9.9%	3.3%	25.1%
	Likely			3.3%	11.4%	7.4%	22.1%
	Definitely			.8%	3.3%	12.9%	17.0%
	Total	3.0%	9.1%	31.2%	31.2%	25.4%	100.0%
Foc.	Definitely Not	2.3%	6.8%	2.3%	2.3%		13.6%
	Unlikely	2.3%		11.4%			13.6%
	Maybe/Not Sure			6.8%	6.8%	6.8%	20.5%
	Likely			6.8%	11.4%	11.4%	29.5%
	Definitely			2.3%	6.8%	13.6%	22.7%
	Total	4.5%	6.8%	29.5%	27.3%	31.8%	100.0%

Table 2-4: Likelihood of sensory enhancement vs general feeling on human enhancement (Sam. – Sample, Foc. – Focus)

This positive correlation can be seen within the data for both groups with a similar pattern; i.e. as the general feeling of human enhancement tends towards the extreme positive (excited) both groups tend towards the positive extreme of likelihood for implant

(definitely). Furthermore a significant ($P < 0.001$) strong correlation exists between these two questions for the sample ($R = 0.66$) and focus ($R = 0.673$) groups alike.

One of the main objectives for this survey was to determine the likelihood of the population to undergo a sensory enhancement. From these results it shows that 39.1% of the sample group responded positively to this question, i.e. likely and definitely. The focus groups' responses are slightly more accepting, 52.2% positive. This increase of acceptance within the focus group over the sample group could be attributed to a number of factors; such as, the focus groups' field of study, or perhaps their age.

Although the percentage of acceptance for both groups seems low, a noticeable part of both groups responded maybe/not sure 25.1% and 20.5% from the sample and focus group respectively. With careful publicity of this research, and others like it, these respondents may tend towards a more positive acceptance of sensory enhancement.

Group	How likely would you undergo an implant/procedure to improve your physical capabilities, if it were to become available?	How does the general idea of Human Enhancement make you feel?					Total
		Scared	Negatively	Okay/Not Sure	Positively	Excited	
Sam.	Definitely Not	1.80%	5.30%	2.30%	1.00%	0.30%	10.70%
	Unlikely	1.00%	2.00%	8.90%	3.80%	0.50%	16.20%
	Maybe/Not Sure	0.30%	1.50%	12.40%	10.20%	4.10%	28.40%
	Likely		0.03%	6.30%	11.70%	7.60%	25.90%
	Definitely			1.30%	4.60%	12.90%	18.80%
	Total	3.00%	9.10%	31.20%	31.20%	25.40%	100.00%
Foc.	Definitely Not	2.30%	6.80%	4.50%	2.30%		15.90%
	Unlikely	2.30%		11.40%			13.60%
	Maybe/Not Sure			4.50%	9.10%	4.50%	18.20%
	Likely			4.50%	6.80%	11.40%	22.70%
	Definitely			4.50%	9.10%	15.90%	29.50%
	Total	4.50%	6.80%	29.50%	27.30%	31.80%	100.00%

Table 2-5: Likelihood of physical enhancement vs. general feeling on human enhancement. (Sam. – Sample, Foc. – Focus)

Table 2-5 presents the relationship between the likelihood of physical enhancement and the general feeling on human enhancement. Similarly to the likelihood of sensory enhancement versus the general feeling on human enhancement there is significant statistical evidence for both the sample ($\chi^2 = 260.478$, $P < 0.001$) and focus group ($\chi^2 = 38.736$ $P = 0.001$) to suggest that these two questions are not independent. Furthermore

exploring the data shows a similar positive correlation which is similarly shown in the previous comparison. This is reflected in the statistical analysis as a significant strong correlation exists between these two questions for both the sample ($R = 0.65$, $P < 0.001$) and focus ($R = 0.672$, $P < 0.001$) groups alike.

Group	How likely would you undergo an implant/procedure to enable your location to be seen by friends and family, and alert the social services in emergency situations, if it were to become available?	How does the general idea of Human Enhancement make you feel?					Total
		Scared	Negatively	Okay/Not Sure	Positively	Excited	
Sample	Definitely Not	1.5%	5.1%	10.2%	8.4%	4.1%	29.2%
	Unlikely	1.0%	3.0%	9.9%	10.7%	3.6%	28.2%
	Maybe/Not Sure	0.3%	0.8%	6.6%	8.6%	8.6%	24.9%
	Likely	0.3%		4.1%	2.8%	5.6%	12.7%
	Definitely		0.3%	0.5%	0.8%	3.6%	5.1%
	Total	3.0%	9.1%	31.2%	31.2%	25.4%	100.0%
Focus	Definitely Not	2.3%	4.5%	6.8%	6.8%		20.5%
	Unlikely	2.3%	2.3%	13.6%	9.1%	6.8%	34.1%
	Maybe/Not Sure			4.5%	2.3%	11.4%	18.2%
	Likely			4.5%	6.8%	6.8%	18.2%
	Definitely				2.3%	6.8%	9.1%
	Total	4.5%	6.8%	29.5%	27.3%	31.8%	100.0%

Table 2-6: Likelihood of GPS Implantation vs. general feeling on human enhancement

Table 2-6 shows the cross tabulation respondents answers to the likelihood of having a GPS implant versus their general feeling towards human enhancement. Within the main sample group there is significant statistical evidence ($\chi^2 = 70.591$, $P < 0.001$) to suggest that there is a relationship between these two questions however this is not true for the focus group ($\chi^2 = 17.692$, $P = 0.342$).

The data from the sample groups seems to point towards a weaker positive correlation ($R = 0.341$, $P < 0.001$) than the previous implant procedures (i.e. improved senses and physical capabilities). A likely reason for these results is that this particular implant would directly affect the privacy of the respondents. Research shown in [13] seems to suggest that the general public are not willing to further expose their privacy through biometrics and technology.

The focus group does show a similar trait to the sample group, in that 34.1% of them would be unlikely to undergo the GPS implantation; however the results show a stronger positive correlation ($R = 0.505$, $P < 0.001$) when compared with the sample group. The

reason for this again could perhaps be attributed to their choice of study; where here the respondents understand the negative connotations of the implant but also can envisage the positive benefits.

Group	How much would the risk of the implantation/procedure affect your decision upon getting an enhancement?	How much would social factors affect your decision upon getting an enhancement?					Total
		Not at all	Very little	Not sure	A little	A lot	
Sample	Not at all	2.5%	2.0%	.3%	.3%		5.1%
	Very little	4.6%	3.0%	1.0%	1.0%	.8%	10.4%
	Not sure	3.0%	4.1%	2.3%	1.0%		10.4%
	A little	5.3%	11.2%	3.0%	7.1%	1.3%	27.9%
	A lot	6.1%	13.2%	5.8%	15.7%	5.3%	46.2%
	Total	21.6%	33.5%	12.4%	25.1%	7.4%	100.0%
Focus	Not at all	6.8%	2.3%				9.1%
	Very little	6.8%	4.5%	2.3%			13.6%
	Not sure	4.5%	6.8%	4.5%	6.8%		22.7%
	A little	2.3%	11.4%	2.3%	6.8%	2.3%	25.0%
	A lot	2.3%	13.6%	4.5%	4.5%	4.5%	29.5%
	Total	22.7%	38.6%	13.6%	18.2%	6.8%	100.0%

Table 2-7: Cross tabulation of the Implantation Risk and the Social Factors affect

Table 2-7 presents the respondents' answers to factors which would affect them having an implant or procedure for any human enhancement. The question specifically focused around how the risks involved with implantation and social factors would affect the respondents from undergoing any human enhancement procedure. Statistical evidence suggests there is a relationship between these two questions within the sample group (χ^2 = 58.932, P < 0.001) but not for the focus group (χ^2 = 16.817, P = 0.389). There is however a significant weak positive correlation and between these variables also for the sample (R = 0.328, P < 0.001) and focus (R = 0.407, P = 0.006) group alike.

Group	What is your gender?	How much would the risk of the implantation/procedure affect your decision upon getting an enhancement?					Total
		Not at all	Very little	Not sure	A little	A lot	
Sample	Female	6.0%	7.1%	11.5%	22.0%	53.3%	100.0%
	Male	4.2%	13.2%	9.4%	33.0%	40.1%	100.0%
	Total	5.1%	10.4%	10.4%	27.9%	46.2%	100.0%
Focus	Female	20.0%		40.0%	20.0%	20.0%	100.0%
	Male	7.7%	15.4%	20.5%	25.6%	30.8%	100.0%
	Total	9.1%	13.6%	22.7%	25.0%	29.5%	100.0%

Table 2-8: Gender versus risk of implantation

Further analysis of these 'affecting factors' are shown in Table 2-8 and Table 2-9 which show the risk factor of implantation versus gender and the social factors versus age group respectively. Statistical evidence suggests that there is a relationship between the effect of the risk of implantation and gender, and also the effect of social factors and age within the sample group (χ^2 = 12.473 and 57.718, P = 0.014 and P = 0.012); however, this is not the case for the focus group (χ^2 = 2.479 and 14.227, P = 0.648 and 0.286).

The suspected reason for gender only having a relationship in the sample group is that the focus group had a very low female response rate (5). Looking at the male responses for both the sample and focus groups however shows a steady increase towards risk factor their decision greatly. The females within the sample group however seem to have a greater tendency towards the extreme positive response, i.e. 'a lot'. This result is unsurprising as it is human nature to avoid potentially hazardous risks.

Group	How old are you?	How much would social factors affect your decision upon getting an enhancement?					Total
		Not at all	Very little	Not sure	A little	A lot	
Sample	>18	14.3%	42.9%	28.6%	14.3%		100.0%
	18-22	20.0%	38.5%	6.2%	32.3%	3.1%	100.0%
	23-27	16.0%	28.2%	16.0%	29.0%	10.7%	100.0%
	28-32	40.3%	17.7%	11.3%	25.8%	4.8%	100.0%
	33-37	13.3%	43.3%	16.7%	26.7%		100.0%
	38-42	33.3%	23.8%	19.0%	19.0%	4.8%	100.0%
	43-47	21.1%	47.4%	5.3%	15.8%	10.5%	100.0%
	48-52	10.5%	47.4%	10.5%	26.3%	5.3%	100.0%
	53-57	18.8%	62.5%	6.3%		12.5%	100.0%
	58≤	20.8%	41.7%	8.3%	12.5%	16.7%	100.0%
	Total	21.6%	33.5%	12.4%	25.1%	7.4%	100.0%
Focus	>18			100.0%			100.0%
	18-22	22.5%	42.5%	12.5%	15.0%	7.5%	100.0%
	23-27	50.0%			50.0%		100.0%
	28-32				100.0%		100.0%
	Total	22.7%	38.6%	13.6%	18.2%	6.8%	100.0%

Table 2-9: Effect of social factors on respondents on getting an Enhancement versus the age groups of the respondents

Given the age range of the focus group it is unsurprising to see that age holds no significant relationship to the social factor, as opposed to the sample group. Interestingly 55.1% of the sample group and 61.3% of the focus group responded negatively to social factors affecting their decision to get an enhancement (i.e. not at all or very little). Social factors aspect could be explained on a multitude of levels, two of which are explored here.

Firstly, the popularity of augmentation or improved human capabilities has recently been brought to the general public in the form of comic based media, such as the X-Men, Spiderman and Superman franchises. As these are popular medium throughout the globe, social factors could be skewed due to a 'cool' factor. Secondly, unfortunately the survey failed to ascertain in marital status and dependencies of the respondents. It would be interesting to determine whether social factors would have a relationship within these factors. Hypothetically (and somewhat predictably) it may have shown that individuals with dependencies would take into account social factors more greatly than those that are single and without them.

Table 2-10 presents the relationship between whether the respondents would likely undergo the procedure for thought communication and their general feeling towards it. Exploring the data clearly suggests a linear relationship for the sample (χ^2 = 384.554, P < 0.001) and focus (χ^2 = 60.195, P < 0.001) groups alike. This result is quite logical seeing that those with good feeling towards a piece of technology would typically be more likely to utilise it.

Group	Would you undergo the implant/procedure to give yourself thought communication?	How does the general idea of thought communication make you feel?					Total
		Scared	Negatively	Okay/Not Sure	Positively	Excited	
Sam.	Definitely Not	6.3%	11.4%	2.8%	1.3%	.3%	22.1%
	Unlikely	3.0%	5.1%	7.9%	2.0%	1.3%	19.3%
	Maybe/Not Sure	.3%	.5%	9.9%	10.9%	2.8%	24.4%
	Likely	.3%	.5%	1.3%	15.5%	6.1%	23.6%
	Definitely	.3%		.3%	1.3%	8.9%	10.7%
	Total	10.2%	17.5%	22.1%	31.0%	19.3%	100.0%
Foc.	Definitely Not	4.5%	9.1%	4.5%			18.2%
	Unlikely	2.3%	6.8%	4.5%	2.3%		15.9%
	Maybe/Not Sure			15.9%	2.3%		18.2%
	Likely				20.5%	15.9%	36.4%
	Definitely				2.3%	9.1%	11.4%
	Total	6.8%	15.9%	25.0%	27.3%	25.0%	100.0%

Table 2-10: Thought Communication, thoughts of the general idea vs. likelihood of undergoing the procedure (Sam. – Sample, Foc. – Focus)

As this technology may appear quite alien to most, the results of the sample group seem to suggest a slight reluctancy towards this technology. Looking at the total percentages as to the feeling of the respondents towards thought communication it seems there is a positive response tendency, i.e. 51.3% in positively + excited. However this

positive response tendency figure decreases when looking at the likelihood of actually undergoing the procedure for thought communication i.e. 34.3% in likely + definitely.

Exploring the focus group percentages for positive response tendency shows slightly more acceptance; 52.3% feel positively + excited about the idea and 47.8% would likely + definitely undergo the procedure. This is reflected in the correlation statistics which is stronger within the focus group ($R = 0.854$, $P < 0.001$) compared to the sample group ($R = 0.741$, $P < 0.001$).

Group	Would you undergo a medical procedure involving nanotechnology?	How does the general idea of nanotechnology for medical purposes make you feel?					Total
		Scared	Negatively	Okay/Not Sure	Positively	Excited	
Sample	Definitely Not	1.0%	.8%				1.8%
	Unlikely	.3%	.5%	2.3%	1.0%		4.1%
	Maybe/Not Sure	.8%	.8%	10.2%	11.9%	1.3%	24.9%
	Likely			.8%	23.4%	12.9%	37.1%
	Definitely				4.3%	27.9%	32.2%
	Total	2.0%	2.0%	13.2%	40.6%	42.1%	100.0%
Focus	Definitely Not	9.1%		2.3%			11.4%
	Unlikely			2.3%			2.3%
	Maybe/Not Sure	4.5%		6.8%	9.1%	6.8%	27.3%
	Likely				11.4%	13.6%	25.0%
	Definitely				2.3%	31.8%	34.1%
	Total	13.6%		11.4%	22.7%	52.3%	100.0%

Table 2-11: Nanotechnology for medical purposes, thoughts of the general idea vs likelihood of undergoing the procedure

Table 2-11 displays the cross tabulation of the feelings towards and likelihood of undergoing medical procedures using nanotechnology. Statistical evidence suggests that there is a relationship between these two questions for both the sample ($\chi^2 = 444.215$, $P < 0.001$) and focus group ($\chi^2 = 47.924$, $P < 0.001$). The use of nanotechnology within technology has been publicised in the media for many years now, more specifically in medical technology it has shown many promising areas for its uses. The figures for the positive feelings towards the technology for both the sample and the focus groups are thus relatively high 82.7% and 75% respectively.

The positive responses towards the likelihood of undergoing a medical procedure involving nanotechnology (likely + definitely) is again relatively high in both the focus and the sample groups, 59.1% and 69.3% respectively. Strong positive correlation exists

between these questions for both the sample (R = 0.762, P < 0.001) and focus (R = 0.796 P < 0.001) groups alike.

Group	Would you undergo a medical procedure involving nanotechnology?	Would you undergo the implant/procedure to give yourself thought communication?					Total
		Definitely Not	Unlikely	Maybe/Not Sure	Likely	Definitely	
Sam.	Definitely Not	1.5%	.3%				1.8%
	Unlikely	1.3%	1.5%	.5%	.8%		4.1%
	Maybe/Not Sure	8.9%	6.3%	4.8%	4.8%		24.9%
	Likely	7.9%	8.9%	10.7%	7.4%	2.3%	37.1%
	Definitely	2.5%	2.3%	8.4%	10.7%	8.4%	32.2%
	Total	22.1%	19.3%	24.4%	23.6%	10.7%	100.0%
Foc.	Definitely Not	6.8%	4.5%				11.4%
	Unlikely	2.3%					2.3%
	Maybe/Not Sure	4.5%		13.6%	9.1%		27.3%
	Likely	4.5%	2.3%	2.3%	13.6%	2.3%	25.0%
	Definitely		9.1%	2.3%	13.6%	9.1%	34.1%
	Total	18.2%	15.9%	18.2%	36.4%	11.4%	100.0%

Table 2-12: Likelihood of undergoing thought communication enhancement against the likelihood of undergoing a procedure involving nanotechnology in a medical context (Sam. – Sample, Foc. – Focus)

When comparing these results to the thought communication questions there seems to be a much greater acceptance of this type of technology with regards to a higher likelihood of use, within the medical sector. Table 2-12 explores this comparison, to which a significant relationship between these two questions has between for both sample (χ^2 = 106.429, P < 0.001) and focus (χ^2 = 34.358, P = 0.005) groups alike. Given the subject matter of these two enhancements and the context in which they have been portrayed to the general public; i.e. thought communication through 'sci-fi' and nanotechnology for medical purposes through reputable news broadcasters; it is unsurprising to see this difference in acceptance. A significant positive linear correlation between these questions exists for both the sample (R = 0.444, P < 0.001) and focus (R = 0.523, P < 0.001) groups alike.

Finally Table 2-13 presents the relationship between the general feeling towards nanotechnology for medical purposes and whether the respondents would consider having an artificial organ or limb if they ever hypothetically needed a transplant. From the results it is clear that the majority of both the sample and focus group would consider having an artificial organ or limb; 96.7% and 95.5% give response of yes respectively.

Group	How does the general idea of nanotechnology for medical purposes make you feel?	Would you consider having an artificial organ or limb, if you hypothetically ever needed a transplant?		Total
		Yes	No	
Sample	Scared	1.8%	.3%	2.0%
	Negatively	1.5%	.5%	2.0%
	Okay/Not Sure	11.7%	1.5%	13.2%
	Positively	40.1%	.5%	40.6%
	Excited	41.6%	.5%	42.1%
	Total	96.7%	3.3%	100.0%
Focus	Scared	13.6%		13.6%
	Okay/Not Sure	6.8%	4.5%	11.4%
	Positively	22.7%		22.7%
	Excited	52.3%		52.3%
	Total	95.5%	4.5%	100.0%

Table 2-13: General Idea of nanotechnology for medical purposes cross tabulated with consideration for artificial limb or organ in a hypothetical transplant scenario

2.3 The Global View on Magnetic Implants

2.3.1 Introduction

The main aim of the 'Global View on Magnetic Implants' survey was to understand the perceptual experiences of individuals with magnetic implants. As stated in the thesis introduction, magnetic implants for non-medical purposes originated within trans-humanist movements and the body modification world. A variety of people have since had magnets implanted for a number of reasons. Hence this survey was conducted in order to determine not only the individuals' perceptual experiences of the implant, but also; the specifics of their implant, where they heard about the implant and who implanted them.

The survey was published throughout social media forums and targeted body modification forums. Furthermore the survey was distributed through social media connections with a number of body modification artists such as Mr M. McCarthy a.k.a. Dr Evil; as it was he who performed the implant procedure upon the author (further discussed in section 5.3.3). In total the survey received responses from 56 respondents.

Similarly to the global view on human enhancement survey respondents of the survey were given a brief introduction which outlined the background information and the reason for the survey. The full survey questionnaire is presented in Appendix C.

2.3.2 Questions and Rationale

This section presents the questions in the human enhancement survey, along with the rationale for each of them. The first four questions were identical to that seen in the human enhancement survey and again were aimed at determining basic information of the respondents, i.e. age group, residency, ethnicity and gender. The following questions were magnet-based questions specific to the respondents' individual experiences. Firstly the survey asks when the individual got their magnet(s) implanted. This question was asked in an attempt to find a relationship between the number of implants, and good or bad perceptual experiences.

The candidates were then asked for the location of their magnetic implant(s), which was checkbox question including all the fingers and an 'other' box. This was an attempt to find if there is a more popular location for the implant within the group of respondents. This question was followed by asking the respondents who implanted them. The respondents were presented with a list which includes, well known body modification artists, self-implantation, local Doctor/Surgery and options to specify others. This was investigated to determine if there is a popular body modification artist; but also to link implant methodology (perhaps which is individual to each artist) to 'how long it took for the implant to heal?' which is examined later in the survey.

Next the respondents were asked to specify where they heard/read about the implant. They are again presented with a list which included body modification circles, word-of-mouth, YouTube, and again an 'other' option where they could specify themselves. This was asked in an attempt to determine who is providing information to the general public about this particular procedure.

The following question was asked to determine whether the respondent understood the risks they were taking with this implant before they underwent the procedure. A list of the risks is shown as part of the question which includes, having an MRI, neodymium poisoning, implant rejection and tissue damage. The response was a 5-PS answer ranging from 'strongly disagree' to 'strongly agree'. There were a number of reasons for asking this question which include, profiling of the individual, whether self-implanted respondents understood the risks and similarly whether the preforming the implant relayed risk information to the individuals prior to the implant.

This question in combination with 'why you did you get the implant?' (which is asked further down in the survey) could potentially show some devastating trends. For example if the respondent read about the implant on a website, didn't understand the risks, and underwent the implantation on the basis that 'it looked cool', this research could potentially be under threat of media scrutiny.

The three questions which followed all revolved around the specifics of the implanted magnet, i.e. the coating, the dimensions and the magnetic material. The answers included relevant popular choices for each of the three questions along with another answer (where the respondents could specify the answer) and an unsure/don't know answer. These were asked for two main reasons, firstly to establish whether there were popular answers and secondly to determine whether the respondents actually knew the specifics of the magnet which was implanted in them.

Three questions were asked which all where themed around the perceptual experiences of the respondents. These included why did they get their implant, have they had any bad experiences and finally have they been able to feel any electromagnetic fields (from devices such as microwave ovens computer fans or laptop power supplies). Each of these questions had a text box answer field, enabling the respondents to give their personal views. The rationale for the 'why did they get the implant?' question was to determine whether there was common factors for the individuals to get the implant. Furthermore as mentioned above to check whether the implant attracted individuals who perceived it to be 'cool'. Most interestingly however was to see whether the respondents underwent the implant for perceptual purposes, i.e. the perception of electromagnetic fields.

The final two questions were based around FAQs directed at the author of this research. These were 'how many times have you been stopped at security scanners in airports due to the implant specifically?' and 'have you ever been prevented from medical treatment due to the implant, procedures such as MRI'. The rationale for the MRI question was an attempt to establish potential medical risks and drawbacks of this implantation.

2.3.3 Responses & Discussion

This section outlines and discusses the responses from the magnetic implant survey. The tables and graphs used within were generated using SPSS. A number of questions

within this survey were text based answers, the full text responses and (if appropriate) their categorisations can be found in Appendix C.

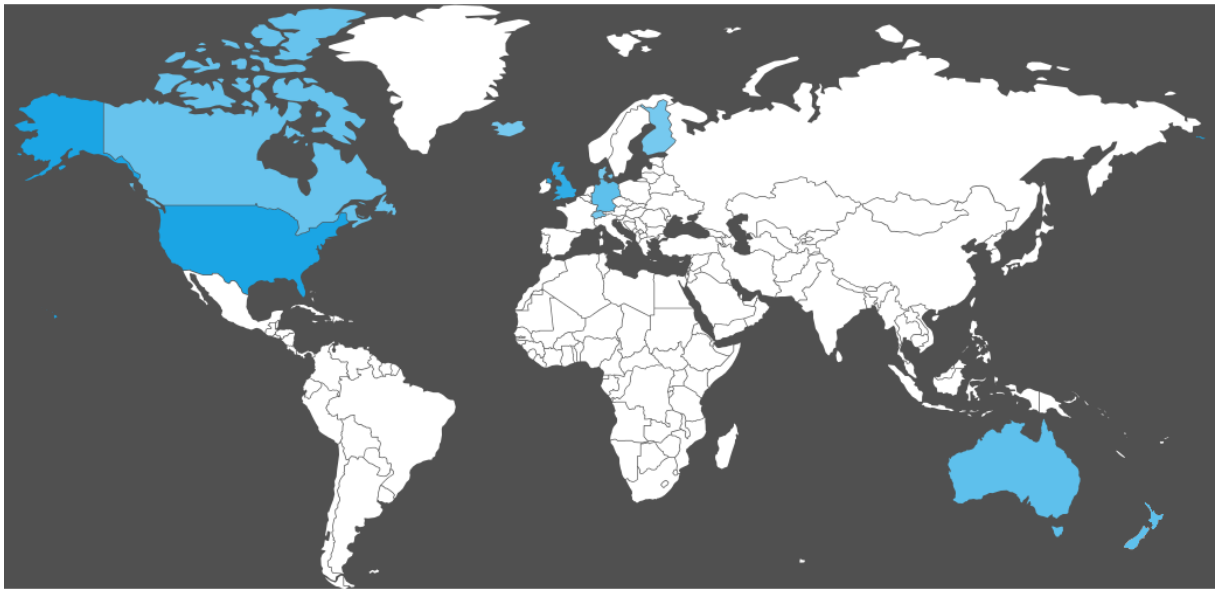


Figure 2-2: Graphical representation of the respondents' country of residence from the survey

Figure 2-2 and Table 2-14 show a graphical representation and tabulated figures of the respondents' country of residence. The graphic was again created by FluidSurveys™ based upon the IP address of the respondents. The frequency of the respondents' country of residence as presented in the table suggests that the majority of individuals with magnetic implants are located within the USA (46.4%).

Table 2-15 presents the cross tabulation of the respondents age and their gender. It is clear from the results that the central tendency of respondents lays within the younger respondents (i.e. 23 to 27). One could infer from this table that magnetic implants are more popular within males than females; however this is not possible as the survey may not have reached all females with the implant.

Figure 2-3 shows a histogram representation of the year that the respondents had their magnets implanted. 2012 is the year at which the majority of respondents received their implants. A potential reason for this could stem from the social publicity from various online blogs, which perhaps could have been in result to the earlier publication of this research in late 2010 [4].

Data	Where do you currently live?	Frequency	%	Valid %	Cumulative %
Valid	UK	14	25.0	25.9	25.9
	Australia	3	5.4	5.6	31.5
	Canada	2	3.6	3.7	35.2
	Denmark	1	1.8	1.9	37.0
	Finland	1	1.8	1.9	38.9
	Germany	4	7.1	7.4	46.3
	Maldives	1	1.8	1.9	48.1
	New Zealand	1	1.8	1.9	50.0
	Switzerland	1	1.8	1.9	51.9
	USA	26	46.4	48.1	100.0
	Total	54	96.4	100.0	
Missing	NA	2	3.6		
Total		56	100.0		

Table 2-14: Frequencies of respondents' country of residency

What is your gender?	How old are you?						Total
	18-22	23-27	28-32	33-37	38-42	53<	
Male	9	18	10	7	3	1	48
Female	2	3	2	0	0	0	7
Total	11	21	12	7	3	1	55

Table 2-15: Summary of gender versus age of respondents

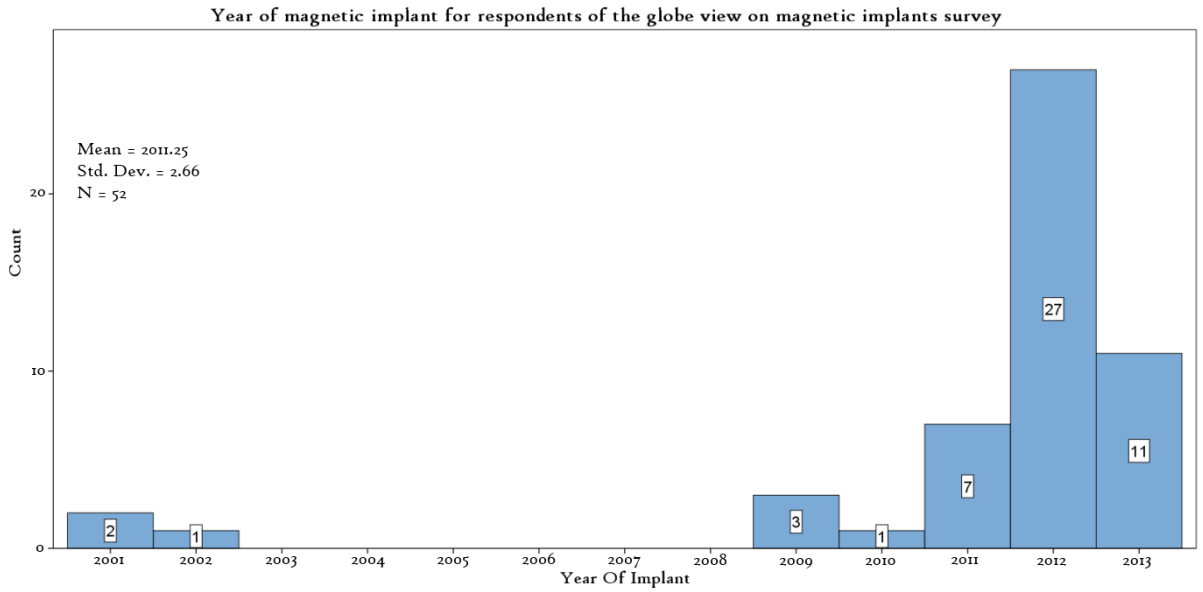


Figure 2-3: Year of magnetic implants for respondents

Table 2-16 and Table 2-17 present the frequencies of the respondents implant location and the frequencies of the number of implants that each of the respondents has respectively. Interestingly there is a single, very popular choice of location for the implant, the left ring finger. This choice alone accounts for 54.9% of the respondents' choice of location.

Of the 12 respondents with two implants, 10 of the respondents have either same hand adjacent fingers implanted (e.g. left index and middle) or both hands and identical fingers (e.g. left and right ring finger). One of the two implanted respondents has their implants in their left thumb and middle finger; the other one has their implants in their left ring finger and the centre of their forehead. The only respondent with 4 implants has them all in his left hand, index, middle, ring and pinky.

Implant Location	Frequency	%	Valid %	Cumulative %
Left Thumb	2	.9	2.8	2.8
Left Index	5	2.2	7.0	9.9
Left Middle	5	2.2	7.0	16.9
Left Ring	39	17.4	54.9	71.8
Left Pinky	3	1.3	4.2	76.1
Right Middle	2	.9	2.8	78.9
Right Ring	7	3.1	9.9	88.7
Right Pinky	4	1.8	5.6	94.4
Back of Left Hand	1	.4	1.4	95.8
Outer Edge Of Left Palm	1	.4	1.4	97.2
Centre Of Forehead	1	.4	1.4	98.6
Just above the thumb on the top of the hand	1	.4	1.4	100.0
Total	71	31.7	100.0	

Table 2-16: Frequencies of Implant Location for respondents

Number of Implants	Frequency	%	Cumulative %
1	43	76.8	76.8
2	12	21.4	98.2
4	1	1.8	100.0
Total	56	100.0	

Table 2-17: Frequencies of number of implants

Where did you hear/read about the implant?		Frequency	%	Valid %	Cumulative %
Valid	Body Modification/Transhumanism Circles (Artists, Websites, etc.)	30	53.6	57.7	57.7
	Word of mouth (Friends, Family)	9	16.1	17.3	75.0
	YouTube	2	3.6	3.8	78.8
	Reddit	4	7.1	7.7	86.5
	Wired	2	3.6	3.8	90.4
	Publication	1	1.8	1.9	92.3
	Technology Website	1	1.8	1.9	94.2
	Online Lecture/Talk	3	5.4	5.8	100.0
	Total	52	92.9	100.0	
Missing	Missing	4	7.1		
	Total	4	7.1		
Total		56	100.0		

Table 2-18: Frequencies of where the respondents heard about the implant

Table 2-18 shows that the majority of people read about this implant through the body modification/Transhumanism circles, which suggests that the influx in 2012 was not a

result of the previously discussed publication. However where the authors of these media organisations obtained information for this implant remains speculative.

Table 2-19 is a cross tabulation between whom implanted the respondents' implants and how long it approximately took to heal. There is no statistical evidence to suggest that there is a relationship between these two questions. Unfortunately 'how long did your implant take to heal?' is a very subjective question. For instance healing could be subjectively put down to the time taken for a scab to form. However those with greater medical knowledge understand that tissue damage would have occurred during the implantation process, and may have understood 'healed' to mean, the time taken for recovery of this. The majority of respondents believed there implants took two weeks to heal (39.3%).

Who implanted them?	How long did your implant take to heal (approximately)?					Total
	1 - 3 Days	1 Week	2 Weeks	3 Weeks	1 Month +	
Self-Implantation		7.1%	8.9%		1.8%	17.9%
Brian Decker			7.1%	1.8%	5.4%	14.3%
Steve Haworth		5.4%	3.6%	7.1%	1.8%	17.9%
Mac 'Doctor-Evil' McCarthy	1.8%	5.4%	5.4%			12.5%
Patrick Kielty	1.8%	1.8%	1.8%		3.6%	8.9%
Other Body Modification Artist	1.8%	3.6%	10.7%	5.4%	5.4%	26.8%
Piercing Studio			1.8%			1.8%
Total	5.4%	23.2%	39.3%	14.3%	17.9%	100.0%

Table 2-19: Who implanted the respondents' implants versus their perceived healing time

Exploring who implanted these implants, the majority of the respondents sought professional body modification artists to perform their implant (82.2%). However worryingly 17.9% of the respondents performed self-implantation, which is concerning due to a possible lack of sanitation for both the magnet and the equipment required to perform the procedure.

Table 2-20 presents a cross tabulation of the reasons why respondents underwent this procedure and whether they understood the risks beforehand. This result is hugely significant for this research as surprisingly the majority of respondents underwent the procedure for the purposes of magnetic "vision" (60%). It is also positive that 96% agreed that they at least mostly understood the risks before the implantation.

Table 2-21 presents the frequencies of the respondents' magnet size. From these results it shows that the most popular choice is 3 mm diameter and 0.7 mm thick, this is the dimensions of the authors implant also. However the majority (30.4%) were unsure/did not know the size of the magnets that they were being implanted with.

Why did you get this implant?	Please specify your views to the following statement: Before having the magnet(s) implanted, I fully understood the risks involved.			Total
	Strongly Disagree	Mostly Agree	Strongly Agree	
Magnetic Vision		16.0%	44.0%	60.0%
Interest/Fun		4.0%	12.0%	16.0%
Transhumanistic	2.0%	4.0%	6.0%	12.0%
Performance/Arts			2.0%	2.0%
Experimental	2.0%	2.0%	4.0%	8.0%
Practical Purposes			2.0%	2.0%
Total	4.0%	26.0%	70.0%	100.0%

Table 2-20: Why did the respondents get the implant versus did they understand the risks prior to getting it

What is the size of your magnet?	Frequency	%	Cumulative %
6 mm Diameter, 0.7 mm Thick	6	10.7	10.7
3 mm Diameter, 1.6 mm Thick	2	3.6	14.3
3 mm Diameter, 1.4 mm Thick	1	1.8	16.1
3 mm Diameter, 0.7 mm Thick	15	26.8	42.9
2 mm Diameter, 1 mm Thick	8	14.3	57.1
Other	7	12.5	69.6
Unsure/Don't Know	17	30.4	100.0
Total	56	100.0	

Table 2-21: Sizes of respondents' magnets

What type of coating is on your magnet?	Frequency	%	Cumulative %
Parylene	20	35.7	35.7
Silicon	26	46.4	82.1
Sugru	1	1.8	83.9
PTFE (Polytetrafluoroethylene)	1	1.8	85.7
Teflon	2	3.6	89.3
Microfilm	1	1.8	91.1
Unsure/don't know	5	8.9	100.0
Total	56	100.0	

Table 2-22: Coatings of respondents' magnets

Table 2-22 presents the frequencies of the various coating types upon the respondent's magnets. It is clear there are two popular choices, Parylene and Silicon which overall accounts for 82.1% of the respondents with knowledge of their coating. Although it is a small percentage it is concerning that almost 9% of the respondents were unsure or did not know coating type on their magnet. Coating material is rather important with regards to this implant as failure in the coating could cause exposure to neodymium or other

magnetic compounds, which would lead to potential health risks and subsequent explantation; an example of which is shown in section 5.4.1.

Table 2-23 presents the frequencies of the respondents' magnets' material. The results of this question show that recipients of the implant were either not fully informed of their implant or have forgotten specifics of their magnet, as the majority answering unsure/don't know. If the respondents were informed and have forgotten this information, this is acceptable. As the risks of implantation procedure could have been known and evaluated by the respondent at the time. However if the respondents were not informed by the person whom implanted them, or failed to ascertain this information themselves in the case of a self-implantation; this shows negligence and is, ethically dubious and possibly illegal.

What is the material of the magnet(s)?	Frequency	%	Cumulative %
Neodymium N52	6	10.7	10.7
Neodymium N50	1	1.8	12.5
Neodymium N48	8	14.3	26.8
Neodymium N42	3	5.4	32.1
Neodymium Grade Unknown	6	10.7	42.9
Unsure/don't know	32	57.1	100.0
Total	56	100.0	

Table 2-23: Materials of respondents' magnets

Hypothetically, if an individual requires medical attention due to coating rupturing and said individual did not know the magnets' material; the time taken to for the medical staff to determine this information, could potentially put the individual's health at greater risk, due to toxicity effects of various compounds. This is similar to the dimensions of the magnet; as if the magnet shattered and was explanted the medical staff preforming removal would not know if the entirety was removed unless an X-ray was taken; which would ultimately take up more time again putting the respondents' health at further risk.

Summary of respondents' knowledge of their implants	Frequency	%	Cumulative %
All - Size, Material, Coating	20	35.7	35.7
Size Only	2	3.6	39.3
Coating Only	14	25.0	64.3
Size and Coating Only	14	25.0	89.3
Size and Material Only	1	1.8	91.1
Coating and Material Only	3	5.4	96.4
Completely Unsure/Don't Know	2	3.6	100.0
Total	56	100.0	

Table 2-24: Summary of the respondents' knowledge with regards to their implants

Table 2-24 shows a summary of the respondents' knowledge of their implants. The majority of the respondents knew all the specifics of their magnet (35.7%). However a large proportion of respondents either only knew their coating type, or their coating type and dimensions of their magnets (50%).

Table 2-25 presents a summary of respondents' responses to the recurrent pain, bad experiences or hindrance question. The textual answers given were categorised in order to analyse the data more efficiently. As previously stated, the full textual answers along with their categorisations can be found in Appendix C. The vast majority of respondents (80.3%) thankfully have not experienced negative effects from this implant. This statistic is based upon a culmination of the 'No', 'Inexplicit No' and inferred from the 'No Answer' responses.

Since having the magnet(s) implanted have you had any bad experiences, recurrent pain or been hindered in day-to-day activities due to them?	Frequency	%	Cumulative %
No	13	23.2	23.2
Lifting Objects (Light Pain/Uncomfortable)	3	5.4	28.6
Playing Sports/Instruments (High Pain)	2	3.6	32.1
Inexplicit No	4	7.1	39.3
Light Soreness Work Related	1	1.8	41.1
Unusual/Uncomfortable/Pain Sensation	3	5.4	46.4
Coating Rupture Subsequent Removal	1	1.8	48.2
Recurrent Subtle Pain	1	1.8	50.0
No Answer	28	50.0	100.0
Total	56	100.0	

Table 2-25: Bad experiences summary

In order to clarify the 'Inexplicit No' categorisation, the 4 textual responses are shown below.

"Nope, but I couldn't start bouldering as a hobby. The only day-to-day activity where my magnet sometimes bugs me is when I hover the floor (probably because of the way I grip the handle)"

"Pain: only when carelessly playing with neodymium magnets. On occasion my pinky nail will graze the raised skin."

"Too soon to tell"

"The magnet flips position fairly often and it's become a bit of a tic to push it back down, but it doesn't really hinder me too much."

The remaining respondents excluding one seemed to all have pressure related pain. The following answer is an example that has been placed in the 'Lifting Objects (Light Pain/Uncomfortable)' category;

> *"They only (very slight) downside is that the one in my middle finger, which was originally more on the ring-finger side of my middle finger, migrated to the center of the pad on my finger, which makes direct pressure on the pad slightly uncomfortable. However, this has not hindered me at all, as even when doing heavy lifting pressure is typically on my palm and base of my fingers, not on the pad. There has been no pain."*

One respondent unfortunately reported an incident which resulted in coating rupture, and subsequent removal of the implant. This case of explantation and others are described in section 5.4. Due to the limited number of respondents accurate correlation data between bad experience and other factors such as year of implant for example could not be established. The respondents were asked whether they were able to feel a variety of appliances that produce strong electromagnetic fields and also to name their favourite. Below is a list of the favourite devices of the respondents which has been extracted from the textual data.

- RFID ID Removal Device
- Subway Generators
- Microwave Ovens
- Speakers
- Monitor Degaussing
- Dentists X-Rays
- Power Transformers
- Laptop Power Packs
- Security Scanners
- Electric Motors
- Welder
- Automotive engines
- Hard Drives
- Bar/Tavern Pumps
- Strong Magnets
- Appliances Power Cabling
- Tattoo Machine
- Metro Power Cables
- Pencil Sharpeners
- Hair Clippers
- Hearing AID Pads

Interestingly one of the respondents has made use of the implant for his profession. A 28- 30 year old male from Florida works as an IT technician and was able to use the implant to help him diagnose a problem with a troublesome laptop.

> *"I work on computers and had my favourite experience while working on a computer. My clients' computer would not boot, and they diagnosed a dead hard drive and stated they didn't even think it was spinning. By hovering my hand over the laptop, I was able to feel the laptop spinning, and spinning at what I believed to be a normal speed. That allowed me to skip some of the troubleshooting process and diagnose/fix the issue quicker."*

Another respondent has found great enjoyment from the implant again within the workplace. This respondent is a 33-37 year old male from the UK and works as a welder.

"Setting the welder to pulse in time with my music, it's like having the beat inside your fingers also AC welding is a blast..."

Also interestingly another respondent has described differences in sensation between various appliances and devices. The 33-37 year old Californian male describes his perceptual differences between an automotive battery charger and an electric motor.

"...My favourite feeling comes from an automotive battery charger I own. High amperage DC voltage has a very "chunky" feeling, almost like being mildly electrocuted, as opposed to the field from an electric motor, which feels more "fuzzy", like a warm, fast-moving wind across the skin."

How many times have you been stopped at security scanners (e.g. Airport Security) due to your implanted magnet/s?	Frequency	%	Cumulative %
0	54	96.4	96.4
1	1	1.8	98.2
2	1	1.8	100.0
Total	56	100.0	

Table 2-26: Airport Security Scanners FAQ

Table 2-26 shows the frequencies of how many times the respondents have been stopped at airport security due to their implant specifically. The response seems to indicate that the vast majority of the respondents have not been stopped at airport security due to their implant (96.4%). However the question had no response for 'I have not travelled on an aircraft since having my magnet implanted'; without which this unfortunately means the question holds no significance.

Of the respondents that did report hindrance at airport security due to their implant the respondent who answered once reportedly has a 6 mm diameter and 0.7 mm thick magnet implanted in his left ring finger. As this is quite a large magnetic object it seems plausible that the respondent may have been stopped by security specifically due to his implant. However the respondent who answered that they had been stopped twice reportedly has a single 2 mm diameter 1 mm thick silicon coated magnet implanted in his left index finger.

Although this particular respondent was unsure of the material it seems unlikely to the author that his reason for obstruction at airport security was solely due to his implant.

This conclusion is drawn by the author after having undergone a full 3-D body scan at airport security; he also has passed through heighten security at airports in the US, to which nothing was found or reported. To clarify the author also has two 3 mm diameter 0.7 mm thick magnets; one of which is similarly implanted in his left index finger.

However it should be pointed out that this respondent has had his implant since Jan 2001, and possibly after multiple stops at airport security; the respondent could have deduced that the reason was due to his implant. Due to the anonymous nature of this survey, it is unfortunately impossible to contact any of the respondents and ask further follow up questions.

The final question, 'have you ever been prevented from medical treatment due to the implant, procedures such as MRI' only received one written answer of note. This has been subsequently been omitted here and is examined in the explantation section of this thesis (section 5.4). Further on from the scope of this survey, multiple individuals have posted online blogs of their experiences with magnetic implants. With relevance to this question one individual called "Chai", a body modification artist from Sweden accounts his experience of entering an MRI without magnetic shielding [14].

> *"As soon as I entered the room where the Siemens 3 T MAGNATOM was located I felt a pull in the larger magnet in the back of my hand and a strong tingling sensation in the smaller implant in my finger. I told the technician that I wanted to try going in the machine without shielding and he told me that it would be ok. He asked me why and I told him that this would be a perfect opportunity to test what happens. My hand was inside the machine during the procedure."*

Chai continues to comment about the sensation perceive in firstly his smaller finger implant followed by his larger implant.

> *"It gave a tingling sensation as it was oscillating while just lying in the machine but as soon as the machine started to do its work it started spinning like crazy in my finger. The tingling sensation started to travel up in my arm and it was quite amazing. No discomfort but a bit weird."*
>
> *"This magnet was pulling while I was just laying inside the machine but when the machine started it started pulling towards the machine like crazy and it hurt quite a lot. After a couple of minutes in the machine it started to get really painful but not agonizing. It left quite a bruise and it was a bit sore for a couple of days."*

In Chai's concluding remarks he comments that 'he doesn't recommend MRIs if they can be avoided'.

> *"There were no burns after the procedure and they weren't ripped out of my body all thou I wouldn't recommend going in a MRI with magnetic implants but if you have to its possible as far as I have experienced... Once again this post is not a scientific study but based on my personal experience."*

In subsequent comments to this blog, other individuals comment on their experience with MRI machines. Kim Andre [14] comments somewhat positively about the experience:

> *"Since it was just my knees and not all of me had to be inside the machine did they agree to do it as long as I would take the chance. Stretched my arm as far as I could and when it started... the tingling! No pain or discomfort, but I could feel it all the time. If I had to be any further inside the machine then they would have to reschedule and I would need to have it removed. All in all, not too bad!"*

While this experience seems relatively positive, experiences from Chai and this survey's respondent do not agree with this. It is the personal view of the author that any SMI should most certainly be removed prior to any MRI procedure. This view is based upon the author's personal experiences with 'strong' electromagnetic coils (~50 mT), which were relatively weak in comparison to the central field strength of a medical MRI (1 – 3 T). Furthermore with such strong magnetic fields acting upon the implanted magnet, there may be a strong possibility of serious tissue damage. Further analysis of the effects of an MRI exam on a SMI has been left for future work, see section 10.6.2.

2.4 Summary

This chapter discussed and presented the results of two social surveys that were conducted as part of this research in order to grasp the social views of human enhancement and the perceptual views of individuals whom possess SMIs.

- **The global view on human enhancement** – This survey aimed to ascertain individual's standpoints on a number of questions revolving around the concept of human enhancement. The survey respondents were split into two groups. The first was a general group who consisted of 407 respondents from across the globe, named sample group. 394 responses analysed as there was missing data in 15 of the

respondents. The second group was a focus group for comparison consisting of 44 responses. Whilst several questions were asked regarding this topic, the seen key for the progression of this research was: "how likely an individual would be to undergo a procedure to improve their senses if it were to become available?" To which ~39% of the sample group and ~52% of the focus groups responded positively, a further ~25% and ~20% respectively gave an indecisive response (i.e. maybe/not sure). If the dissemination of this, and similar, research is carefully and considerately thought out, these respondents may tend towards a more positive acceptance of sensory enhancement, which is quintessential for the uptake of this research. When asked "how much would the risk of the implantation/procedure effect affect your decision upon getting an enhancement?" The majority of both groups, i.e. ~74% and ~55%, of the sample and focus group respectively responded positively (i.e. a little or a lot). Thus the risk of the SMIs would also require careful publicity in order for uptake of this research.

- **The global view on magnetic implants** – The survey received a total of 56 responses and queried respondents whom have (or have had) an SMI about their personal experiences regarding them. From the responses there were some rather interesting results within the context of this research. When asked 'why did you get this implant?' the majority of the respondents (60%) replied for magnetic vision purposes (i.e. the perception of magnetic fields); and that the vast majority of respondents ~80% responded that they had not had any bad experiences, recurrent pain or been hindered in day-to-day activities due to their implant. Furthermore whilst there was only one case of an individual who responded to the survey with a personal account of undergoing an MRI procedure with an SMI; this particular case is omitted here and examined in the explantation section of this thesis (section 5.4). In absence of this case personal experiences have been included from online blogs of individuals whom have undergone an MRI procedure with an SMI. Further analysis of the effects of an MRI exam on a SMI has been left for future work, see section 10.6.2.

Chapter 3 – Literature Review

3.1 Introduction

Research in the area of SMIs, to the author's knowledge, has yet to be established, asides from Hameed *et al.* in 2010 [4] which briefly introduces the topic. Therefore this chapter aims to provide a review of relevant two subject areas where this research may be used and also two topics for the consideration of the reader:

- **Sensory substitution** – This section aims to provide a brief review of this ever expanding topic, in order to provide the reader with background information and key concepts. The section describes the history of the subject, the ever growing requirement of the subject, and examples of experimental and commercial technologies that have emerged from it.
- **Vibrotactile devices and Haptics** – This section explores the recent advancements of the subject. The review focusing on the creation of vibrotactile stimuli, furthering with examples of the technology and a brief review of the use of this technology within the automotive industry.
- **Sensory perception – limitations of human perception** – This section examines human sensory perception and compares it to that found within the animal kingdom. Focusing on the auditory system, the visual system and examples of sensory systems that are not innate to humans.
- **Restoration & Experimental Implantation Technologies** – This section reviews a multitude of implantation technologies that are being used in the healthcare sector and explored within the realms of research. The section covers, cochlear implants, deep brain stimulation, implantable pacemakers, retinal implants and the brain gate array. With the purpose of illustrating that human enhancement on an individual level exists, to the population however it is seen as restorative.

3.2 Sensory Substitution

Various diseases, conditions and genetic disorders can cause individuals to be left rendered with limited, if not complete loss, of a particular sensory systems input. "It said that the number of people with age-related macular degeneration, AMD, could rise by a quarter by 2020. - Briefly, the model estimates that 608,213 people had AMD in the UK in 2010. By 2020, this figure is predicted to rise to 755,867." [15]. AMD is a condition that starts off in the 'dry' state causing partial visual loss, in the later 'wet' stage severe visual loss is predicted. The amount of UK citizens suffering from partial or full hearing loss reached 10 million in 2010 with a predicted rise to 14.5 million by 2031 [16]. This is one of the numerous conditions that has led to a copious amount of research in sensory substitution; which is examined within this section.

Sensory substitution is the concept by which one sense can be substituted by another. The most common example of which is the use of braille in visually impaired individuals; where the hindered or lost sense, vision, is substituted by the tactile sense enabling an individual to read. This section explores this field of study and how multiple technologies have been created in order to preform sensory substitution tasks. This research has the potential to form a basis for such a technology and hence this subject is discussed.

"As early as the 1920s, researchers were interested in using vibration of the skin as a means of information transfer (for example Gault in 1926)." [17]. Reed *et al.* in 1982 [18] reviewed tactile communication of speech, in which they explored both tadoma and spectral displays. Reed *et al.* define tadoma in their review by stating the following. "Tadoma is a method of tactile speech communication based on monitoring the actions present on the face and neck during articulation." Spectral displays present auditory data in a spatial manor across an array of stimulators. These devices are roughly analogous to that of an audio equaliser, where the columns of the array depict the frequency bands and the rows depict the amplitudes of each frequency. Multiple authors have used this approach in order to present auditory information to the tactile sense; an example of such a device is presented in Table 3-1 by Sparks *et al.* in 1978 [19]. In terms of sensory substitution spectral displays form an area which is referred to as tactile auditory sensory substitution, TASS.

Kay in 1984 [20] discussed the rapid progression in the area of 'electronic aids for the blind'; reviewing in excess of 70 papers. Kay makes comment that this area in particular is highly emotive "because of the innovation the field has seen over the past 20 years and the controversy over what is best for the user and what is appropriate as a manufactured technology" [20]. This review was furthered by Kaczmarek *et al.* in early 1991 [21]; whom released a highly comprehensive journal article reviewing a vast number of sensory substitution devices and the various approaches that had been taken.

Kaczmarek *et al.* [21] discussed the devices available at the time and future applications of sensory substitution devices, SSDs; focusing on the following areas: Tactile Visual Sensory Substitution, TVSS, TASS and remote tactile sensing or feedback (teletouch). Kaczmarek and Bach-y-Rita, in 1995 furthered this review with a book section [22] by discussing more applications of sensory substitution devices and commenting on the success of commercially available devices. Such as Optacon [23] (see Table 3-1) commenting that in 1995 it had made sales of over 15,000 worldwide. Kaczmarek and Bach-y-Rita, comment on the practical considerations for both vibrotactile and electrocutaneous stimulation, discussing the following; safety, comfort and power considerations.

In later works of Bach-y-Rita, he and Kercel in 2003 [24], continued to review the subject of sensory substitution, by exploring advancements in technology and new applications of SSDs. Bach-y-Rita focuses on: TVSS, Audio Visual Sensory Substitution, AVSS, and Tactile-Vestibular Sensory Substitution, TBSS (Tactile Balance Sensory Substitution) along with implanted human-machine technologies.

Tactile sensory substitution was further reviewed by Visell in 2009 [25] in which he explored the recent advancements in the field. In the paper numerous topics are covered, examples of which include; the properties of tactile perception (which is further discussed in section 4.2), tactile displays and methods of encoding tactile displays (i.e. tactile stimulus design, which is further discussed in 3.3.1). Visell expresses his view on the subject with the following summative statement:

> *"The evaluation of sensory substitution devices is made more difficult, because the most interesting questions facing both scientists and device designers do not merely concern whether users of the devices are able to better perform tasks, but how a given*

level of performance is achieved in relation to device design parameters and the capacities of the user."

Examples of commercial and experimental SSDs are listed in Table 3-1.

Type	Developers	Description / Name	Features/Information
AVSS	Meijer* (1972) [26]	vOICe	The device takes in images via a camera and creates 'soundscapes', audio signals which vary in; pitch for object height in image, amplitude (loudness) for greyscale value, and time & stereo panning for left and right.
AVSS	Kay *et al.* (1984) [20]	Sonicguide	Sonicguide conveys visual spatial information to a user's auditory system; using head mounted ultrasonic sensors as input and then converts this found information into an auditory signal. This is achieved by altering pitch to relay object distance.
AVSS	Montandon (2003) [27]	Eyeborg	The device receives colour information from a head mounted camera and converts the wavelength into an audio frequency.
TASS	Sparks *et al.* (1978) [19]	MESA*	An auditory signal is recorded from a microphone. The signal is converted via a cochlear filter, and is expressed on an electrode array attached to the abdomen.
TBSS	Tyler *et al.* (2003) [28, 24]	Vestibular Substitution Device	The device utilises accelerometers in order to provide feedback of an individual's posture via their electrocutaneous tongue stimulation. Created in order to aid those suffering from BVD*.
TVSS	Linvill & Bliss (1966) [23]	Optacon	Optacon converts textual information from a camera, in to vibrotactile information; which is relayed to the user using an array of thin reed vibration generators.
TVSS	WSAIL (1977) [20]	Mowats	Mowats conveys visual spatial information to a user's tactile system; using head mounted ultrasonic sensors as input and then converts this found information into vibrotactile stimulation via a handheld device. This is achieved by altering the frequency of the stimulation dependent upon distance.
TVSS	Segond and Weiss (2005) [29]	Spatial Navigation Device	The device maps a black and white image from a camera to an array of vibrotactile stimulators. Experimentally tested on individuals in a 3D maze task, providing directional information via the stimulation array.
TVSS	White and Harwin (2013) [30]	Tactile Visualization of Scientific Data	This prototype system was developed in order to allow visualisation of scientific data for visually impaired users, making use of two commercially available haptic devices (explored in 3.3) in order to relay graphical information to the user.

Table 3-1: Summary of Commercial and Experimental SSDs. Meijer* – Originally developed by Meijer (1972) Revised by Haigh *et al.* (2013) [26]. MESA* – Multipoint Electrotactile Speech Aid. BVD* – Bilateral Vestibular Disorder.

The Eyeborg (summarised in Table 3-1) is known to be used by a gentleman called, Neil Harbisson, who suffers from achromatopsia (complete colour-blindness). Yasenchak accounts Harbisson's story in 2013 [27] and how his life has altered with the device, which

he has now had surgically implanted. Harbisson spoke publically about his experiences of the device in 2012, stating 'that he is now able to recognise not only the entire viable spectrum, but infra-red and ultraviolet also; furthermore he now "dreams in colour" [31]'. The properties of the device make its classification an AVSS device; however it appears that, the device now tends to an example of a sensory extension device, seeing that now it outperforms that of what it was intended to perform.

Sensory substitution concepts are discussed extensively within philosophy. Bértolo in 2004 [32] explores the literature with regards to the debate of 'visual imagery without visual perception'. Bértolo critically compares arguments for and against the question "if it is possible to have visual imagery without visual perception". Bértolo states that this debate remains open and "the characteristics and neural basis of visual imagery remain as a futile field of research." Focusing further into sensory substitution the debate arises as to "which sensory modality the acquired perception belongs to", which is reviewed in the works of Auvray and Myin in 2009 [33].

In conclusion the study of sensory substitution is a rather broad, ranging from technology right to behavioural psychology and boarding into philosophy. The purpose of including this summary is, as stated previously, that this research may form a basis for new SSDs. In previous works (Hameed *et al.* in 2010 [3]) the possible applications of this research are briefly discussed. The concept of using this technology in conjunction with ultrasonic sensors for a navigational aid is discussed (i.e. SSD for TVSS) and has been tested in unpublished works.

3.3 Vibrotactile Devices and Haptics

Vibrotactile devices have been shown in the previous section to create sensory substitution devices; however large quantities of researchers have explored the concept of using these devices to facilitate tactile communication for the purpose of human-machine interfaces. The field of study in which encumbers tactile communication and feedback is known as Haptics. Gerald in 1960 [34] articulated his thoughts regarding the use of the tactile sense as an informer, in which he discusses concepts such as: locus, intensity, duration, frequency, language of vibration, intensity as a function of time, wave-form variations and spatially discrete loci.

A multitude of publications have since been published in order to establish the perceptual capabilities of the human tactile sense. Examples of the examined variables are: frequency, intensity and time; these factors are explored in detail in section 4.4. In this section the literature regarding information transfer via the vibrotactile sense is explored along with devices which have been created in order to perform this operation. A multitude of research in this field has been produced; this section focuses upon three main topics:

1. **Haptic Icons (aka Tactons)** – Tactons are defined as "structured, abstract messages that can be used to communicate messages non-visually" [35]. This section outlines the various techniques used to construct these messages.
2. **Various Vibrotactile Devices** – This section explores aims to summarise the vast quantity of vibrotactile devices which have been created.
3. **Automotive Application** – This section focuses on vibrotactile devices and related experimentation which has been conducted within the automotive industry.

3.3.1 Haptic Icons (aka Tactons)

In this section the parameters that have been used to design tactons and vibrotactile stimuli are explored along with the examples of them being used in practice.

Gunther in 2001 [36] presented a whole body vibrotactile system named 'Skinscape'. Gunther and O'Modhrain in 2003 [37] describe the system as "A system that facilitated the composition and perception of intricate, musically structured spatio-temporal patterns of vibration on the surface of the body". Gunther [36] reviews the design of vibrotactile stimuli by exploring multiple parameters which include; duration, frequency, spectral content intensity and spatial. He makes comment on the works of Rowan and Hayward in 2000 [38] in respect to the use of spectral content as a vibrotactile stimulus; "Qualitative use: spectrum from sine to square to noise perceived as smooth to rough." Within the context of this research waveform is explored in the frequency discrimination task (see sections 6.3 and 7.5.2). However, here it is explored quantifiably as opposed to qualitatively.

Van Erp in 2002 [39] released guidelines for the use of vibrotactile devices for human machine interfaces, in which he discusses a range of topics, the main categories of which are: tactile information coding, comfort and possible pitfalls. Points of note specifically to

this research and this topic are the comments on frequency and temporal patterns. Van Erp commenting on frequency states that "No more than 9 different levels of frequency should be used for coding information". Whilst commenting upon temporal patterns van Erp comments "When using a single actuator of a tactile display to encode information... ...the time between signals must be at least 10 ms... ...i.e. 10 ms pulses and 10 ms gaps can be detected." The idea of temporal gap detection is examined in this research. A literature review of this topic is presented in section 4.4.7 and the experimental work in sections 6.4 and 7.5.7.

Brewster and Brown in 2004 [35] furthered reviewed the design considerations of tactile icons, focusing on the following topics; frequency, intensity, waveform, duration, rhythm, body location and spatiotemporal patterns. Brewster and Brown review the works of Gill whilst looking into the intensity parameter of tactons, stating "no more than four different should be used..." Brewster and Brown comment on the previous statement with "the number of useful discriminable values will depend on absolute or relative presentation of stimuli".

Brown *et al.* in 2005 [40] performed perceptual tasks on individuals, focusing on roughness perception and recognition of stimuli relating to mobile devices (i.e. informing individuals of voice calls, text messages and multimedia messages). The roughness perceptual task saw respondents decide which of a set number of sinewave based stimuli (sinewave signals with and without modulation) felt the roughest. Results presented show that by modulating the sinewave it can be distinguished from the non-modulated signal in terms of roughness. The second task saw the individuals being subjected to tactons created using both rhythm and roughness. While no significance was found between the two methods, the results clearly show an improved recognition rate with the rhythm parameter. This is further explored by Brown *et al.* in 2006 [41], which presents similar results and add the location of stimulus as a parameter, which showed almost perfect (100%) correction of recognition.

Research such as this has now been used in the commercial sector by mobile phone manufactures, where by vibrotactile alerts, typically comprised of rhythmic change, are being used to relay various message types to the user. The mobile phone company Nokia filled a patent to the US (March 2012), which describes using technology in a similar manner to that of this research. The patent describes the use of "a material attachable to

skin, the material capable of detecting a magnetic field and transferring a perceivable stimulus to the skin, wherein the perceivable stimulus relates to the magnetic field" [42]. However to the author's knowledge no further development has come of this patent.

MacLean in 2008 released a review paper of tactile information design [43] along with an extension of this which explored 'haptic interaction design for everyday uses' [44]. Within [43] MacLean focuses around three main points:

> *"UTILITY: Where and how will haptic signals be useful?"*
>
> *"FORM: What should the underlying stimuli be and how should they be created?"*
>
> *"LEARNING: How are icons most easily acquired, and what limits of constraints pertain"*

Exploring the "*FORM*" section of the paper, MacLean focuses on representation approaches and implications, with regards to learnability and capacity. With regards to capacity MacLean comments:

> *"Representation may have little impact on the ultimate capacity to learn icons. Our ability to recognize visual symbolic depictions seems inexhaustible: there are 3,000 Chinese ideograms, and a literate person can pick up 50,000 words without analysis in a single language. Essentially, there is no known limit to long-term symbolic memory... ...Computer Braille maps the English alphabet plus punctuation to 256 tactile images, and experienced Braille readers say that they feel words and not characters, albeit at 1/3 the speed of sighted readers..."*

Furthering on with "*FORM*" MacLean explores design considerations in great detail, but further focuses on a method of "Perceptual Optimization of Stimulus Sets" in which multidimensional scaling is used. MacLean expertly explains this concept [43]:

> *"Multidimensional Scaling (MDS) is a visualization tool that can reveal the underlying structure of data sets [49] and to analyze perception in complex stimulus spaces. In perceptual MDS, the algorithm takes as input a "dissimilarity matrix" containing user-perceived distances between **s** items (here, haptic stimuli, which may have been created along **n** design dimensions) and locates them in a Euclidean **m**-dimensional perceptual space such that inter-item distances approximate the degree of dissimilarity described by the input matrix. The algorithm also delivers model "stress," indicating goodness of fit as a function of **m**: a higher order model may provide a tighter fit (lower stress value) but at the cost of abstraction and/or clarity. Ideally, a knee in*

> *the **stress = f(m)** curve will suggest the best value for **m**. We take the **m** dimensions as the most salient aspects of the set; stimulus coordinates recovered in the scaling locate the objects"*[1]

While this research mainly focuses around actual perceptual differences, this method of stimulus ordering could potentially be used in further research for the design, optimisation and ultimately choice of the final stimuli for a particular task. In order to remain concise upon these papers, the reader should consult [44, 43] for further reading.

Haptic devices have been proven beneficial within the medical field. Okamura *et al.* in 2011 [45] present a review which "reflects the research community's strong interest in haptics in medical and clinical skill acquisition". The review focuses on three areas where haptics are used:

1. Medical examinations and procedures.
2. Training and evaluation of clinical skills.
3. Performance of medical interventions.

The work reviewed within the paper [45] does show promising progress in to the advancement of haptic uses within the medical field. One of the devices reviewed, "VerroTouch", is described in Table 3-2.

3.3.2 Various Vibrotactile (Haptic) Devices

Certain haptic devices enable the user feedback in a virtual spatial environment, enabling not only the perception of object dimension, but with modern technology texture discrimination also. Haptics has enabled greater telemanipulation, which has seen advancements within medical surgical methods enabling procedures such as laparoscopic surgeries. Some examples of commercial and experimental devices in this field are shown in Table 3-2.

[1] (N.B. italicised letters in the quote have been made bold for format consistency)

Developers	Description/ Name	Features/Information
Wagner *et al.* (2002) [46]	Tactile Shape Display	A prototype designed to cause indentation upon the skin using an array of 6×6 mechanical pins and RC servomotors to convey shape, such as a 2D sinewave.
Ye and Auner [47] (2003)	Haptic Interface using CyberGlove®	Development of a prototype haptic interface for feedback of a vital environment was developed. The future aim of the project was to provide real-time haptic feedback of a robot system; which aims to integrate readings from multiple smart sensors.
Chatterjee *et al.* (2007) [48]	BCI* using Vibrotactile Biofeedback	As opposed to the norm (i.e. visual feedback), the prototype developed in the paper, provided vibrotactile biofeedback in a BCI; tested using a high/low motor imagery task, feedback provided location of a virtual bar.
Réhman and Li (2008) [49]	Vibrotactile Emotions on Mobile Devices	Experimental platform designed in order to convey facial expressions obtained from a video feed to a vibrotactile stimulator on a mobile phone was developed; design incorporated two methods of encoding the vibrotactile data, results shows reduction in terms of estimation error post training on the method.
Visell *et al.* [50] (2009)	Floor Surfaces Haptic Feedback	Prototype floor surface haptic feedback design presented relaying various tactons relating to floor surfaces, physical objects and musical notes by altering waveform, testing two methods 'waveshape' and 'impact'. Recognition of stimulation was tested on participants showing that the 'impact' waveform method produced greater correction rates.
Kyung and Lee [51] (2009)	Ubi-Pen	A prototype of a device named Ubi-Pen has been presented. The devices consisted of a stylus like device that incorporates an array of 3×3 mechanical pins used to provide tactile feedback as a form of interactive display. Experimentally tested to relay textural information in a recognition task.
McMahan *et al.* (2011) [52]	VerroTouch	The system 'VerroTouch' adds tool acceleration feedback (in the form of vibrational and auditory) to the telerobotic surgical system called the Intuitive Surgical da Vinci S System; which allows the "surgeon to feel and hear tactile cures that are known to be in important for humans during manipulation tasks" [52]. "Experiments with the system... ...revealed that users appreciated the inclusion of tool contact acceleration feedback, although it did not have measurable impact on user task performance." [45]
Geomagic® [53]	Touch™ X	"The Geomagic Touch X haptic devices allow users to feel 3D on-screen objects by applying force feedback on the user's hand, and the Touch X delivers expanded true-to-life sensations with a more fluid feel and lower friction." [53] The device is specifically marketed for Medical and Research Use.

Table 3-2: Examples of Commercial and Experimental Vibrotactile (Haptic) Devices. (BCI* - Brain Computer Interface)

Table 3-2 portrays the vast extent of applications where haptic feedback is being made use of.

3.3.3 Automotive Application

The automotive industry has adopted the concept of using haptic feedback to relay vital information to the driver; for example rear-to-end collision alerts or awakening

drowsy drivers. This research for instance is being funded by a leading automotive manufacturer, showing the expanse of research that is being conducted for this industry. This section briefly explores the concept of using haptic feedback as an aid for drivers.

Spence and Ho in 2008 [54] presented a review paper of tactile and multisensory spatial warning signals for drivers. The review contains a reference count exceeding 100 papers, which further shows the vast amount of research being conducted in this area. The paper focuses on a number of topics which include: cost benefit assessments, awakening drowsy drivers, attentional alert systems, reduction in workload for drivers and warning signals for the ageing drivers. This highly comprehensive review is an impressive overview of the technology available at the time and insight as to where this research may tend towards. For example in their concluding remarks Spence and Ho state "Finally, more research is needed to determine how to design tactile (and multisensory) warning signals that can help the growing population of ageing drivers to drive safely".

Ho and Spence in 2009 [55] conducted an experiment to determine the effects of warning tones on drivers in a head re-orientation task. Individuals were sat within a driving simulator with the visual display in front of them and were instructed to have their head orientated in three positions; frontward facing, leftward facing and rightward facing. The simulator then randomly acted out a rear-to-end collision scenario. The drivers received: no warning, auditory warning or a vibrotactile warning (presented at the wrist). The startling result showed that without warning signal the error (i.e. missing collision stimulus) of the driver, whilst reorienting head position from left to centre and right to centre, was ~45%, with warning signal this was reduced to <5%.

Ryu *et al.* in 2010 [56] evaluate the use of vibrotactile stimuli to relay information to a driver. In the paper Ryu *et al.* begin by exploration of the background vibration that drivers are subjected to in order to determine a minimum frequency (60 Hz) that their created stimulation signals required. They subsequently created 18 sinusoidal vibrotactile signals and had their participants preform a dissimilarity task on each of the pairs of stimuli. These results were analysed, as shown by MacLean [44] by the use of MDS. A learnability study was conducted and the stimuli were tested using a menu selection task (where the stimuli provided feedback of the menu selected) whilst preforming a driving-like task as the primary task. Results in terms of percentage of correct menu navigation all on average exceeded 96%. This use of feedback would allow drivers to manipulate car

systems like heating without averting their visual attention from the road; which is a possible future direction for this research.

Gray *et al.* in 2014 [9] compared the effects of vibrotactile warnings and how they can be used to reduce brake reaction times of drivers. The warning signals were presented using a vibrotactile stimulators positioned at the waist and the head. The stimulator on the head was comprised of three tactile stimulators, which were either stimulated upwards or downwards. The effect of providing a warning signal significantly reduced the drivers simulated brake reaction time, the largest reduction was achieved when stimulating the head upwards. The concept of using vibrotactile warning signals to reduce braking times is further explored in section 4.4.2.

With a multitude of possibilities that vibrotactile stimulation presents, this research, may provide a basis for a number of applications for the automotive industry, such as, collision warning signals, reduction of drivers workload (e.g. using feedback in a similar manner to Ryu *et al.* [9]) and informative alerts (e.g. speed alerts, stimulating the driver when he/she exceeds the speed limit of the road). Furthermore the review of this literature has provided great examples of excellent experimental setup as explained by authors such as that presented by Spence and Ho [55].

3.4 Sensory Perception – Limitations of Human Perception

In the author's opinion, the human body is quite restricted in its ability to perceive stimulus modalities by the physical capabilities of the sensory systems 'we' possess. As a species, 'we' humans have multiple levels of perception (e.g. colour, speech and haptic) that can be categorised by the five universally accepted exteroceptive sensory systems, namely: auditory, somatosensory, visual, olfactory and gustation. The aim of this subsection is to provide a comparative view of human perception capability against that of the other animals.

3.4.1 Auditory

Auditory systems enable the perception of sound pressure-waves, by transduction of the mechanical energy of the waves into neuronal responses. The sound pressure-waves first enter the ear and applies force upon the tympanic membrane (the ear drum), from here the force is structurally transmitted through to the inner ear. The inner ear is filled

with fluid which carries the signal of the pressure-wave. The movement of fluid is then transduced into the neuronal responses via 'frequency-tuned' hair cells along the length of the basilar membrane within Organ of Corti [57] (located in the cochlear). The size and sound transmission properties of the basilar membrane define its frequency absorption properties [57]. Therefore alteration in the dimensions of the membrane and structural properties of the cochlear ultimately lead to variation in the perceptual frequency range of sound waves.

In humans this range is ~20 Hz to an approximate maximum of 20 kHz; this maximum however does decay with age. Cats, in comparison, have a smaller basilar membrane which enable them to have a much higher maximum frequency for auditory perception ~60 kHz [57].

Bats are widely known to make use of ultrasonic signals in order to perform echolocation. They perform this process by emitting ultrasonic chirps and perform multiple cross comparisons between the emitted chirp and the perceived re-bounded signal. Lawrence and Simmons in 1982 [58] make comment that "the frequencies used by bats are predominantly ultrasonic, in the 10 to 200 kHz range". Smith in 2008 [59] reviews how their auditory system and echolocation process functions, and draws analogy with their sense and process to that of colour vision; which is said to be termed echo colours.

The process of echolocation has been reported in cases of blind individuals. Thaler *et al.* in 2011 [60] performed a neurological study on two blind individuals whom reported they are adept to echolocation. They have started to perform this process "by producing mouth clicks and listening for the returning echoes". Interestingly the results presented show that during the processing of click-echoes, the visual cortex of both individuals showed activity during an fMRI scan. However the frequency range in which the individuals perform this process is still restricted by the frequency range available to humans.

3.4.2 Vision

Vision systems enable the perception of the 'outside world' by the perceived changes in wavelength of reflected light from objects. The typical human vision system makes use of four types of visual receptors situated within the retina. These receptors elicit neuronal

responses as particular ranges of wavelengths of light cause a breakdown of chemicals known as opsin within each of the receptors. The receptors are:

- **S-Cone (short) cell** – Blue wavelength detection (maximum absorption ~419 nm).
- **M-Cone (medium) cell** – Green wavelengths detection (maximum absorption ~531 nm).
- **L-Cone (long) cell** – Red wavelengths (maximum absorption ~558 nm).
- **Rod cells** – Low light perception with no specificity of colour.

Overall this enables humans a perceptive range of ~400 nm (violet) to ~700 nm (red) on the electromagnetic spectrum, which is commonly referred to as the visible light spectrum [57, 61]. Jameson *et al.* in 2001 [62] performed a study which compared women with four-photopigment genotypes (heterozygotes) against male and female with three-photopigment genotypes (trichromat) control individuals. The women with four photo pigment genotypes were "found to perceive significantly more chromatic appearances" compared with the control group. In the discussion of the results Jameson *et al.* make a general statement upon the findings "heterozygotes perceived more delineations in the spectrum and exhibited finer grained discrimination differences in the interval between approximately 580 and 780 nm".

While this genetic alteration has shown to increase discrimination and ultimately (perhaps) increase the heterozygotes colour spectrum resolution, the research presented does not suggest that the overall range of the visible system within the zygotes is increased. In comparison the sensitivity range to visual perception in certain species of bird has been experimentally shown to outperform that of humans.

Cuthill *et al.* in 2000 [63, 64] explored the visual perceptual capabilities of four particular species of bird, more specifically the estrildid finch. Results presented in the study show that four spectrally distinct types of cone cell were present. The first three were similar to 'normal' human cone cells, i.e. the S-cone, the M-cone, and the L-cone; each of which presented similar wavelength absorption properties to that of humans. However the fourth cone reported a maximum absorbance at 370- 373 nm, which ultimately enables the perception of ultraviolet, UV. Similar UV perceptual capabilities have been found in the budgerigar in research presented by Arnold *et al.* in 2002 [65]; who

stated that the results of the study revealed a strong evidence for (UV) fluorescent sexual signalling.

Liu *et al.* in 2014 [66] proposed a design for a graphene based photodetector which "demonstrated room-temperature photodetection from the visual to the mid-infrared range". The intriguing element of this development is the proposed applications that one of the authors Zhong stated in a press release from the University of Michigan [67]:

> *""If we integrate it with a contact lens or other wearable electronics, it expands your vision," Zhong said. "It provides you another way of interacting with your environment.""*

This may lead to further research in sensory extension, and perhaps ultimately allow humans to perceive a wider range of a the electromagnetic spectrum.

3.4.3 Sensory Systems Not Innate to Humans

Bossomaier in 2012 released a book [57] that introduces each of the sensory systems. Also included in the book is a section on 'non-human sensory systems'. Bossomaier covers the following sensory systems within this section:

- **Electrical Sense (Electroreception)** – Sense found within sharks, the transduction of electrical energy occurs as sacks called 'ampullae of Lorenzin' deform under electrical fields. It is hypothesised that this sense is typically used for prey detection. Electroreception has been found in a wide range of aquatic animals [68]. The process itself is found in both passive and active forms, which was reviewed in detail by Albert and Crampton in 2005 [69].
- **Heat Sensor (Infrared, IR Receptors)** – The jewel beetle formally known as, Melanophila Acuminata, has '~90 IR sensors located on both sides of its body' [70], its typical use is detection of forest fires [57]. Schmitz *et al.* in 2009 [70] proposed a new model for technological IR sensors based upon the mechanics and operation of this system.
- **Magnetic Sense and Navigation (Magnetoreception)** – Multiple animals have been postulated to make use of the Earth's magnetic field for navigation purposes, such as: birds, turtles, fishes, honey bees and cetaceans. Johnsen and Lohmann in 2005 [71] review this sense and postulate how it is used. They conclude by stating 'magnetoreceptors have not been identified and the transduction process for

magnetoreception still remains unknown'. Bossomaier [57] further explores reports upon claims of magnetoreception in humans, and states that 'This is a fairly controversial area'.

3.5 Restoration & Experimental Implantation Technologies

3.5.1 Introduction

There are a number of technologies that integrate with the body, and have been widely accepted for restorative purposes for many years. This subsection explores a few of the crucial technologies that enable the vast quantity of the population to restore loss of control or sensation due to a variety of medical conditions. These technologies range from the very widely known and accepted such as, cochlear implants, to the new and upcoming technologies such as deep brain stimulation. The purpose of which is to emphasize that technology integration within humans is rapidly evolving. This is opening up new possibilities for future acceptance of technologies to enhance/improve 'our' sensory range, physical capabilities and mental capacity.

3.5.2 Cochlear Implants

Cochlear Implants are considered to be "the most successful neural prosthesis" [72], from the initial conceptual idea in 1800 by Volta, to their first, U.S. food and drug administration (FDA) approval in 1984, the technology has progressed rapidly and continued to improve. Figures show that the implant had helped more than 120,000 people as of 2008 restore aspects of their auditory input [72]. This number has estimated to have almost doubled, affecting over 219,000 people as of December 2010 (as reported by the FDA [73]). An in depth review of cochlear implants can be found from Zeng *et al.* [72] which was published in October 2008. Figure 3-1 (adapted from [72]) summarises the technologies' evolution chronologically.

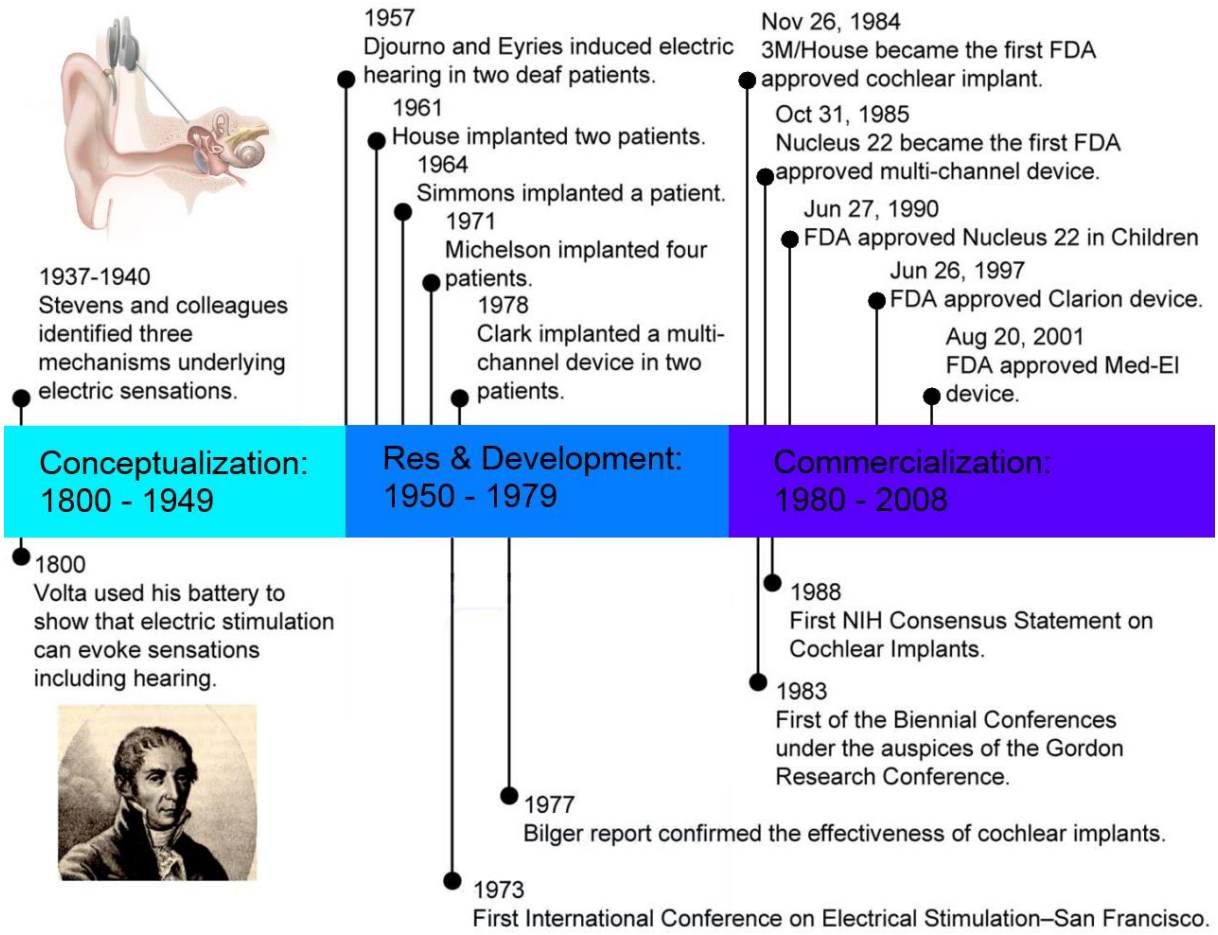


Figure 3-1: The Major Historical Events of the Cochlear Implant (adapted from [72])

3.5.3 Deep Brain Stimulation

Parkinson's disease is seen as hugely debilitating for the patients in later stages. As the disease progresses the common chemical treatment levodopa no longer suffices as long-term effects are complicated with movement disorders such as dyskinesia [74]. Animal models have shown that, lesions created in the Subthalamic Nucleus, SN, and the Pars Interna of the Globus, PIotG, improves movement capabilities; although permanent lesions came with the risk of inducing neurological defects. A relatively high-frequency (90 – 185 Hz) stimulation of the SN and PIotG areas simulates the effect of creating a lesion. This treatment is known as Deep Brain Stimulation, DBS. Documented testing form the Parkinson's disease study group [74] was conducted from July 1995 to July 1999; findings showed an improvement in related movement disorders in the majority of the test patients. Techniques to predict tremors have been examined with the overall goal of providing stimulation only when required are being developed to reduce power consumption and potential damage, as described by Bakstien et al. in 2010 [75].

3.5.4 Implantable Pacemakers & Defibrillators

Numerous heart conditions, e.g. arrhythmia, require patients to have implantable pacemakers. There initial conceptualisation came in the late 1950's, where the devices simply outputted 1 ms pulses at 70 ppm [76]. The technology rapidly progressed sensing for biological processes such as; blood pH [77], respiratory rate [78, 79], vibration and motion [80], blood temperature [81] and QT interval [82]. The views of patients with implanted pacemakers are discussed in [83]. In 2002 there were an estimated 3 million people worldwide who have had implantable pacemakers, with an estimated 600,000 per year being implanted [83]. This puts the estimation for 2013 at approximately 9.6 million people in the world having implantable pacemakers. The most recent technology is the Leadless Cardiac Pacemaker, LCP [84]. Being leadless this approach removes any complications with breaking stimulation cabling. The LCP shows that pacemaking technology is continuously improving in terms of size, mass, longevity and reliability.

3.5.5 Retinal Implants

Throughout the globe there is an estimated 20-25 million people ([85] 2012) who suffer from varying levels of blindness or facing blindness. As populations increase and live longer this number is likely to increase this is due to varieties of diseases. The most prominent of which are: Retinitis Pigmentosa and AMD (previously discussed in section 3.2). This daunting statistic points to the requirement of an interdisciplinary approach to create necessary advancements in technology for aid. The initial conceptualisation of retinal implant dates back to 1929 by Forrester [86]. Forrester reports that one of his patients described seeing a small spot of light directly in front and motionless during electrical stimulation at the "extreme occipital pole" [86]. Throughout the years multiple teams have worked on a wide variety of retinal implants [86, 87, 88, 89, 90]. A more recent ground-breaking advancement in this area has come from Nirenberg and Pandarinath [85]. The posed issue of current visual prosthesis is that they allow vision of "spots of light and high contrast edges but not natural images". The paper discusses their aim to tackle this issue by decoding the neuronal input to the optic nerve such that the images received by a camera can be pre-processed to resemble the image in a form of neuronal encoded signals.

3.5.6 Brain Gate Array

Patients who suffer traumatising experiences such as spinal injury or conditions such as tetraplegic are left rendered with lack of limb control. However, advancements in technology permit us to be able to read neuronal signals and this field of study is now driving developments in the applications of neuro-prosthetics with the aim of providing alternative means mobility in such cases. In 2002 Professor Kevin Warwick underwent a surgical procedure in which he was implanted with a neuro prosthetic implant, referred to as the Utah/brain gate array. The Utah was implanted into the median nerve [91, 92, 4]. This implant coupled with percutaneous signal cables connected to a custom-built information transfer platform enabled Professor Warwick to interact with a number of devices, ranging from light switches to a wheelchair. While Warwick's work offers a glimpse into the possibilities of human machine interaction, other works furthered this concept for restorative purposes. Collinger *et al.* in 2013 [93] reported a case of a 52-year-old woman undergoing a procedure similar to Warwick, however this time two implants were used and both were implanted directly onto her motor cortex. The lady was previously diagnosed with spinocerebellar degeneration which rendered her unable to control her limbs and torso. However with the use of these implants and 13 weeks of training, she was able to drive and control her high-performance modular prosthetic limb.

3.6 Summary

This chapter aimed to provide a review of the relevant subject areas of where this research could potentially be utilised along with topics for the consideration of the reader; as summarised below:

- **Sensory Substitution** – This section provides an overview of sensory substitution, which is the concept by which one sense can be substituted by another. Beginning with a historical overview, the main review focuses predominantly on tactile sensory substitution devices. Furthermore examples of both experimental and commercially available sensory substitution devices have also been presented.
- **Vibrotactile Devices and Haptics** – This review is divided into three sections: haptic icons, examples of vibrotactile devices and a review of the literature regarding the application of vibrotactile devices within the automotive industry. The review of haptic icons focuses on previous literature regarding the creation of signals created

to relay information via the vibrotactile sense and methods used to evaluate them. The vibrotactile devices section provides examples of both experimental and commercially available vibrotactile devices. Finally the automotive application part focuses on the multiple empirical studies conducted which presents the benefits of utilising vibrotactile feedback within vehicles.

- **Sensory Perception – Limitations of Human Perception** – This section explores the literature regarding perception and cross examines the sensory capabilities of humans to that of examples found in the animal kingdom. The examples discussed are of species which outperform 'our' sensory capabilities, along with examples of sensory systems that are completely non-existent to humans. Future research in sensory augmentation or extension may prove vital in gaining further understand of not only these species, but 'our' surroundings also (as discussed in the opening pose of this thesis).
- **Restoration & Experimental Implantation Technologies** – This section provides a brief review of commercially available and experimental, restorative implant technologies: cochlear implants, implantable pacemakers/defibrillators, deep brain stimulators, retinal implants and the brain gate array. The examples provided indicate an ever increasing uptake in the use of implants. This increase in uptake coincides with an increase in the range and type of available devices as well as literature on the subject. Provided that publicity is well managed whilst research in implant technologies progresses, a further increase in social acceptance of implants will be seen for not only restoration, but also sensory augmentation/extension. As stated in the introduction of this chapter the inclusion of this section is to illustrate that human enhancement on an individual level exists, to the population however it is seen as restorative.

Chapter 4 – Somatosensory Sensory Perception and Psychophysics

4.1 Introduction

This chapter aims to provide a focused literature survey of the subject areas which are directly linked to this research's underlying biological principles and experimental methodologies. The areas that are covered within this chapter along with their purpose for inclusion are as follows:

- **The Somatosensory System** – This section aims to explore how the perception of implanted or superficial magnets under electromagnetic fields occurs within the human body. Firstly by focusing on cutaneous mechanoreceptors (mechanical stress and strain receptors), the section looks to provide a reference as to the underlying biology of vibrotactile perception. Furthering on in to a brief summarisation of the neuronal pathway take from the mechanoreceptive afferent fibres to the projection on the somatosensory cortex.
- **Psychophysics & QUEST** – Quantifying perceptual benefits and/or detriments of SMIs in comparison with superficially attached magnets to skin (which is a key aim of this research) requires perceptual experimentation. The study of which is known as psychophysics. The subject of psychophysics is briefly explored focusing on the key concepts that have been used throughout this research's psychometric experimentation (see Chapter 6 and Chapter 7). QUEST is a psychometric method which is used extensively within Chapter 7 and here the methodology is detailed.
- **Vibrotactile Psychometric Thresholding & Mental Chronometry** – Within this research 6 perceptual experiments have been conducted: simple reaction time, amplitude detection, amplitude discrimination, frequency discrimination, temporal discrimination and temporal numerosity discrimination with respect to temporal

gap detection. This section covers the literature regarding each of the experiments individually.

4.2 The Somatosensory System

The human somatosensory system (aka the touch or tactile sense) obtains sensory information from stimulation of various receptors situated throughout the body. In terms of fetal development it is our earliest sense to develop [44]. This impressive system obtains stimulation from the following areas: skin, tendons, muscles and internal organs except the brain [94]. Examples of the receptors within this system are shown in Table 4-1.

Receptor Name	Stimulus Sensitivity	Function in Somatosensory System
Thermoreceptors	Thermal Change	Temperature Perception and Nociception
Mechanoreceptors	Mechanical Stress/Strain	Proprioception, Kinaesthesia and Nociception
Chemoreceptors	Chemical Stimulants	Irritants and substance detection from injured tissue

Table 4-1: Summary of receptor groups within the somatosensory system (Nociception – pain perception, Proprioception – one's own perception, Kinaesthesia – ability to infer ones movement) [94, 59, 57]

The functional properties of the mechanoreceptors are essential to this research; i.e. they facilitate an individual's perception of the MIVS.

4.2.1 *The Cutaneous Mechanoreceptors*

Cutaneous mechanoreceptors slightly differ in glabrous (hairless skin) and non-glabrous (hairy skin) [95]. Common mechanoreceptors to both glabrous and non-glabrous skin are the: Pacinian corpuscles, Ruffini corpuscles and Merkels discs. The difference between the two skin types is that hair-follicle receptors are located in the non-glabrous skin only and the Meissner corpuscles are exclusive to glabrous skin. As this research focuses on SMIs within the hand, and mainly the fingertip, this section focuses on mechanoreceptors within glabrous skin. The four mechanoreceptors within glabrous skin (Pacinian, Meissner and Ruffini corpuscles and Merkels discs) are illustrated as to their approximate location in Figure 4-1.

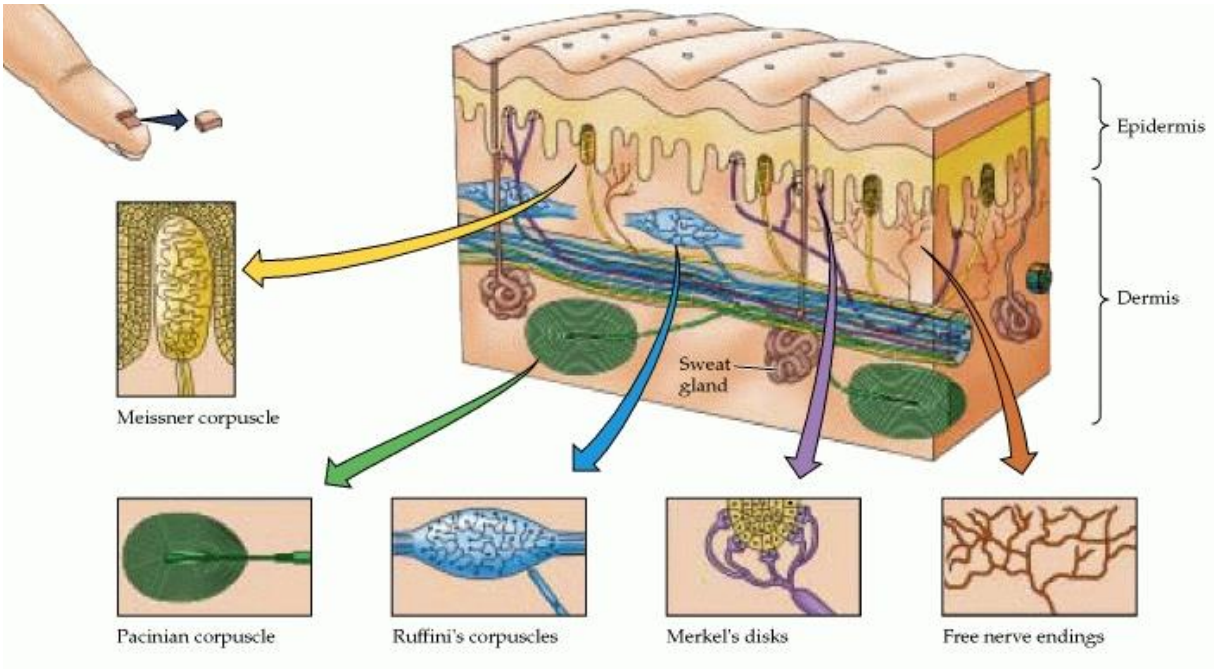


Figure 4-1: Illustration of glabrous mechanoreceptors adapted from [96]

These mechanoreceptors can be categorised into two groups, rapidly adapting, RA (Meissner and Pacinian corpuscles) and slowly adapting, SA (Ruffini corpuscle and Merkels disc). Furthermore they are categorised by type, either type I or II, which refers to receptive range. Type I (Meissner corpuscle and Merkels disc) have a short receptive field and type II (Pacinian and Ruffini corpuscles) have a larger receptive field [97] (each specific field range is shown in Table 4-2).

Meissner corpuscle (RA type 1, RA1) are located in the epidermis, these receptors elicit neuronal responses under low frequency vibrations and are most sensitive to 20 to 40 Hz [98]. These receptors also "generate rapidly adapting action potentials following minimal skin depression" [96].

Pacinian corpuscles (RA type 2, RA2) are located lower in the dermis, an area which is often referred to in literature as the subcutaneous tissue (see Figure 4-1). These receptors also respond to frequency stimulation however in comparison to Meissner corpuscles they respond at higher frequencies and are most sensitive to 200 to 300 Hz [98]. They also have a lower response threshold than the Meissner corpuscles, meaning they require less stimulus intensity in order to elicit a neuronal response (see section 4.4.3). Smith in 2008 [59] makes comment on the structure and functional process of this corpuscle. Ranging in length (0.5 - 2 mm) these oval cells have an onion-like layered structure when observed in

section, which consists of connective tissue which surrounds unmyelinated nerve fibre. Smith continues by expertly commenting on how the Pacinian corpuscle operates:

> *"It is believed that the layered structure has the function of transforming a steady indentation of the skin into a transient stimulus. This is accomplished by the indentation causing a momentary slippage of the layers over each other until, rapidly, a new equilibrium is reach, when the pressure on the sensory nerve ending is relieved. Hence Pacinian corpuscles are able to detect vibration even when subject to steady pressure. A generator potential (depolarization) can be detected in the unmyelinated ending, when the corpuscle is compressed. This results in a short burst of impulses in the sensory fibre, which adapts in one or two seconds to zero or a very low frequency." [59]*

This incredible structure and its functional properties are an astonishing example of the beautiful complexity of nature. Smith does continue to explain the structural properties of each of the mechanoreceptors. However in order to remain concise the author points the reader to [59] for further reading.

Merkel's discs (SA type 1, SA1) is the collective name for a Merkel cell cluster, the cluster elicits a neuronal response under mechanical pressure [95]. They were originally named 'touch spots' [99] relating their characteristic domelike structure to their physical sensory modality of touch. Located high in the epidermis (see Figure 4-1) these receptors account for ~25% of mechanoreception in the hand. They respond to indentation on the skin and are reported to play a "vital role in static discrimination of shapes, edges and rough textures" [96].

Ruffini's corpuscles (SA type 2, SA2) also referred to as Ruffini endings, elicit a neuronal response under lateral skin stretching [100]. Cutaneous Ruffini endings are located high in the dermis, however, they do not breach the epidermis (see Figure 4-1). Approximately they account for 20% of receptors in the hand [96]. Table 4-2 summarises the characteristics of each of the four receptors presented; as well as additional information such as their primary functions and their neuronal response to stimuli.

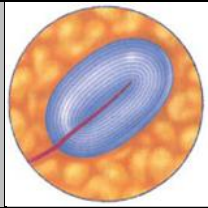
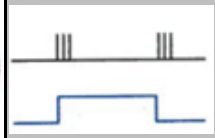
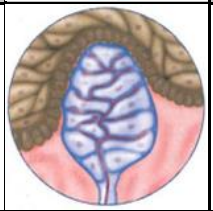
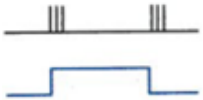
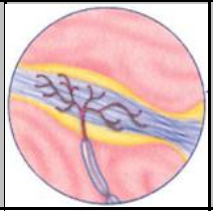
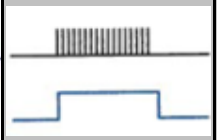
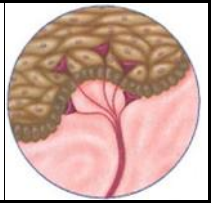
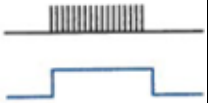
Receptor	Image	Neuronal Response (black) to stimuli (blue)	Position In Dermis	Receptive Field (mm^2) (Median)	Frequency Range (Most Sensitive)	Maximum Feature Sensitivity	Primary Functions	Receptors /cm^2 Finger Tip (Palm)
Pacinian Corpuscle (RAII)			Hypodermis bordering Dermis	10-1000 (101)	40-1000 Hz (200-400 Hz)	• Temporal changes in skin deformation	• High-Frequency vibration Detection • Course texture perception • Pattern/form detection • Stable precision grasp and manipulation	21 (9)
Meissner Corpuscle (RAI)			Epidermis bordering Dermis	1-100 (12.6)	10-200 Hz (20-40 Hz)	• Temporal changes in skin deformation	• Low-frequency vibration detection • Stable prevision grasp and manipulation • Texture perception • Surface Texture	140 (25)
Ruffini Ending (SAII)			Dermis closest to Epidermis	10-500 (59)	7 Hz	• Sustained downward pressure • Lateral skin stretch	• Direction of object motion and force due to skin stretch • Stable prevision grasp and manipulation • Finger position	9 (15)
Merkels Discs (SAI)			Epidermis bordering Dermis	2-100 (11)	0.4-100 Hz (<~5 Hz)	• Sustained Pressure • Maximally sensitive to very-low frequencies	• Very-low-frequency vibration detection • Course texture perception • Pattern/form detection • Stable prevision grasp and manipulation	70 (8)

Table 4-2: Summary of Glabrous Skin Mechanoreceptors ([21, 101, 97, 59, 61, 22, 102, 57])

4.2.2 *Somatosensory Cortex*

After physical stimulation and the given mechanoreceptor(s) have elicited a neuronal response, the 'information' about the stimuli is projected onto the somatosensory cortex. The pathway in which the neuronal signal follows is illustrated in Figure 4-2, beginning at the mechanoreceptors' afferent fibres and ending at the cortex. This pathway is known as the 'Dorsal (Postcentral) Column – Medial Lemniscus Pathway' [57, 103]. Within Figure 4-2 the Spinothalamic tract is also represented, this pathway provides neuronal information from free nerve endings to the somatosensory cortex which in turn provides the perception of temperature and nociception [61].

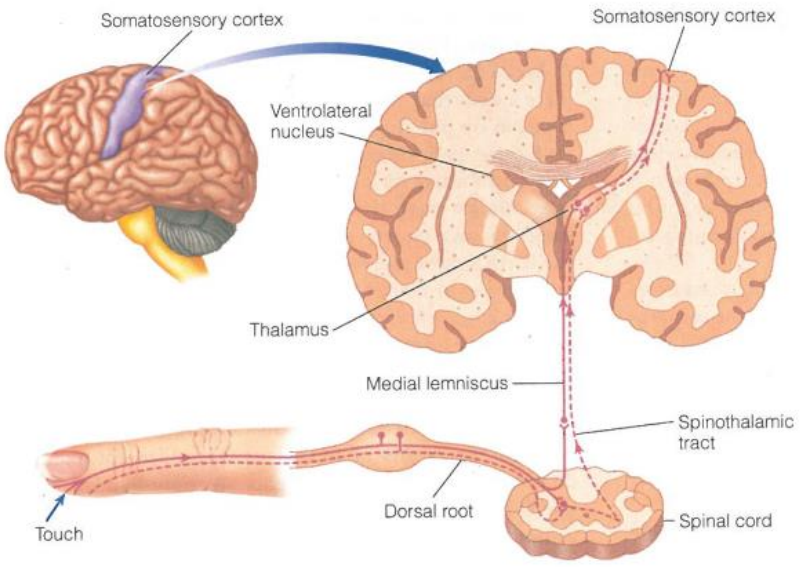


Figure 4-2: Illustration of the Dorsal Column – Medial Lemniscus Pathway and the Spinothalamic tract (from [61])

Focusing on the dorsal column – medial lemniscus pathway, the dorsal column (aka the first-order neuron) refers to the grouping of two (Gracile and Cuneate) fasciculi ('axon bundle') within the spinal cord. This specific region transfers information of fine touch, vibration and proprioception from the mechanoreceptive afferent fibres to the brain stem. The medial lemniscus (aka the second-order neuron) is pathway within the brain stem. It begins at the medulla oblongata, passing up through the pons and midbrain and finally to the thalamus. The medulla oblongata/pons areas of the brain stem are where the neurons 'cross over' to the opposite side, the process is referred to as 'decussation'. This causes the expression of the right side neuronal input of the body, on

the left hemisphere and vice versa [57]. From the thalamus, thalamo-cortical fibres (the third-order neuron) then finish the pathway by sending projections to the somatosensory cortex. Figure 4-3 shows the somatosensory cortical representation.

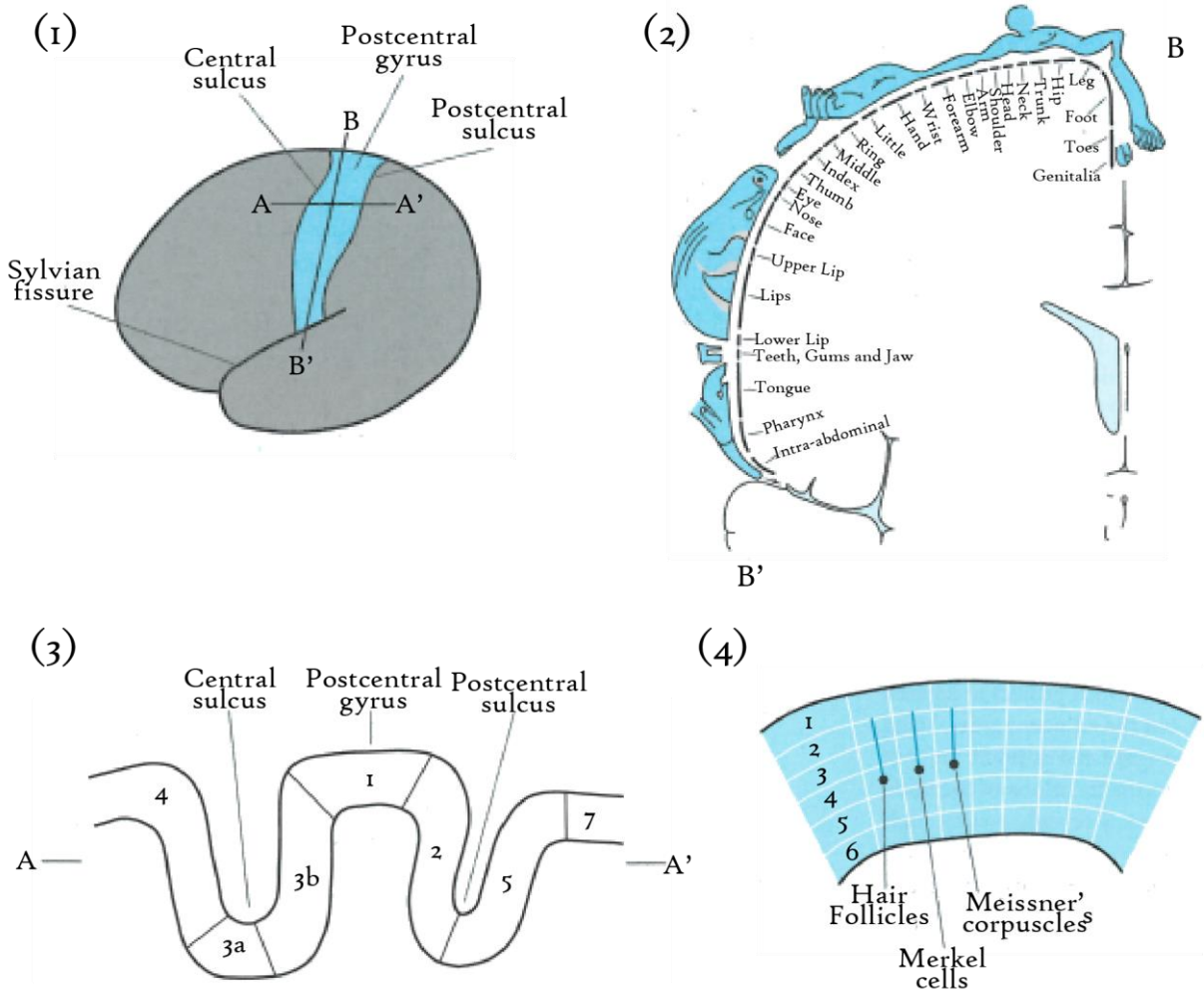


Figure 4-3: 'Cortical representation of somatosensation. Thalamic neurons project to cells in a long, thin strip ending across the cortex from ear to ear (1). Cross-sections along the line A-A' are shown (3). In common with areas of cortex, somatosensory cortex can be sub-divided in six layers, labelled 1-6 moving down from the surface. Thalamic axons terminate in layer 4 of area 3. Within a thin column of cortex, cells in all layers receive inputs from just one receptor type (4). A large scale cross-section along line B-B' shown in (2). Each cell is selectively responsive to stimulation in a particular region of the body (commonly referred to as the Penfield map [59]). Moving across the cortex from B-B', there is an orderly progression in the body part covered by the cells.' (Modified from [103]).

For a more detailed exploration into the neurophysiology of the dorsal column – medial lemniscus pathway the author points the reader to [61, 103, 59, 57].

4.3 Psychophysics & QUEST

4.3.1 Introduction

In order to evaluate the perceptual benefits of SMIs over superficially attaching magnets to the skin (the main aim of this research) quantifiable perceptual data of both groups needed to be empirically determined (introduced in Chapter 7). The data collected provides information as to the perceptual capabilities of the vibrotactile sense, when stimulated through MIVS (as explained in section 1.1). The field of study that examines the measurement of perception of the physical world is known as psychophysics or psychometrics. The name Psychophysics originated (from the German, Psychophysik) in the 1860's by Gustav Theodor Fechner, where he outline the principles of the subject in his paper Elemente der Psychophysik [104].

This section introduces the key concepts of psychophysics with respect to this research. Additionally by briefly exploring the history of adaptive psychophysics methods, this provides the rationale for the choice of QUick ESTimation, QUEST procedure. Finally this section provides an explanation of the QUEST procedure in reference to its operation. The reason for this review is that QUEST is the thresholding method used within the participant experimentation (Chapter 7).

4.3.1.1 Thresholding

A core concept of Psychophysics is the determination of thresholds, a word originating from the Latin, Limen. In essence thresholds are "a boundary separating the stimuli that elicit one response from the stimuli that elicit a different response" [105]. There are three main thresholds: the lower threshold, the difference threshold and the terminal threshold.

The lower threshold is often referred to as the absolute/stimulus threshold and abbreviated RL (from the German "Reiz Limen") [105]. This threshold measures the minimum stimulus intensity required for an individual to perceive its presence. For example with audio, prior to hearing anything there is a point at which an incrementing volume level breaches the amplitude at which a (non-auditory impaired) individual would be able to perceive it. This volume level would be that individual's amplitude RL.

The difference threshold is also known as the just noticeable difference, JND, or difference limen, DL. JNDs are measured from a standard (also referred to as the baseline) intensity. The JND or DL refers to a difference in stimulus intensity such that

an individual perceives there is a difference. For example if a weight of 10 grams was placed in one hand, and a weight of 10+x grams was placed in the other, assuming the perceptual experience was equal in both hands. The value of the JND comes from the answer to the question, "what is the minimum increase of x, such that an individual can correctly determine there is a difference 50% of the time?"

Weber in 1834 [105] experimentally determined that there was a relationship between the baseline stimulus and its JND. This relationship is known as the Weber fraction (referred to as Weber's Law) which is shown below.

$$\frac{\Delta I}{I} = K \tag{4.1}$$

This law states that the ratio between the change in intensity, ΔI, and the baseline intensity, I, for a given stimulus, is proportional to a constant K. This constant "differs widely from sense to sense, being as small as 0.016 for brightness and as large as 0.33 for loudness" [105].

The terminal threshold is also known as the Terminal Limen, TL, the value of which alters per stimulus as the threshold examines the maximum stimulus value. For example within cutaneous senses the value of TL is the point at which pain is induced. Whereas the auditory sense's frequency TL, is the point at which frequency is no longer perceived (~>20 kHz) [105].

4.3.1.2 *Methods of Obtaining Thresholds & Trial Paradigms*

Multiple experimental methodologies have been created in order to determine thresholds, which can be categorised into two groups. The first of which are often referred to as classical methods of psychophysics, examples of these are: the method of constant stimuli, the method of adjustment and the method of limits [104, 105, 106]. The constant stimuli method determines a threshold by randomly subjecting an individual to a predefined set of trials (see sections 6.3.2 and 6.4.2 for examples of this method).

The second group of methodologies are called the adaptive methods. Adaptive methods of thresholding alter the stimulus presented to an individual based upon the individual's response to previous trials. Over multiple trials of testing an individual's perception to various stimuli a threshold for that particular stimulus is thus determined.

A trial refers to presenting a stimulus to an individual and asking an appropriate question (which is task methodology dependant) regarding their perception of said stimulus. The number of stimuli presented per trial affects which type of task that that trial and ultimately the test (as trial structure does not vary per test) falls under. Table 4-3 provides some examples of task paradigms with respect to the number of stimuli.

N	Task Name	Task	Used in Section
1	Yes/No	Typically to determine RL, present individual with incrementing stimulus intensities, until it is perceived.	(NA)
2	2IFC	Typically to determine DL, present individual with two consecutive stimuli, questioning which was the greatest in intensity.	7.5.6
2	1AFC (Same-Different)	Typically to determine DL, present individual with two consecutive stimuli, questioning whether the stimuli felt were the same or different.	6.3.2
3	3IFC (Oddity)	Typically to determine Oddity, present individual with 3 stimuli, two identical intensities and one oddity, questioning which is interval was odd.	(NA)
5	5AFC	Multiple uses, used in this research within the temporal gap detection experiment.	7.5.7

Table 4-3: Examples of Trial Task paradigms, N = number of stimuli presented per trial. 'The number that prefixes AFC/IFC (Alternative/Interval Forced choice) is M, the number of stimulus alternatives presented per trial' adapted from figure 3.2 within [104].

Within the participant experimentation (Chapter 7) the two paradigms used were the 2 interval forced choice, 2IFC and the 5 alternative forced choice, 5AFC. The reason for choosing these task paradigms was mainly in order to meet the aim of each experiment. The 2AFC methodology is explored and used as an example in the initial QUEST paper [107]. The rationale for the 5AFC is discussed in section 7.5.7.1.

The difference between AFC and IFC is the presentation of the stimuli to the individual. IFC requires temporal ordering of the stimuli; for example a 2IFC test to determine audio frequency discrimination threshold, one interval is played followed by the other. AFC also can also use temporal ordering in its presentation (see section 6.3 for example of a 1AFC test paradigm with temporal ordering) however it is not essential. For example a 2AFC test to determine visual orientation discrimination thresholding, where two stimuli are presented on a screen at the same time [104].

4.3.1.3 *Psychometric Function*

When determining the JND threshold through non-adaptive methods, such as the methods used in to determine frequency discrimination and temporal gap detection in sections 6.3.2 and 6.4.2 respectively, the results can be fitted to a Psychometric Function, PF. Psychometric functions are used to describe 'an individual's probability of a desired response at each level of intensity of a particular stimulus' [108]. The term 'Psychometric Function' was first introduced by Urban in 1910 [109].

Referring again to the previous weight example where 10 grams is placed, randomly and blindly, in one hand and (10 + x) grams in the other. A 2AFC method for determining the individual's weight threshold could be conducted as follows. Firstly 5 values for x, ranging from not noticeable to very noticeable would need to be randomly trialled on the individual a multiple number of times (e.g. 20 per x). After each trial the individual would be asked, 'which weight is the heaviest, the left or the right?'. Hypothetical data points from this task are shown in Figure 4-4, where the average proportion of (hypothetical) correct responses is presented at each stimulus level.

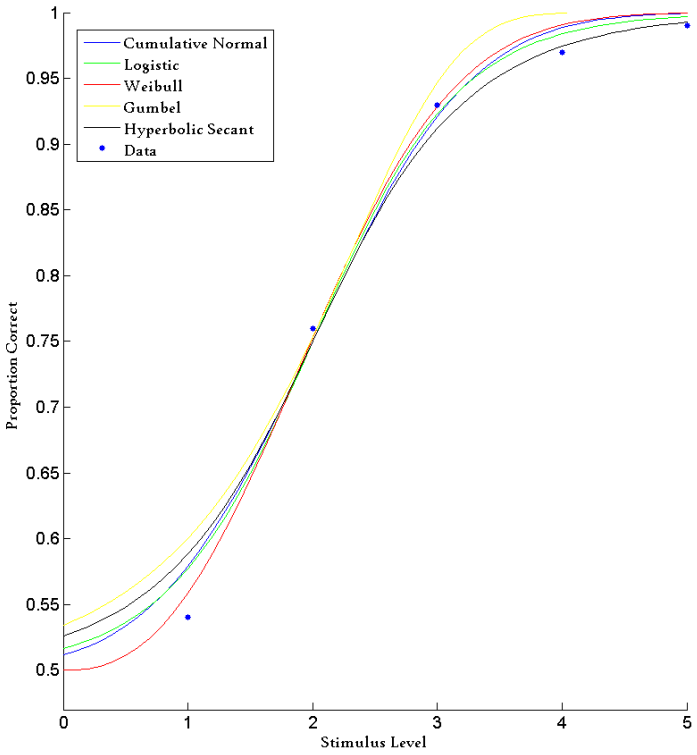


Figure 4-4: Examples of 5 different Psychometric Functions fitted to illustrative data

Multiple mathematical functions exist in order to model a PF: the Logistic, Weibull, Gumbel (often referred to as the log-Weibull, and in the case of QUEST, simply,

Weibull), Cumulative Normal and Hyperbolic secant. Graphical examples of these have been fitted to the hypothetical data presented in Figure 4-4.

PFs are fitted to data dependent upon a number of variables defined below:

- $\boldsymbol{x}$ – Stimulus Intensity or Log Stimulus Intensity.
- $\boldsymbol{\beta}$ - Describes the slope of the psychometric function.
- $\boldsymbol{\gamma}$ – The Guess Rate; The probability of success at zero intensity, i.e. the probability of the correct response when $\log(x) = -\infty$.
- $\boldsymbol{\lambda}$ – The Lapse Rate; The probability of incorrect response irrespective of the stimulus.

The QUEST function (explained in section 4.3.2) makes use of the Weibull (Gumbel) PF, the cumulative density function, CDF, of which is (as detailed in [108, 104, 110]),

$$G(x) = (\gamma) + (1 - \gamma - \lambda)e^{[-10^{(x-\alpha)\beta}]} \tag{4.2}$$

where x in this function is the log stimulus intensity and α is the unknown threshold. The γ value for a nAFC/IFC test is simply n^{-1} [107]. Hence in the example of Figure 4-4, the PFs begin at 0.5 (2AFC) on the y-axis (proportion correct) as values below this probability can be attributed to random chance. A typical λ value is 0.01 as it accounts for individual error, e.g. 'finger mistakes' as discussed in [107]. Figure 4-5 displays how variations in the values γ and β affect the shape of the Weibull psychometric function.

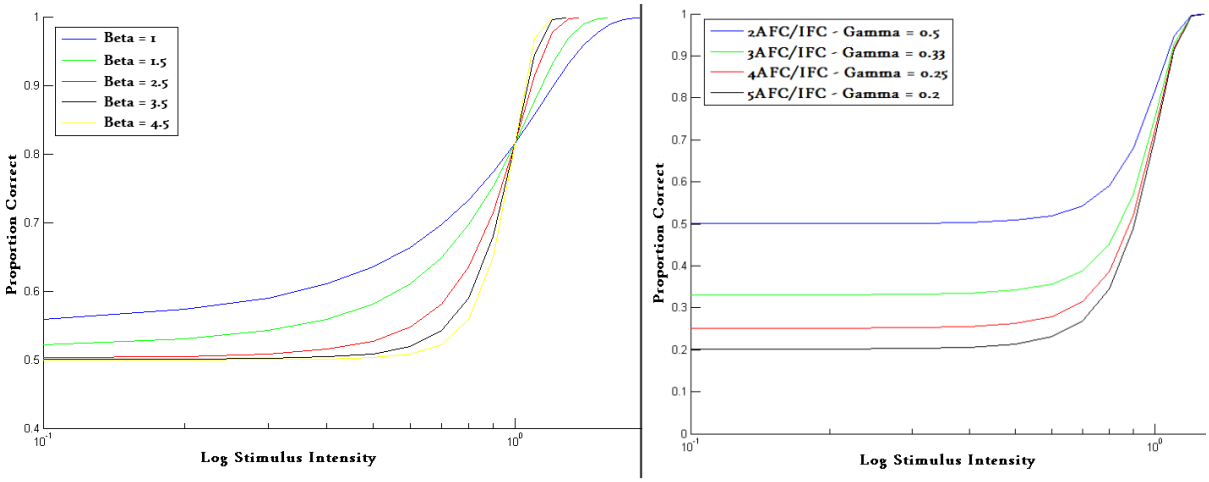


Figure 4-5: Left – Gumbel function with varying β values (γ value = 0.5). Right – Gumbel function with varying γ values (β value = 3.5).

4.3.1.4 *Brief history of adaptive methods and the rationale for the choice of QUEST*

The first documented adaptive method was the up down method also called the staircase method, which was initially developed by Dixon and Mood in 1948. The staircase method simply places the next trials' stimulus intensity based upon a yes/no response from the previous trial. From its initial conception, the staircase method has been modified by many people. Notably: Wetherill and Levitts (1965) who improved the accuracy of the method by introducing their transformed method; Kaernbach (1991) who introduced the weighted method which also improved accuracy; and finally García-Pérez (1998) who combined both the transformed and weighted methods [104].

The staircase method has the benefit of being simple to implement. Unfortunately, this method's limitations outweighed its benefits in one important factor, the time taken to determine the threshold. Research presented by García-Pérez [111] suggests that in order to achieve a high accuracy and precision with regards to the threshold, the trial number of the staircase method has to be very large. Within the context of the experimentation conducted in this research, (i.e. the participant experimentation described in Chapter 7) time taken per experiment was a key factor in the choice of methodology for numerous reasons, such as the participants': availability, comfort and fatigue levels etc. For this reason the staircase method was not chosen as the thresholding method for the participants.

Following the staircase method, a group of adaptive methods known as, running fit methods, were developed. Running fit methods alter the change in stimulus intensity based on all previous trial results of the current test. This is done by fitting a psychometric function to the entire data collected after each trial. The idea was first proposed by Hall (1968). The first documented running fit method was called the best parameter estimation by sequential testing, PEST, which was proposed by Pentland in 1980 [104]. However it is not uncommon for PEST to take a large number of trials to reach stimulus intensity near the threshold. This is due to the first step size being exceptionally large, "The first step size is only bound by the interval of stimulus values defined by the experimenter" [104]. As such the adaptive method chosen for the participant experimentation was QUEST (which is detailed in the following section). Further reading of both the history of psychophysics and adaptive procedures can be found in [109] and [112] respectively.

4.3.2 QUEST

Developed in 1983 by Watson and Pelli [107], the QUEST procedure is a Bayesian adaptive psychometric method. Much like other adaptive psychometric procedures QUEST adaptively estimates an individual's threshold to a particular stimulus via sequential testing. QUEST differs from other psychometric procedures in that it uses Bayesian estimation in order to estimate the intensity of the stimulus presented at each trial. In order for the procedure to operate QUEST makes three assumptions as described in [108, 107].

1. The individual (observer) has a Psychometric Function. Furthermore this PF remains the same shape under all conditions when expressed as a function of log intensity [107].
2. The desired correct response rate set by the user does not alter throughout each test.
3. Individual trials are statistically independent.

Based on assumption 1 any PF denoted $P_T(x)$ characterised by a threshold T, can be written in canonical form $\Psi(x)$, by the equation below as in [107].

$$P_T(x) = \Psi(x - T) \tag{4.3}$$

Here x is again log intensity, the parameter T is the chosen correct response rate desired within the function Ψ e.g. the 95% point. Rewriting the PF in canonical form enables the simplification of the QUEST function as described later in this section. As stated previously, the PF that is used within the QUEST procedure is the Weibull (Gumbel) function (see section 4.3.1.3 equation 4.2).

The QUEST procedure begins by firstly querying the user for an approximate threshold location, 'based on previous knowledge such as previous experiments, hunches and the like' [107]. This is represented within QUEST as the prior probability density function, PDF, of the threshold, $f_T(T)$. As stated in [107] 'typically $f_T(T)$ might be a broad Gaussian or rectangle distribution, centred on T_{prior} (the best guess of the threshold location)'. The second threshold information source comes from the observed results from the set of trials performed on an individual. This data, D, is then expressed as a likelihood function $f_{D|T}(D|T)$ which is the PDF of D conditional upon T. Combining this

PDF with the prior (i.e. $f_T(T)$) forms the posterior PDF ($f_{T|D}(T|D)$) which is determined using Bayes Rule:

$$f_{T|D}(T|D) = \frac{f_T(T)f_{D|T}(D|T)}{f_D(D)} \tag{4.4}$$

Seeing that the prior PDF of the data $f_D(D)$ is a constant for this particular data, all information about the threshold estimation is contained in the numerator of equation 4.4. Equation 4.4 can be re-written as 4.5 in order to remove $f_D(D)$.

$$f_{T|D}(T|D) = \frac{f_T(T)f_{D|T}(D|T)}{\int_{-\infty}^{\infty} f_T(T)f_{D|T}(D|T)dT} \tag{4.5}$$

The posterior PDF (i.e. $f_{T|D}(T|D)$) thus contains all information about the threshold estimation. It is this PDF (T_{Post}) which is used to estimate the next trial placement. As each trial is ran the variance of T_{Post} is aimed to be reduced by the QUEST procedure. Therefore after multiple trials the mean of the posterior PDF becomes the best estimate of the threshold at the end of a run [108]. Figure 4-6 illustrates how multiple trials cause a reduction in the variance of the PDF of threshold.

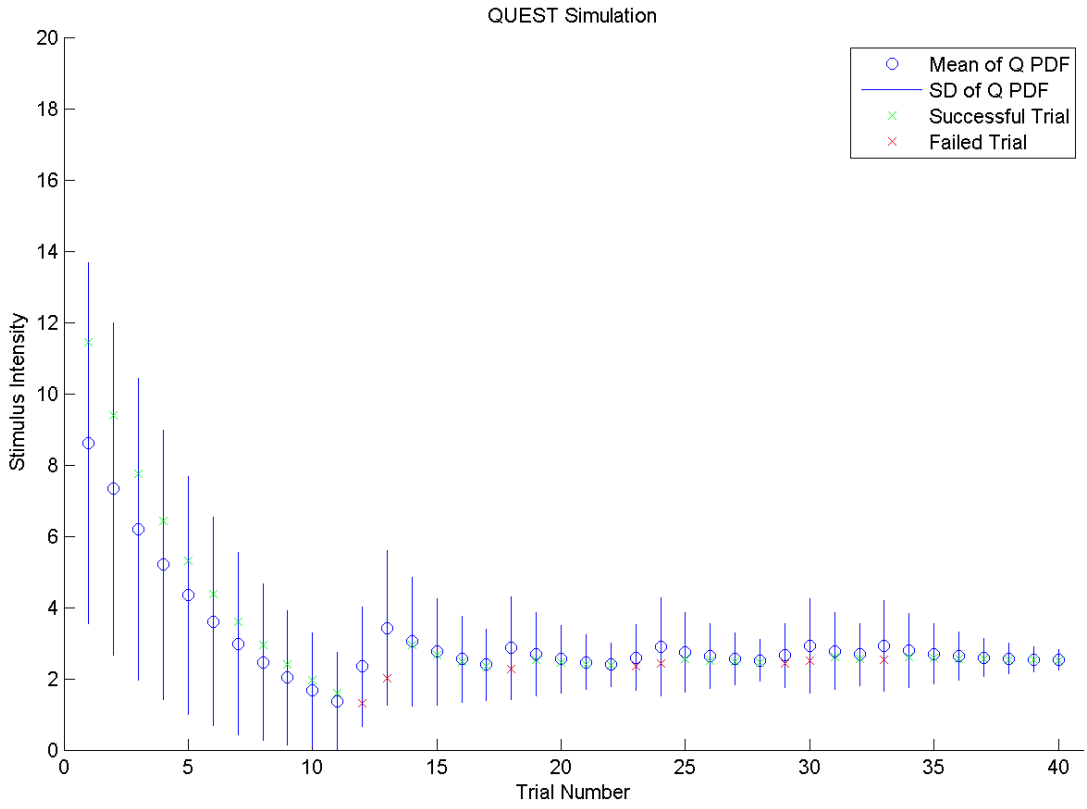


Figure 4-6: An overview of all trials from a simulated QUEST function. SD – Standard Deviation

In order to place the next trial estimate various approaches have been attempted. In the initial paper proposed by Watson and Pelli [107] the best estimation of the next trial placement was postulated as the mode of the post PDF (i.e. T_{Post}). This method for the next trial position has been through subsequent revisions, namely using the mean [113] and the quantile range [108, 114]. The quantile range function (i.e. QuestQuantile from the psychophysics toolbox) reduces the variance of the PDF more rapidly than the other methods and is recommended by the creator of QUEST and the psychophysics toolbox, D. Pelli [110]. The QuestQuantile function operates based on the assumption that the upper quantile of T_{Prior} is the best trial location (i.e. threshold estimate).

As shown above $f_D(D)$ (eq. 4.4) can be derived from the integral of the product of the first two terms (eq. 4.5), which is used within QUEST as a normalisation factor for the threshold PDF. Thus all information about the posterior PDF is contained within the numerator of equations 4.4 and 4.5. Which is the joint density function of T and D, $f_{T,D}(T, D)$. Taking the log of this joint density function gives the QUEST function, $Q(T)$:

$$Q(T) = \ln f_T(T) + \ln f_{D|T}(D|T) \tag{4.6}$$

Where $\ln f_T(T)$ is the natural log of the prior density function of T_{Prior} and $\ln f_{D|T}(D|T)$ is the natural log of the likelihood function. The calculation of the likelihood function is explained by Watson and Pelli in [107]:

> *"Following in trials, the dataset (D) consists of a sequence of responses, r_i at log intensities x_i, where i = 1,..., N. Each response is either a success (r_i = 1) or failure (r_i = 0). The probability of success as log intensity x is given by the psychometric function PS|T(x) = PT(x) the probability of failure is PF|T(x) = 1-PT(x)."*

Based upon assumption 3 i.e. 'each of the trials are statistically independent', the likelihood function can be defined in standard form as,

$$f_{D|T}(D|T) = \prod_{i=1}^{n} P_{r_i|T}(x_i) \tag{4.7}$$

Substituting this equation back into the QUEST function (eq. 4.6) the expression for QUEST after n trials is thus,

$$Q_n(T) = \ln f_T(T) + \sum_{i=1}^{n} \ln P_{r_i|T}(x_i) \tag{4.8}$$

As defined, the QUEST function after n trails is equal to the QUEST function after n-1 trials, plus the log of either the success or failure function, defined below. Furthermore the QUEST function before any trials is just the natural log of the prior PDF (T_{Prior}) [107].

$$Sucess\ Function = \ln P_{s|T} = \ln P_T(x) = \ln \varphi(x - T)$$

$$Failure\ Function = \ln P_{F|T} = \ln[1 - P_T(x)] = \ln[1 - \varphi(x - T)] \quad (4.9)$$

Which are rewritten in [107] as,

$$Success\ Function = S(x) = \ln \varphi(-x)$$

$$Failure\ Function = F(x) = \ln[1 - \varphi(-x)] \quad (4.10)$$

In order to simplify and summarise the equations thus far,

$$Q_n(T) = Q_{n-1}(T) + {}^{S(T-x_n)}_{F(T-X_n)}$$

$$Q_0(T) = \ln f_T(T) \quad (4.11)$$

In order to clarify the QUEST process, Figure 4-7 provides a visual representation of the current and previous state of the QUEST PDF at particular 4 trial numbers of the QUEST simulation shown in Figure 4-6. Furthermore the trials success and failure functions are displayed upon logarithmic probability graphs.

In practice the QUEST function can only test the observer at a set number of log intensities. The interval between these intensities is defined by Δx (the grain), which is predefined in the QuestCreate function within the psychophysics toolbox as 0.05 [110]. Furthermore the QuestCreate function enables the user to select the correct response rate required for the test. This is achieved when the psychometric function is created. Once the PF has been created the chosen correct response rate is then interpolated and the PF is then shifted such that the interpolated value is centred around stimulus intensity 1 on the log scale.

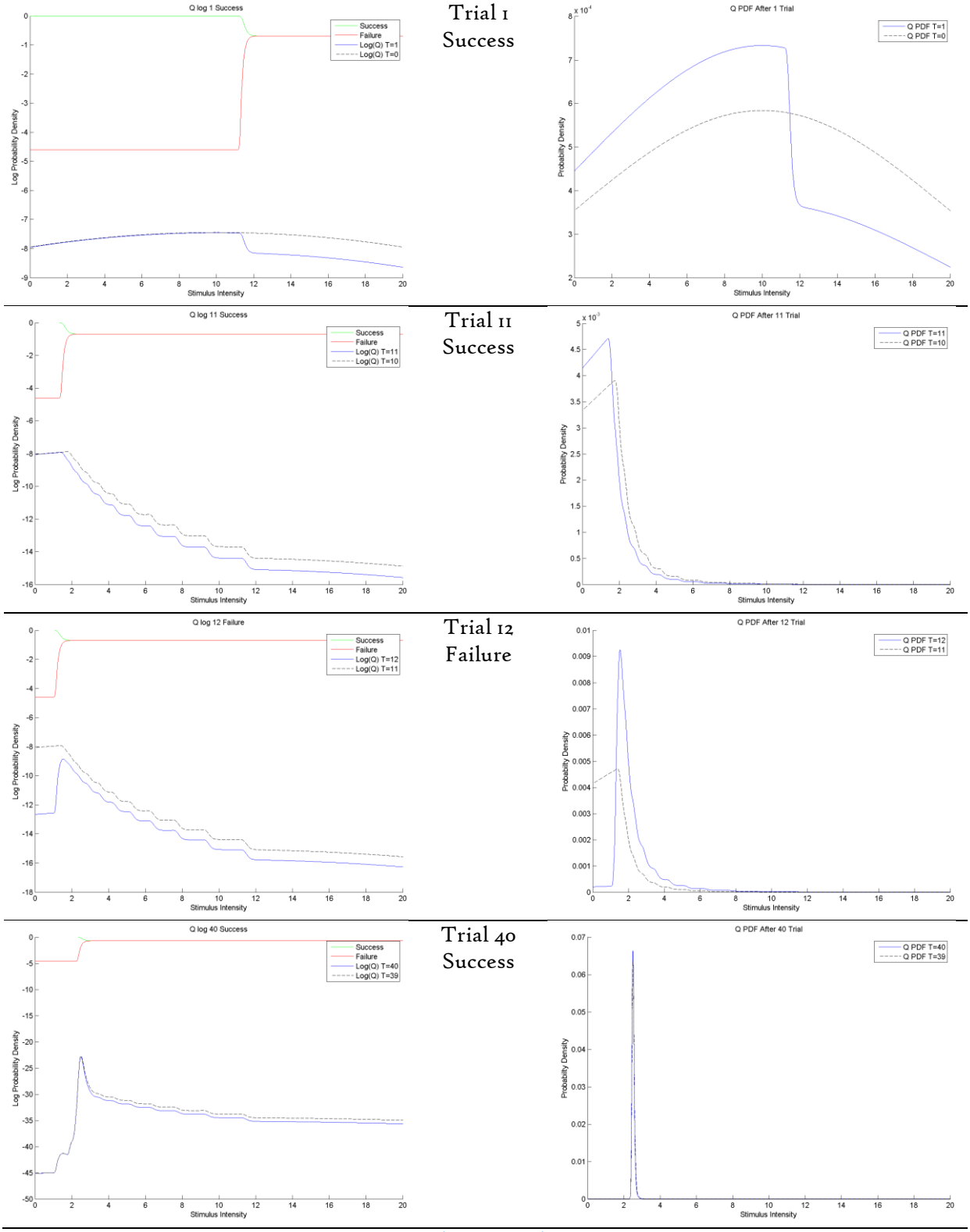


Figure 4-7: The Simulated QUEST PDF (Figure 4-6) visualisations at various trials. The left column shows the log of the PDF, along with the success and failure functions, the title of each indicates if the trial is a success or a failure and thus that function is added to the prior (T-1) .The right column shows how this addition affects the Posterior PDF in comparison to the Prior. N.B the scaling on the y-axis is altered per graph in order to visualise the data correctly.

QUEST incorporates the probability of 'finger mistakes' (i.e. the lapse rate – λ, explored in section 4.3.1.3) in the creation of the Gumbel function (shown in eq. 4.2 section 4.3.1.3). This creates an upper asymptote of the PF which ensures that at any stimulus intensity the probability of success is never 1. The typical value used for λ is 0.01 [107].

Watson and Pelli postulated in the initial paper that a possible end condition for the procedure was to stop when the confidence interval for the threshold location is smaller than a specified size [107]. However the termination rule adopted in the participant experimentation (Chapter 7) is a set number of trials, also postulated in [107], 'which loses some efficiency but has the advantage of enabling tests to be ran as a block structure much like, conventional psychometric experiments'. The final estimate of the threshold is determined from the mean of the QUEST function ($Q(T)$), as recommended by D Pelli and King-Smith [110].

4.4 Vibrotactile Psychometric Thresholding & Mental Chronometry

4.4.1 Introduction

This section individually examines the literature which accompanies the experimentation conducted in Chapter 6 and Chapter 7. The experiments that have been conducted are: reaction time, amplitude detection, amplitude discrimination, frequency discrimination, temporal discrimination and temporal numerosity discrimination with respect to temporal gap detection.

4.4.2 Reaction Time

The subject of Mental Chronometry, MC draws conclusions about human information processing capabilities based upon observed reaction times, RTs. The study of MC can be traced back before 1850 [115] where it was initially thought that cognitive processes were instantaneous. Assumptions such as these led to a new field of study which aimed to ascertain the temporal properties of receptors, their link with the nervous system, and furthermore their expression on the cortex. Early work specific to the study of RT is by Donders (1868) who described three kinds of RT experiments [116]. These are in order of speed (fastest to slowest) simple RT, recognition RT, choice RT [117]. Within the context of this research simple RTs are examined (section 7.4). A simple RT experiment

measures the time taken for an individual to response to a given stimulus. Previously reported RTs are shown in Table 4-4.

Source	Stimulus Modality (time in ms)		
	Auditory	Tactile	Visual
Robison [8] **(Range of Values from Table 7** [8]**)**	120-182	117-182	151-225
Woodworth and Schlosberg [105] **('typical adult subject RTs')**	140	140	180
Brebner and Welford [118] **(Values from Table 1.2)**	140	155	180

Table 4-4: Previously published and generally accepted reaction time data for auditory, tactile and visual stimuli

The list of documented factors which affect reaction time is simply colossal. For example Silverman in 2010 [119] whilst reviewing the subject, makes reference to a number of factors including: life expectancy, height, weight and obesity, myopia, running speed, and IQ. Further factors include:

- **Age** [120, 121, 105] – Dependant on RT task shows a decay in early years to a plateau in early 20's with general increase in RT as age increase in later years.
- **Alcohol** [122, 105] – Over a review of multiple studies, showing unsurprisingly an impairment of RT as blood alcohol content increases.
- **Gender Differences** [121] – Males have been experimentally shown to have reduced reaction times in comparison to females.

Mohebbi *et al.* in 2009 [10] measured RTs of breaking whilst participants were within a driving simulator and communicating on a simulated mobile phone. Phone conversations varied from none, to simple and finally complex. Participants were given rear-to-end warning alerts through tactile and auditory stimuli. This was compared to no warning stimuli given, i.e. only the visual information from the simulator. The results shown suggest that tactile alerts enabled the shortest breaking times, measured from time of alert to breaking being initiated (i.e. simple RT task). Results from Scott and Gray [11] support this finding in a similar breaking task. Reporting that drivers with a tactile warning had not only the shortest mean RT in the braking task but that these results were significantly shorter than those without warning.

The remarkable RT study conducted by Der and Deary in 2006 [121] has a participant number of over 7200. This study like others prior [7, 8], each suggest there is an increase in RTs recorded in the peripheral vision when compared to the focal area.

4.4.3 Amplitude Detection

Within the vibrotactile experimentation conducted using psychophysics methods amplitude detection (amplitude RL) has been examined at great lengths by several authors. The standard result for tactile amplitude RL in the literature is by measure of skin displacement expressed in μm. All dB values quoted are thus referenced against 1 μm. A huge variety of factors contributing to changes in amplitude RL have been explored, a summary follows.

- **Glabrous versus non-glabrous skin** [123] – Glabrous skin shows greater reduction compared to non-glabrous skin (~11 dB and ~20 dB reduction at 25 Hz and 250 Hz respectively).
- **Gender** [124] – Gender has been experimentally shown to hold no statistical difference in amplitude RL; however papers [125, 126] have reported such significance.
- **Effects of the menstrual cycle** [125, 127] – Premenstrual cycle showed a significant reduction in amplitude RL when compared with postmenstrual cycle.
- **Age (child versus adult** [126]**, adult versus old age** [128, 129, 130]**)** – Older individuals showed significantly higher amplitude RL results, with the RA2 results showing the greatest reduction in sensitivity.
- **Skin temperature (changes in** [131, 132]**, heat induced pain** [133]**)** – Amplitude RL was significantly increased (~7 dB) when skin temperature was 20°C in comparison to 30°C and 40°C. Heat induced pain significantly increased amplitude RL also.
- **Masking effects** [131, 134, 135, 136] – Noise masking has been shown to increase amplitude RL with respect to the amplitude of the noise provided.
- **Various equipment** [137] – Two commercially available vibrotactile thresholding systems showed significantly different results.
- **Temporal summation** [136] – Temporal summation effects (theory proposed by Zwislocki 1960 [136]) reduced the vibrotactile amplitude RL in RA2 (i.e. stimulation signal, sinusoid 250 Hz) to an approximate minimum at 1 second, the results presented are multiple stimulation signal lengths, starting at 15 ms.
- **Contactor effects (size** [135, 128, 138]**, configuration** [135]**)** – Contactor size reduces amplitude RL as it increases, shown in Figure 4-8 which is a reconstruction from [139].

- **Body location** [130, 138, 140] – The fingertip has revealed to have significantly reduced amplitude RLs when compared against multiple testing areas (e.g. volar forearm, large toe and heel).
- **Asperger syndrome** [141] – Hypersensitivity is common within the common within the context of this syndrome and has been reported to significantly increase amplitude RL within RA2 receptors (i.e. 200 Hz stimulation signal).
- **Effects of erotic stimuli on males** [142] – significantly reduced amplitude RL found in males after viewing erotic footage when compared with prior.
- **Contact load** [143] – Increasing the contact load increased the contact area of the stimulator, furthermore it decreased the RA2 amplitude RL.
- **Dyslexia** [144] – Dyslexic individuals had significantly larger amplitude RLs when tested at 3 Hz compared with a control group.
- **The effects of local anaesthesia** [145] – The effects of local anaesthesia show a significant increase in both amplitude DLs at the low frequencies (20 and 50 Hz).

The key factor examined in this research with regards to vibrotactile amplitude RL is frequency. Within the literature this factor has been explored extensively [139, 123, 124, 146, 131, 147]. The most prominent relationship found was the U-shaped curve which describes changes in amplitude RL as a function of frequency change. The U-shaped curve is shown in Figure 4-8. This discovery was first described by Verrillo in 1963 [139], and further explored by Békésy in 1966 [146]. This significant discovery shows that each of the four mechanoreceptor channels responds differently to amplitude, with the RA2 receptors responding with the least amount of force [131].

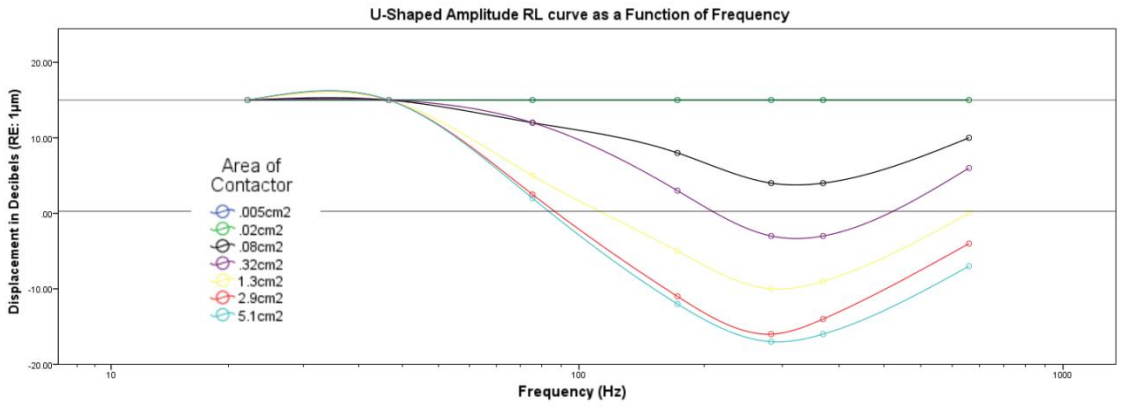


Figure 4-8: U-Shaped response of Amplitude RL when expressed as a function of frequency. Adapted from results in [139] fig 7.

Israr *et al.* in 2006 [148] conducted a study in which the vibrotactile amplitude RL of the hand in a pen hold posture was observed. The results are similar in terms of frequency response to that shown in Figure 4-8; however what is interesting is Israr *et al.* not only present the amplitude in displacement, but in force also, from which they infer mechanical impedance (having previously calculated stimulus velocity). The authors comment on the force curve by stating that:

> *"The force threshold curve obtained in the present study is perhaps the first of its kind... ...The general shape of the force curve was similar to that of the position threshold curve... The main difference between the force and position threshold curves was that the force curve exhibited a lower slope at low frequencies and a steeper slope at high frequencies. The relationship between the position and force thresholds can be better explained by considering the mechanical impedance derived from them..."*

4.4.4 Amplitude Discrimination

Exploration into the literature of vibrotactile intensity discrimination (amplitude DL) has shown, much like amplitude RL literature, that results obtained are altered by a multitude of factors. A further similarity to amplitude RL literature is that the results are presented in measures of skin displacement; all dB values are again with reference to 1 μm. A key quantity quoted in the literature for amplitude DL is the Weber fraction, explained in 4.3.1.1. A summary of the multiple factors which affect amplitude DL are listed below.

- **Continuous vs gated pedestal** [149, 150, 151] – The method of stimulus presentation, during a 2IFC can be presented with (gated pedestal) or without (continuous pedestal) a temporal gap in between. The continuous pedestal methodology has shown to significantly reduce amplitude DL Weber fraction.
- **Masking effects** [152, 153, 154, 155, 156] – Similarly to the amplitude RL literature the effect of masking the stimuli presented with noise, effects the amplitude DL dependent upon the masking intensity.
- **Skin Temperature (Changes in** [132]**, induced pain** [157]**)** – Results presented are again similar to that seen in amplitude RL, skin temperature 20°C shows higher amplitude DL Weber fractions than that of skin at 30°C and 40°C. Furthermore heat induced pain significantly increased amplitude DL.

- **Temporal summation** [151, 153, 154] – The effect of temporal summation significantly reduced the amplitude DL for continuous pedestal methodology, however not within the gated pedestal methodology.
- **Age** [153, 129, 135] – Unlike the results for amplitude RL, age showed no significant reduction in amplitude DL.
- **Contactor size** [156, 158, 135] – An increase in contactor size significantly reduced amplitude DL, much like the results for amplitude RL.
- **Transcranial magnetic stimulation, TMS** [159] – TMS presented over the primary somatosensory cortex significantly reduces amplitude DL when tested at both 30 and 200 Hz. This result supports the 'in series' model of processing tactile stimulation.
- **Stimulation location** [158, 135] – Fingertip again shown to provide minimum amplitude threshold when compared with other body locations (e.g. volar forearm and thenar eminence).
- **Fingertip size** [160] – Much like the effect of contactor size an increase in fingertip size caused a significant reduction in amplitude DL when stimulated over the entire area.
- **Baseline stimulus intensity** [151, 158] – Baseline stimulus intensity, i.e. dB increase of amplitude RL, decreases the amplitude DL. This research presents an example of a "near-miss to Weber's Law", in that the presented results for $\Delta A/A \neq$ a constant, instead however revealed a tendency to decrease with an increase in stimulation level A.

The key factor for amplitude DL (with regards to this research) is again frequency [150, 158]. Similarly to the literature on amplitude RL, an increase in frequency was reported to significantly reduce the amplitude DL. Further observations obtained from the literature are that the Weber fraction is altered greatly for a multitude of reasons. Craig in 1972 [154] stated the Weber fractions of vibrations determined by Sherrick (1950), Schiller (1953), Knudsen (1928) [95], as 0.3, 0.11 and 0.05 respectively. Craig [154] poses 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.* in 1990 [149]. Gescheider also observes that the lowest reported Weber fraction for amplitude DL was 0.05 by Knudson

(1928) [150]. Furthermore the highest Weber fraction reported was 0.3 by Sherrick (1950) [136]. Gescheider *et al.* [149] reasons 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."

4.4.5 Frequency Discrimination

Examination of the literature regarding vibrotactile frequency DL shows that a vast quantity of factors affects the obtained values. A key quantity quoted in the literature for frequency DL is the Weber fraction. Examples of factors tested which affect vibrotactile frequency DLs are explored below.

- **Stimulus amplitude** [161, 162] – An increase in the amplitude (with relation to amplitude RL) of the test stimuli has been shown to reduce the frequency DL. Furthermore by increasing the comparison stimuli amplitude in a 2AFC task and keeping frequency the same for both the comparison and the standard; which has been shown to cause the illusion that the comparison has a greater frequency.
- **Temporomandibular disorders, TMD** [163] – Frequency DL measured at 25 Hz was significantly affected (increased) within individuals with TMD (main symptom being, chronic pain in the jaw area) when compared to individuals without TMD.
- **Waveform (Pulse)** [164] – Concatenated pulse stimuli with varying interval length (relating to frequencies in the range of 1 – 384 Hz) were presented to individuals' middle fingertip; the results show a Weber fraction of ~0.03.
- **Gap time in 2IFC** [165] – The effects of how short term memory effects the ability of an individual in the task of frequency DL is presented showing a significant accuracy reduction as interval (gap) time increased between the stimuli.
- **Effects of being congenitally deaf** [166] – Results show a significant reduction in frequency DL (measured at 200 Hz) of congenitally deaf humans when compared with normal hearing humans.
- **Pre-trial adaptation** [167] – Results presented show a noticeable reduction in the individuals' ability to discriminate frequency (presented as Weber factions) after being subjected to a 15 second adaptation stimulus prior to testing. In the case of the 25 Hz adaptation stimulus, the subjects reduced their 25 Hz DL and increased slightly their 200 Hz DL. In the case of the 200 Hz adaptation the opposite was observed.

- **Glabrous vs. non glabrous skin** [145] – The results presented show a significant difference in the Weber fractions obtained from 5 subjects at the fingertip (mean 0.32, 0.19, 0.21 and 0.14) and the forearm (mean 0.36, 0.38, 0.27 and 0.17), for 20, 50, 100 and 200 hertz respectively. This result could most likely be attributed to a large difference in receptor density.
- **Effects of blindness (various stages and congenitally)** [168] – The percentage of correct responses in the blind groups was significantly greater than in the sighted individuals in frequency DL, with the congenital blind group showing the greatest results.
- **Effects of local anaesthesia** [145] – The effects of local anaesthesia show a significant increase in frequency DLs when examined at low frequencies, i.e. 20 and 50 Hz.

The key points observed from the literature with regards to this research are the baseline frequencies used by Goff in 1967 [161] and Mahns *et al.* in 2006 [145]; the results of which are summarised in Table 4-5.

	Weber Fractions		
Frequency Baseline (Hz)	Goff (35dB above ARL)	Goff (20dB 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

Table 4-5: Summary of frequency discrimination results presented by Goff [161] and Mahns *et al.* [145]. * These values are interpolation estimates from fig 4 in [161]. (ARL – Amplitude RL).

In Goff's publication [161] he summarises Sherrick (1952) work by stating "... that frequency discrimination is poor above 100 Hz and relatively good below 100 Hz".

4.4.6 Temporal Discrimination

The study of temporal perception has been reviewed by multiple authors. Temporal Processing (defined in the auditory sense by Eddins and Green in 1995 [169]) can be divided into two broad topic areas, temporal integration and resolution. Temporal integration is described in time-intensity trades, e.g. how increasing duration of a signal makes it easier to detect (i.e. Temporal Summation). Temporal resolution covers multiple

areas such as temporal discrimination (DL), temporal order, phase detection, temporal gap detection, amplitude-modulation detection and temporal asynchrony.

Within the literature specifically for temporal DL passing stimulation via the tactile sense, the concept of modality integration has been experimentally examined through multiple methods. These concepts along with other factors which affect this threshold are discussed below.

- **Interval duration comparison (modalities: Audio and Tactile)** [170] – Subjective temporal DLs were obtained based upon the interval time between successive clicks, via the auditory and tactile sense. Weber fractions inferred from the results shown in fig 3 in [170] are ~0.08 and ~0.10 respectively. To clarify, the temporal DL measured was not the difference in stimuli lengths but the interval times between stimuli here.
- **Interval duration comparison (modalities: Audio, Visual, Tactile)** [171] – The interval temporal DL was re-examined using multiple methods, of which the 2IFC method produced the smallest threshold (expressed as Weber fractions): audio (0.061), tactile (0.084) and vision (0.103).
- **Baseline stimulus interval length** [172] – Extrapolated results (from fig. 2 in [172]) show that the Weber fraction for tactile temporal DL measured based on interval time alters as the baseline signal interval length does; ~0.27, ~0.18, ~0.17 and ~0.21 (Weber Fractions) for 100, 200, 400 and 800 ms (interval lengths) respectively.
- **Stimuli duration comparison (modalities: Audio, Visual, Tactile)** [173] – Temporal DL measurements based on the stimulus length, altering modality of presentation, produced the following results: auditory (103.25 ms) which was significantly different from the vibrotactile (160.35 ms) and visual (197.76 ms) senses when the stimulus length was a 1000 ms.
- **The effects of TMS over the Superior Temporal Gyrus, STG** [174] – The STG is an auditory modality-specific area, 180 ms TMS over this area, significantly increased errors in tactile temporal DL. This result supports the hypothesis that multisensory integration occurs at an early stage of cortical processing.
- **Effects of TMS over the Somatosensory Cortex in deaf people** [175] – Tactile temporal DL was shown to be significantly lower in sensitivity within in congenitally deaf individuals in comparison to normal hearing individuals. The

effects of TMS when presented over the somatosensory cortex, showed significant reduction in temporal sensitivity in both groups, with a greater reduction found in the deaf individuals.

- **Effect of Musical Training on Temporal DL (modalities: Audio, Tactile)** [176] – The musicians' Weber fractions were significantly reduced in the auditory modality compared with non-musicians; however the results was not visible in the tactile modality.

Key findings in the literature with regards to this research are the Weber fractions recorded for tactile temporal DL measured at a baseline stimulus length of 500 ms. Results from Güçlü *et al.* in 2011 [176] reported a Weber fraction of 0.4 for tactile temporal DL measured with a baseline stimuli length of 500 ms (250 Hz sinewave). However in this experimental procedure the step size changes of the comparison stimulus were set to 25 ms. This paper also reports a tactile temporal DL Weber fraction of ~0.29 when the baseline stimulus was 3 s. Jones *et al.* in 2009 [173] reported (as stated above) a Weber fraction of 0.16 for a baseline stimulus length of 1 s. The methods used in order to obtain this value were a transformed staircase method, with the minimum step size being 10 ms as opposed to the non-adaptive method of limits used by Güçlü. This change in methodology perhaps could be reasonable for the drastic change in Weber fractions obtained by the two authors; which is similar to that seen in the amplitude DL by Gescheider *et al.* in 1990 [149].

Güçlü *et al.* [176] states that this deviation from Weber's Law has been reviewed in the literature. "In the literature on timing, the proportionality between temporal variability of behavioural output and stimulus duration is called the scalar property, akin to Weber's law."

Matell and Meck in 2000 [177] and Buhusi and Meck in 2005 [178] review multiple postulates regarding temporal perception, from traditional models such as the scalar model explained by the pacemaker-accumulator model, to the beat frequency model explained by coincidence-detection which explores the involvement of the basal ganglia as an observer of neuron firing rate in temporal coding. Furthermore in [178] Buhusi and Meck examines the errors in time perception over the time range milliseconds to days in great detail. Occelli *et al.* in 2011 [123] further review of temporal perception with a review of the cross modality interaction between the auditory and tactile sense.

Güçlü *et al.* [176] conclude that "...the most parsimonious explanation is that Weber's law does not hold for duration discrimination in a wide range." This is much like the deviation seen from Weber's law within amplitude RL when examined as a function of frequency (section 4.4.3, see Figure 4-8).

4.4.7 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 in 1975 [179] presented a study on how the number and rate of pulses presented per second effected an individuals' ability to count them; in which he varied modality. The study outcome showed that the auditory modality was most superior in this regard, preforming almost perfectly accurate under all tested conditions. The tactile sense showed underestimation which increased linearly as the rate of stimuli presented per second increased. The visual system preformed least accurately, typically underestimating the number of stimuli presented.

This result was commented on by "Sherrick (1982) concluded that Lechelt's data indicated that numerosity judgements require short-term memory" [147]. Within the literature on temporal gap detection there is a large amount of publications covering the auditory sense (e.g. [180, 181, 182, 183, 184]); however the 'literature concerning this measurement for the tactile sense is very scanty' as stated by Verrillo and Gescheider in 1992 [147]. The factors found to affect tactile TGD are listed below.

- **Hemisphere (left hand versus right hand)** [185] – Results from a TND experiment show that the individuals' responses from their right hand significantly reduces errors when compared with their left hand. This supports the hypothesis the left hemisphere is more suited to tactile and language processing as it is specialised for tasks requiring fine-grained temporal resolution.
- **Audio-tactile integration** [186] – Results presented show a two-way interaction of the effect of distractors when individuals were given a numerosity task. The stimuli were either tactile or auditory, one was the target modality and the other was the distractor. Loud beeps (auditory) significantly influenced the perception of taps (tactile) than quiet beeps. Similarly tactile taps significantly influenced the

perception of quiet beep. The influence of audition on touch was significantly greater than the reverse.

- **Modality (Audio, Tactile, Visual)** [180] – Extrapolated results from fig 1 in [180] show that the SOI for a tactile temporal numerosity discrimination for 3, 4 and 5 pulses are ~20 ms, 80-160 ms, and 160-320 ms respectively. However, no specifics on variables for the tactile stimulation were given other than stating the stimuli were pulses. The results presented also support the findings of Lechelt [179] showing the performance of the auditory system is greatest in terms of accuracy and the visual system is least accurate.
- **Age & Frequency** [187, 188] –Results presented in fig 2 in [187] show that the mean tactile TGD thresholds (using 2 concatenated signals) for young adults, 65 and 50 ms, were significantly lower than those collected by older adults, 75 and 60 ms for during 35 and 500 Hz stimulation respectively. The baseline stimulus length used in this study was 500 ms.
- **Sequential Pulse Number** [189] – The results presented have shown the effects of SOI on accuracy of stimulus recognition for 2, 3, 4 and 6 sequential 7 ms tactile stimuli. Results extrapolated from in fig 7 [189] show that in order for subjects to ascertain a 75% correct response rate, the SOI must be ~26, ~68, ~195 and ~320 ms for the given number of stimuli respectively.
- **Mechanical taps** [190, 147] – TGD for 2 sequential mechanical taps have been reported "as low as ~5 ms for highly damped mechanical pulses" [190].

The key findings from the literature review of TGD are that shown in the '**Age & Frequency'** and the '**Modality**' points presented above. The '**Age & Frequency**' point discusses the results from Bresciani and Ernst in 2007 [186]. They interestingly reported a reduction in TGD of two sequential stimuli as frequency is increased; i.e. 65 and 72 ms to 60 and 50 ms, when frequency changes from 35 to 500 Hz.

The numerosity study in the '**Modality**' bullet point above is the works of Philippi *et al.* in 2008 [180]. The results reported an average of the tested individuals' responses to a particular number of stimuli with a number of set SOIs; hence the results stated (i.e. for 3, 4 and 5 pulses, SOI was ~20 ms, 80-160 ms, and 160-320 ms respectively) are given in ranges of values and not the exact values. As stated the only specific information given with regards to the tactile stimuli was that it was a pulse.

Philippi *et al.* [180] make observation to the errors of observers with regards to TND. "In temporal numerosity judgment, observers systematically underestimate the number of pulses". They further comment in their concluding remarks that "we also found a small tendency toward overestimation for two to four pulses at small SOIs (20 and 40 ms)". This is an interesting point.

4.5 Summary

This chapter aims to provide a focused literature review for this research. Three main subject areas have been covered each of which are summarised below:

- **The Somatosensory System** – This section provides an overview as to the biology of the somatosensory system, in which two main areas are covered. The first being an overview of the neuronal pathway beginning with elicitation of action potentials from fingertip mechanoreceptors and ending at neuronal expression at the somatosensory cortex. The second being a more in-depth overview of the mechanoreceptors themselves focusing on unique characteristics such as, their functional properties, the individual susceptibility to vibration and their approximate density throughout the hand.
- **Psychophysics & QUEST** – This section provides an overview of each of the relevant concepts for this research from the field of study psychophysics. Key concepts such as thresholding, psychometric functions and trial methodologies are presented in order to provide the reader with the relevant background knowledge for understanding of the methodology behind the perceptual experiments conducted in Chapter 6 and Chapter 7. Furthermore an in depth review is presented of the adaptive psychometric method known as QUEST, understanding of which is quintessential for comprehension of the experimental procedures for the psychometric testing conducted in Chapter 7.
- **Vibrotactile Psychometric Thresholding & Mental Chronometry** – This section provides the key literature review for this research regarding each of the 6 experiments conducted as part of the initial investigation and participant experimentation in Chapter 6 and Chapter 7 respectively. The two experiments that have been conducted as part of an initial investigation are the frequency discrimination and TND with respect to TGD experiments. These two

experiments were repeated within the participant experimentation along with: reaction time, amplitude detection, amplitude discrimination and temporal discrimination. Each experimental review provides information regarding the factors which affect the results of each of the experiments, as well as key points for potential cross examination of the results from this research.

Chapter 5 – The Magnet, Implantation and Stimulation Coil

5.1 Introduction

This chapter broadly covers subdermal magnetic implants, SMIs, along with a device produced and utilised within this research in order to provide MIVS. The topics discussed within this chapter are listed below along with a brief description of each of them:

- **A Brief History of Magnets & Their Medical Uses** – This section provides a brief history of magnets, from the earliest documented existence through to modern uses in technology. The section goes on to specifically look at their use within orthodontics and various studies which have been conducted in order to determine cytotoxicity effects of magnets.
- **The Authors SMIs** – This section provides information as to the properties of the authors implanted magnets, the choice of location for the implants and outlines the implantation procedure.
- **Explantation** – This section explores five cases known to the author of individuals who have had their SMIs explanted along with their reasons for doing so.
- **Stimulation Coil Creation** – In order to provide MIVS for the experimentation described in Chapter 6 and Chapter 7, a magnetic field generated by an electromagnetic 'stimulation' coil was required. This section explores the creation of this stimulation coil from its design, to the determination of its magnetic flux density both theoretically and experimentally.
- **Surface Magnetism Experiment** – This section describes an experimental procedure used to approximate the orientation of the authors implanted magnet. This was achieved through analysis of B field measurements taken at a number of locations on the skin surface surrounding the implantation area.

- **Approximation of force applied upon the magnet from the coil (the flipping experiment)** – This section aims to empirically determine indication as to the approximate force applied to the magnet from the created electromagnetic coil. This experiment was conducted to approximate the minimum force required for stimulation during an amplitude detection experiment which is presented in section 7.5.2.

5.2 A Brief History of Magnets & Their Medical Uses

5.2.1 History

The earliest documented magnetic materials were known as lodestones, which were documented by the Chinese author, Gauzhong (who died in 645 BC). However there have been magnetic materials found in archaeological sites which predate the works of Gauzhong [191]. For example "Tutankhamen's tomb (1350 BC) contained a dagger and various other objects made of iron and iron ores" [191]. In ancient Chinese civilization, lodestones were known as 'soft stones' as commented in Gauzhongs' work. The word *magnet* comes from the Greek *Magnēs* (lithos), which now means, *Magnesian* (stone).

The first known uses of magnets were as compasses. Gui Guze and Han Fei (280 BC – 233 BC) were the first to report findings of how lodestones naturally oriented to the Earth's geographical poles [191]. Alexander Neckam [192] documented upon the use of compasses in Europe in 1187. Later in 1269 Petrus Peregrinus, described a compass capable of seafaring [191, 192]; which were utilised in a vast number of naval expeditions.

At present the majority of magnets used are man-made; the strongest produced to date is the chemical alloy comprised of Neodymium, Boron and Iron, $Nd_2Fe_{14}B$; better known as neodymium magnets [193]. These were developed in ~1984 [194] by General Motors and Sumitomo Special metals. In modern technology man-made magnets are mass produced for a wide assortment of purposes; examples of which are listed in Figure 5-1.

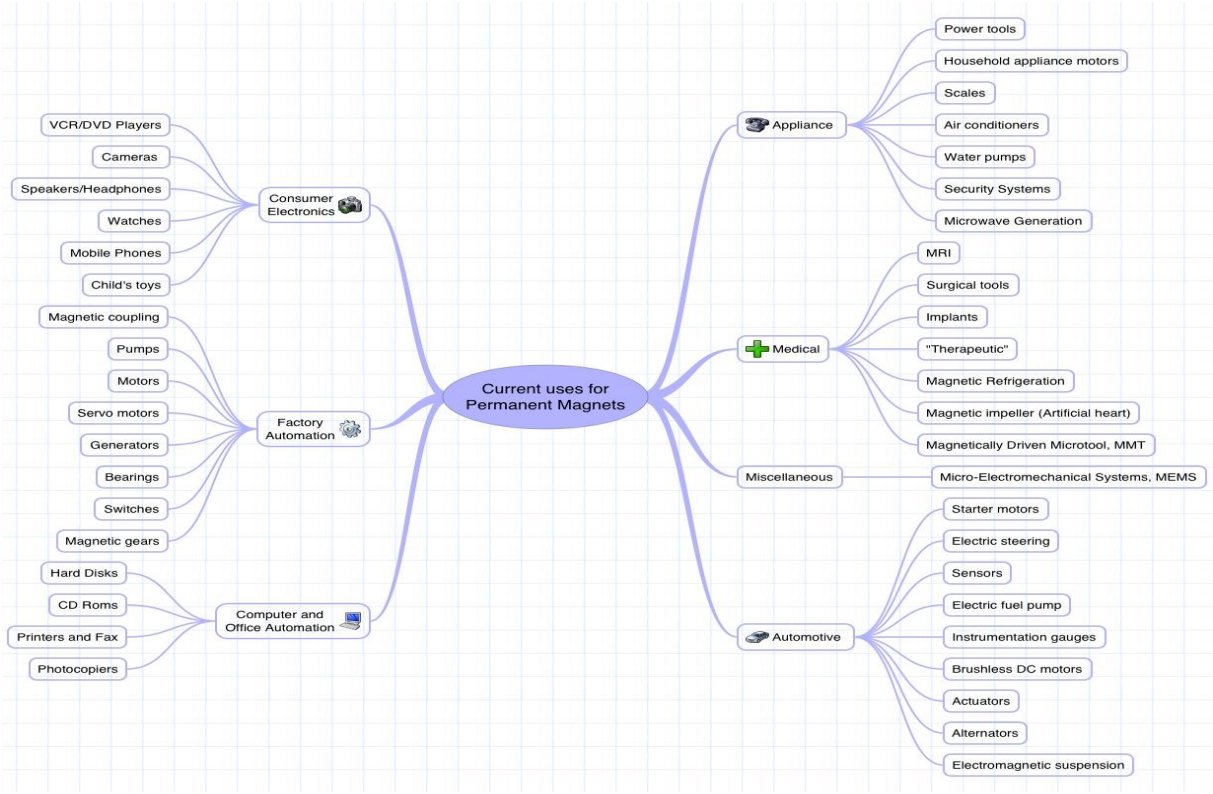


Figure 5-1: Uses of Magnets in Modern Technology [195, 196, 197, 198, 199, 200, 201, 202, 203]

5.2.2 Orthodontic Use and Cytotoxicity Testing

Magnetic implants have previously been used within Orthodontics. Reilly *et al.* [204] in 2001 reviewed magnets in prosthetic dentistry. The paper discusses a summary of magnetic attraction, the improvement in permanent magnets from 1910 to 2000, their clinical uses and corrosive properties. An example of such a system is the AstraTech magnet system [205] which uses titanium nitride coated magnets in order to hold a variety of dental prosthetics.

Donohue *et al.* in 1995 [206] explored the cytotoxicity effects of neodymium magnets, through the use of in vitro cytotoxicity testing. The results of the experiment conducted presented shows that the magnets tested (i.e. uncoated magnetised, and uncoated demagnetised magnets and parylene coated magnetised), were cytotoxic in both human oral mucosal fibroblasts and L929 mouse fibroblasts. Donohue *et al.* discussed the possibilities as to why this occurred, two of the more likely explanation stated magnetic field itself caused the cellular lysis or that parylene coating is itself cytotoxic. The idea that parylene is a toxic material is disputed by the producers of the polymer coating, as described in their proposed medical benefits for the use of the product [207].

The results of Donohue *et al.* are in contrast to that shown by Bondemark *et al.* whom in 1994 [208] stated that "parylene-coated neodymium-iron-boron magnets, showed negligible cytotoxicity". However Bondemark *et al.* do also state that their experiment was conducted only over a short period of time, "short-term exposure to a static magnetic field did not cause any cytotoxic effect on the cells". The study of cytotoxic effects within the context of this research has not been conducted; this has been left open for future work (see section 10.6.4).

5.3 The Author's SMIs

This section briefly describes a number of decisions made by the author prior to his doctoral research with respect to his SMIs.

5.3.1 Locality Choice

The author has two magnets implanted both of which are located within his left hand; one in his index finger pad and one in his middle finger pad. When deciding the location of the magnet, the finger pads were chosen based on mechanoreceptor density which is relatively high within the finger pads compared with the palm (see Table 4-2). Furthermore mechanoreceptor density is believed to be highest within the index and middle finger pads compared with the other distal pads [4].

5.3.2 Magnet Properties & Coating Choice

When deciding which magnets to implant, the author opted for 3.4 mm diameter and 0.73 mm thick neodymium disk magnets of grade 48 MGOe (Mega Gauss Oersteds, 1 MGOe = 7958 kJ/m^3), with a 0.05 mm coating of Parylene C. The rationale for this choice was previously explained in [4]. The points made within the paper are summarised below:

- **Parylene C** – Parylene, as stated previously is a polymer coating, that has been used extensively within medical and other implant devices (e.g. pacemakers [209] and wireless neurostimulators [210]) as it is "biocompatible-biologically stable and chemically inert" and also "non-toxic" [207]. This fact in conjunction with the fact that the magnets used were readily available and came pre-coated, made parylene the ideal choice. Other coatings types were considered, such as silicon and PTFE, however there are reports of silicon coating critically failing [4] and parylene was more readily available than PTFE.

- **Dimensions and Profile** – The following quote is from [4] which paraphrases the choice for the magnets dimensions and profile.

> *"The size and shape of the magnet can have significant implications on the daily experiences of the implantee. Larger magnets require more intrusion in the body thus making it more likely to interfere with physical activities such as gripping objects. Smaller magnets can be less intrusive but may sacrifice the strength of the magnet. Shapes with sharp corners such as cubes and spheres concentrate force on a tiny area and can, as a result of the pressure, agitate and quickly destroy the surrounding tissue. Disc magnets reduce pressure by spreading it over a larger area but can be more prone to breakage."*

- **Neodymium Magnets** – Neodymium magnets are the currently world's strongest man made permanent magnets. The force required, to move or agitate the implanted magnet (i.e. to provide MIVS), is proportional to the magnet's magnetic field strength and the B field that surrounds it (further discussed in section 5.7). Therefore a stronger magnet (with respect to its magnetic field strength) requires less power in order to create the same force and ultimately tactile stimulation. This coupled with the fact that the magnets implanted were neodymium, pre-coated with Parylene and readily available made these particular magnets the optimum choice for the magnet.

5.3.3 Implantation Procedure

The implantation procedure is a relatively simple, minor surgical procedure. In the author's case however this was not performed by a surgeon, but instead by a master body modification artist called Mr M. McCarthy; who is more widely known by his artist name, Dr. Evil. Mr McCarthy is recognised by the UK Health Safety Commission as being highly knowledgeable of the subject; as such he regularly advises them on matters regarding body modification. The implantation procedure performed upon the author is outlined below.

1. The finger which was to be implanted with the magnet was positioned flat on the table palm side up.
2. The implant area was sterilized, as was the magnet to be implanted.
3. A horizontal incision into the pad of the finger, using a sterilized surgical steel scapula.

4. This incision needed to be bored to create a 'pocket' to accommodate the magnet. This was done using a sterilized cylindrical rod, ~4 mm in diameter and rounded at the tips (see Figure 5-2).
5. Once the pocket was created the magnet was slid into the body horizontally, i.e. the magnet face was approximately parallel to the nail peak.
6. The incision was then sealed with butterfly tape.

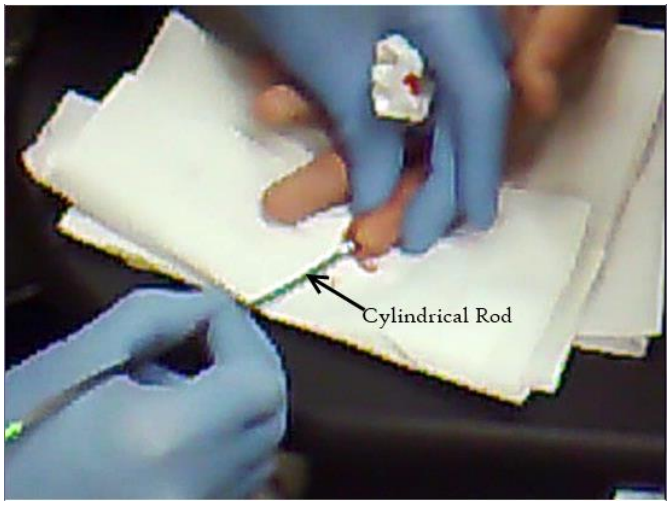


Figure 5-2: The cylindrical rod used in the implantation process

5.4 Explantation

Within this section the explantation of subdermal magnets is explored. There are multiple reasons as to why individuals have had their implants removed. Within this section five known cases to the author of individuals whom have had the explantation procedure performed are explored. These five cases were obtained from the following sources: two from the respondents within the survey conducted in section 2.3; two from personal accounts from friends of the author; finally from the author's personal account.

5.4.1 Two Survey Respondents Explantation Accounts

When asked the following question; "Since having the magnet/s implanted have you had any bad experiences, recurrent pain or been hindered in day-to-day activities due to them?" One of the respondents, a male from Australia in the age range 18-22, who self-implanted his magnet, responded with the following account:

> *"Yes. The magnet was very sensitive when it was in there, and compromised my ability to play the guitar. While it did not affect my ability to climb it was frequently*

quite painful when doing so. After 18 months, the sugru coating failed critically, the magnet rusted and expanded, and stopped working at all. I made an appointment with a local doctor to have it removed. Unfortunately the doctor did not really know what he was looking for (neodymium splinters) and I ended up doing half the operation myself. I still have a lump of scar tissue in my finger; the capsule around the implant folded up and healed into a big clod. It's still fairly sensitive."

This critical failure of the 'sugru', a claylike compound, typically used for repairing products [211] highlights the possible dangers of self-implantation and somewhat naiveté of this particular individual. In a Q&A section of the sugru website [212] a representative of the company which produces the material states that "sugru isn't food or medical grade, therefore we can't recommend it for internal use" [212]. The author comments on possible negative publicity effects which could occur from accounts such as this, by stating that; "inadequate research into the coating of the magnet ultimately caused quite a serious event to occur. If this were to reach the media it would surely produce a negative reaction towards research in this area."

The second account taken from the survey with regards to explantation was in answer to the following question; "Have your magnet/s or implants ever prevented you from receiving medical treatment, for example an MRI? If so, what was the outcome?" The following response came from a male from the USA in the age range 28-32, who also self-implanted his magnet;

"I attempted an MRI with magnet implant after being told by the MRI office that I could leave my magnet in, as it would only demagnetize it. I wasn't that far from the machine; maybe 3 to 5 feet away and my magnet started acting up. Flipping about and pulling on the skin; I even tried to proceed by holding it down, but I felt a pinching and burning sensation and the MRI was stopped. After that I removed my magnet in order to complete the MRI. I soon plan to re-implant my magnet as well."

This account is in contrast to that shown in section 2.3.3 whereby here the experience of the respondent whilst attempting to undergo an MRI with implanted magnets was strongly negative. The assumed reason for the "burning sensation" reported by the respondent could due be to the extreme magnetic forces that the magnet was subjected to. This coupled with the radio frequencies used within an MRI would cause a large amount of kinetic energy to be applied to the implanted magnet, which would ultimately cause the perceived sensation of high temperatures, i.e. the "burning sensation" perceived by

this individual. The account further highlights, as previously stated, the author's opinion as to why not to undergo such a procedure with implanted magnets. Further analysis of the effects of an MRI exam on a SMI has been left for future work, see section 10.6.2.

5.4.2 Two Personal Accounts

The following are two personal accounts from J. Hameed and R. Davey. The accounts given were based upon the following 4 questions:

1. What was the reason initial reason for getting the implant?
2. Prior to the removal (or event leading to) did you have any bad experiences with the implants? Pain, bad event, etc.?
3. Why did you get the implant removed?
4. Did the implant come out intact? (Was there any visible damage to the magnet or coating?)

R. Davey's responses were:

> *"1 – The initial reasons for getting the implant removed were a fear of damaging the implant whilst playing a full-contact sport and also the implant's incompatibility with EPR spectroscopy, a technique I'd soon have to use at work.*
>
> *2 – Prior to the removal of the implant I'd had no bad experiences such as pain with the implant. For the entire time I'd had the magnet there had been occasional twinges but nothing bad and nothing exceptional before the implant was removed.*
>
> *3 – I got the implant removed because I worried I'd damage it whilst doing a full-contact sport and also I'd soon be using EPR spectroscopy at work, which uses strong magnetic fields and is therefore incompatible with a magnet implant.*
>
> *4 – The implant came out in intact. There was no visible damage to the silicone casing.*

Davey's rationale for removal was (as can be seen from her responses) purely precautionary. However this was not the case for Hameed, whom accounts of an impact force causing him to have to undergo the procedure. Hameed's responses to the questions asked were as follows:

> *"1 - I initially got the implant because of an idea I had on using the magnetic implant as a means to use sensory substitution to send signals to the brain, i.e. a man-machine*

interface, and to explore that as the research project in part requirement for my MEng degree.

2 - Prior to the event leading to the removal of one of the two magnets I had initially implanted, I had not had any bad experience with either.

3 - I had one of the two implants removed due to pain and discomfort that started after having the finger and implant area crushed under a very heavy object. The incident created swelling and redness for several days and pain and slight swelling for a few weeks more. When the swelling subsided eventually, the sensations induced by the stimulation of the magnet had subsided entirely and there was recurring discomfort. I had the magnet surgically removed 10 months later after discovering calcium deposits had begun to form around the magnet.

4 - The implant came out intact and there was no visible damage to the magnet. The magnet was encased in thick fibrous tissue that changed the 3 mm x 0.7 mm disc magnet into a sphere of fibrous tissue around 5 mm in diameter.

In reference to Hameed's answer to question 4; the presumed reason for the calcium deposits was damaged to the parylene coating, leaving the body exposed to the neodymium magnet, which occurred as a result of the impact force discussed by Hameed in his response to question 3. This is merely a postulation and subsequent investigation is not explored here as it is not within the context of this research. This incident highlights precautionary guidelines that should be adhered to by anyone who possesses a magnetic implant. Hameed also kindly provided photographs and x-ray images which are shown in Figure 5-3.

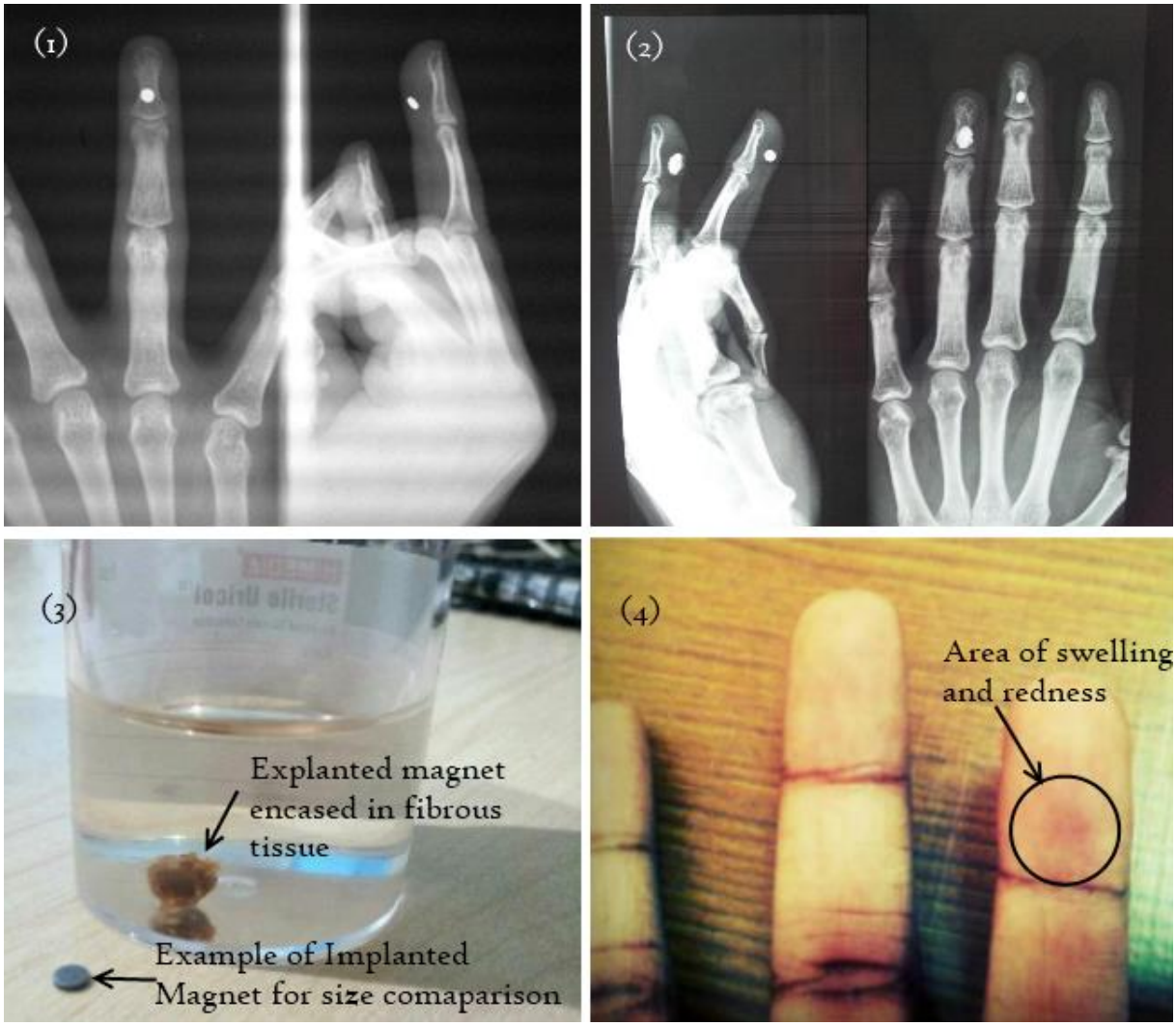


Figure 5-3: X-rays and photographs provided by J. Hameed (annotation have been added by the author for clarity). (1) – X-ray taken in 2011 (prior to impact incident). (2) – X-ray taken in 2012, taken after the impact incident, which shows the calcium deposit build up. (3) – Explanted magnet, against a practically identical magnet for comparison. (4) – Area of swelling and redness prior to removal.

5.4.3 The Author's Explantation

Late in 2012 the author experienced "weird" sensations within his left index finger pad. The sensations were intermittently slightly painful and on occasion a more prominent pain was perceived. The author then sought medical advice, and subsequently an x-ray was performed on 11/12/2012 which is shown in Figure 5-4.

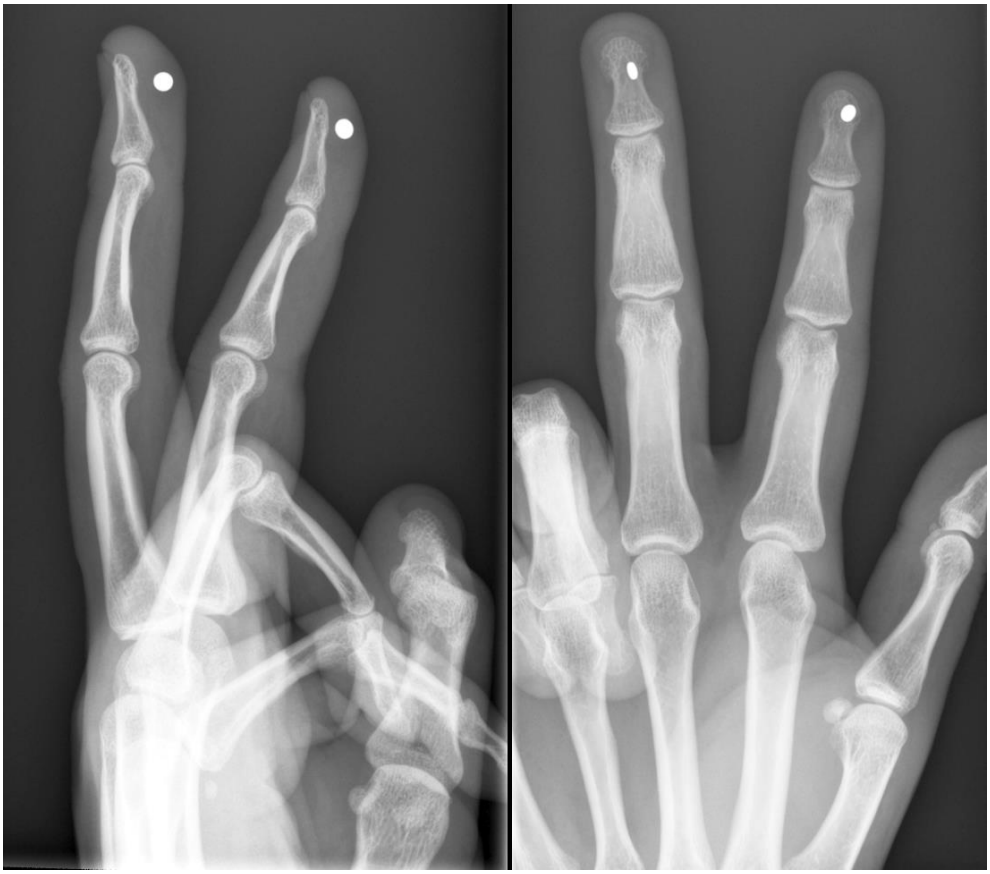


Figure 5-4: The author's X-ray prior to explantation

As can be seen from Figure 5-4, both magnets were perfectly intact and no signs of calcium deposits were observed. However the author decided that explantation was necessary. The explantation took place in January 2013 and was performed by Mr M McCarthy. Unlike Hameed's explantation the magnet came out relatively clean in terms of external tissue see Figure 5-5.

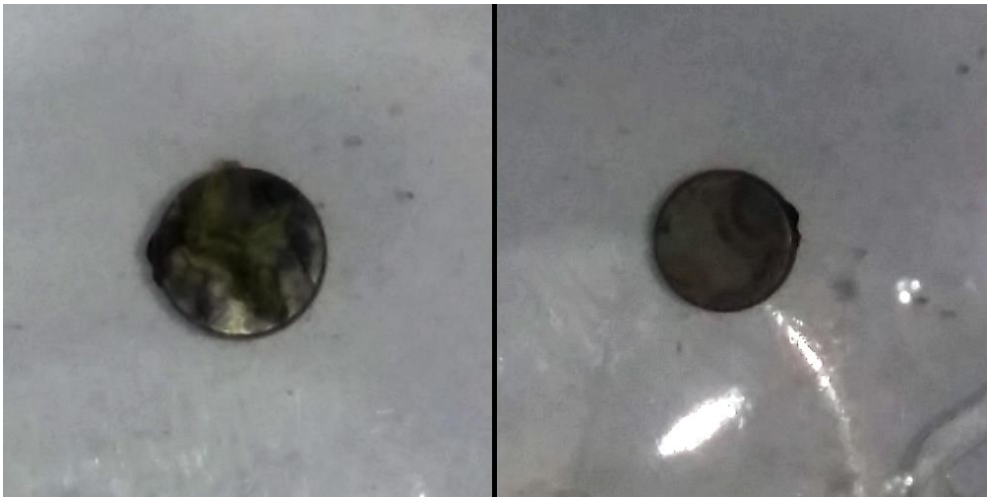


Figure 5-5: The author's explanted magnet

The magnet post removal was placed in a formalin solution in order to preserve the tissue surrounding it. This was subsequently sent for analysis at Dunedin Hospital's pathology lab, Reading, UK. Unfortunately however there was not enough of a tissue sample on the magnet for analysis. The cytotoxic effect of SMIs therefore remains topic for future work of this research as described in section 10.6.4. Subsequently a second implantation procedure was performed in March 2013 to replace the explanted magnet. The cause of the unusual sensations experienced are still unknown, however since having the explantation process and the subsequent reimplantation up to the date of submission of this thesis, no any painful sensations have been experienced.

5.4.4 Summary

The accounts described in this section show examples of why explantation has been performed on various individuals. In summary of which the author would like to state that; anyone wishing to undergo this implantation procedure should firstly be aware and take careful consideration of, the object that they are going to be implanted with. Especially as seen in the case of one respondent, the magnet's coating requires careful consideration prior to implantation. Furthermore the author would like to reiterate that he does not advise undergoing medical MRI procedures if one does have a SMI, due to potential tissue damage and pain that could incur. Further analysis of the effects of an MRI exam on a SMI has been left for future work, see section 10.6.2. Finally caution must be taken in day-to-day activities in order to preserve the implanted magnet and its coating.

5.5 Stimulation Coil Creation

5.5.1 Design and Production

For the experiments within this research that requires MIVS an electromagnetic 'stimulation' coil (solenoid like electromagnetic coil with a free space core) is required. The coil uses created signals from the computer via an amplifier, in order to create the electromagnetic field that induces movement on the implanted or superficially attached magnet, i.e. MIVS. The particular amplifier used to power the coil was the IMG Stage Line, STA-235 1400 W Profession Power Amplifier [213], which meant that the coil's impedance was one of the main specifications. The created coil's impedance was aimed to

be between 4 Ω and 8 Ω at the frequencies used in the experiments conducted within Chapter 6 and Chapter 7; i.e. between 20-300 Hz.

In order to create this coil, two main variables had to be considered:

- The diameter of the coil centre (i.e. where the fingertip will be positioned).
- The length of wire required to create ~4 Ω impedance (in order to be compatible with the chosen audio amplifier).

Given these two variables one can infer:

- The number of turns required upon the coil.
- The overall coil length (taken along the central axis of the coil).
- The radius to the centre of the wire turns (i.e. radius of centre + wall thickness of coil + half the distance of wire 'turns', see Figure 5-6).
- The theoretical field strength at any point along the central axis (described in section 5.5.3).

The equation below shows the relationship between the length of wire and its resistance (assuming the wire is perfectly uniform in its resistance per unit length).

$$L = \frac{R}{\rho} \tag{5.1}$$

Where L equals total length of wire, R equals total resistance of wire and ρ equals the resistance per meter. The wire used was enamelled copper wire (standard wire gauge, SWG 24), which has a resistance of 0.0703 per meter at 20°C [214]. With a requirement of minimum 4 Ω resistance the length of the wire had to be a minimum of 56.899 m, for simplification which was rounded to 57 m.

In order to determine the internal diameter of the coil, empirical measurements from multiple fingertips were recorded; the range of which was found to be between 15.6 mm and 17.6 mm (without skin compression). The internal coil diameter was thus chosen at 18 mm. Due to the mechanical strain put upon the coil from the wire, the internal wall thickness was set at 2 mm. Determining the 'width of the coil turns' (see Figure 5-6) was difficult to calculate a priori; however this was empirically determined at 14 mm, and hence the distance of the 'centre to turn centre' was 18 mm. For clarification the measurements are summarised below.

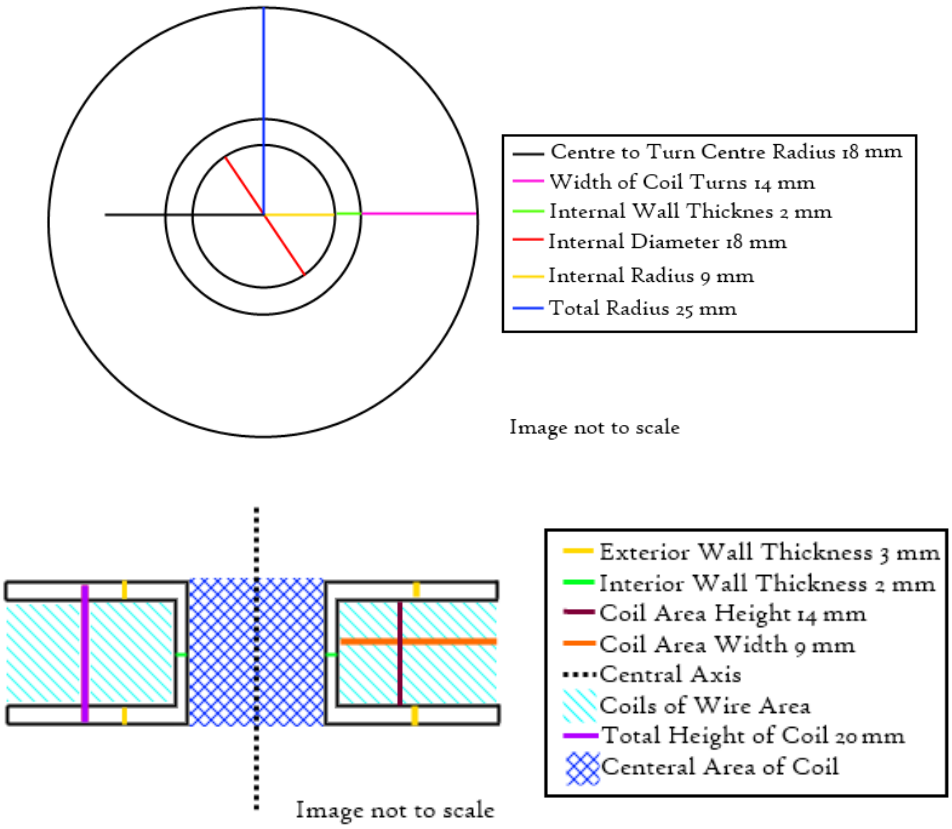


Figure 5-6: Electromagnet 'Stimulation' Coil Measurements. (Top) – Top down view, (Bottom) – Side on Cross Sectional View

Through obtaining a value for the distance of the 'centre to turn centre', the number of turns therefore be calculated using the following equation.

$$n = \frac{L}{2*\pi*R} \tag{5.2}$$

Where n represents the number of turns, L again is the length of the wire (57 m) and R is the radius to the coil turn centre (18 mm). From this calculation the number of turns, n, required was ~504. The number of turns is used when calculating the theoretical flux density which is explored in section 5.5.3.

The 3D model of the coil holder was designed using Solidworks which is a 3D Computer-Aided Design (CAD) package developed by Dassault Systèmes. The schematic of the model created for the holder is shown in Figure 5-7. The model was printed from Acrylonitrile Butadiene Styrene, ABS plastic, using a HP DesignJet 3D Printer [215].

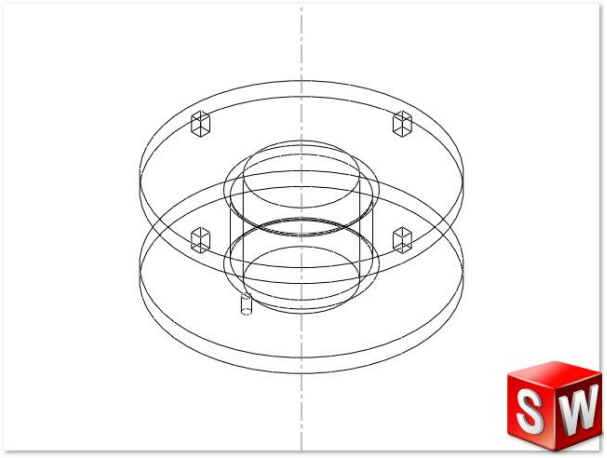


Figure 5-7: Wire frame view of the coil holder, developed in Solidworks

After the coil holder had been printed it then required the wire to be wound. In order to reduce to time taken for this process and to ensure that the number of turns (504) on the coil was accurate, this process was not completed manually, instead a lathe was used. In general, lathes are set with a particular turn speed as the variable and not a set number of turns; as this is not required for a lathes' typical operation. Therefore turn counting was achieved using a counter.

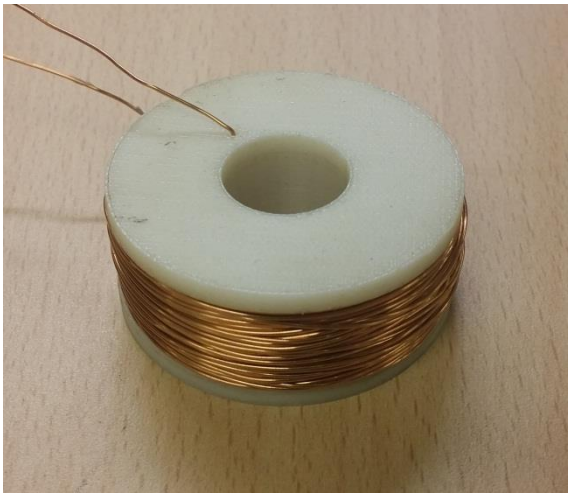


Figure 5-8: Electromagnetic 'Stimulation' Coil

This counter used a Hall Effect sensor to detect a passing magnet that was attached to the rotating spindle of the lathe. This counter was kindly provided by M. Parfitt, whom used the counter for the purpose of coil winding [216]. The spindle shaft was attached to the coil holder and the end of the wire was fed through the small cylindrical hole (shown in Figure 5-7). The lathe was set at a low speed and the winding commenced, until 504

turns were wound upon the holder. Figure 5-8 shows the completed electromagnetic 'stimulation' coil.

5.5.2 Properties of the created coil

In this section the coil produced is examined in terms of both its physical and electrical properties.

5.5.2.1 Dimensions and windings

The coil produced has a number of imperfections in terms of its dimensions compared to that designed. For instance the exterior wall was designed to be 3 mm when in actual fact the produced coil has an exterior wall thickness of 3.1 mm; furthermore the internal diameter of the coil was designed to be 18 mm when in fact its measured diameter is 17.9 mm. This error is due to the accuracy of the HP DesignJet 3-D printer. The minimum available layer resolution is quoted at 0.254 mm [215]. The minimum wall thickness is quoted at 0.941 mm. The minimum layer resolution refers to printing in the Z direction and the minimum wall thickness refers to the accuracy of the XY directions. The coil was printed such that the central axis of the coil was perpendicular to the bed of the printer; meaning that the layer resolution affected the exterior wall thickness and the minimum wall thickness affected the internal diameter.

Printing errors were not the only errors in the dimensions of the produced coil. The length (i.e. height) of the holder was designed to be 20 mm when in actual fact the measured height not only was larger at the coil centre (20.22 mm) but is also different at the coil edge (21.22 mm). This increase in height is due to the coil turns putting pressure on the exterior wall causing it to bow outwards slightly.

This discrepancy in height along with a visual inspection indicates the coil windings are not completely uniform. Uniform winding's refers to an often square like arrangement of coil turns (see Figure 5-9); which is essential for maximum magnetic flux summation from each of the wire turn's magnetic coupling. The concept of coil turns and the efficiency of the coil is discussed by Self [217], stating that a square design for coil windings is efficient due to the coupling of the wires, and circular windings are slightly more efficient.

To determine whether the imperfections mentioned affects the coil's generated B field it has been experimentally measured and cross compared with theoretical and mathematical models in section 5.5.3.

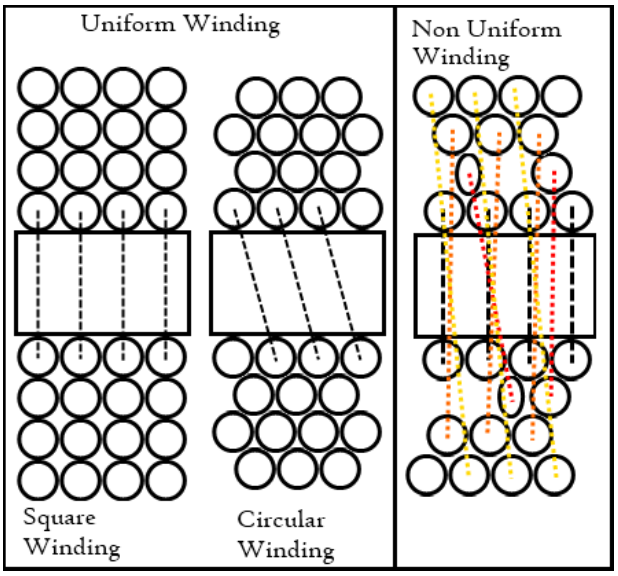


Figure 5-9: Uniform and non-uniform coil winding

5.5.2.2 *Resistance and Impedance measured*

The resistance of the coil was measured at 4.12 Ω using a AIM & Thurlby Thandar Instruments, TTi 1705 True RMS Programmable Multimeter [218]; this value is slightly larger than that calculated, which suggests that the wire length is greater than that determined previously. This could be due to:

- Initial calculation for the length of wire the tail ends of the coil, i.e. the connections to the coil, where not taken into account.
- The calculation for the number of turns assumes that the coil turns are perfectly parallel and do not crossover each other; which would increase the length of wire.
- The resistivity of the wire used in the calculation of resistance may not be entirely accurate; and over a large length of wire this would affect the resistance slightly.

In order to accurately measure the coils impedance an Omicron Lab Bode 100 [219] was used. This device sweeps through sinusoidal frequencies (in this case 10 Hz to 10 MHz) and records the reactance and resistance of the component it is measuring. The readings from the Bode 100 are presented in Figure 5-10.

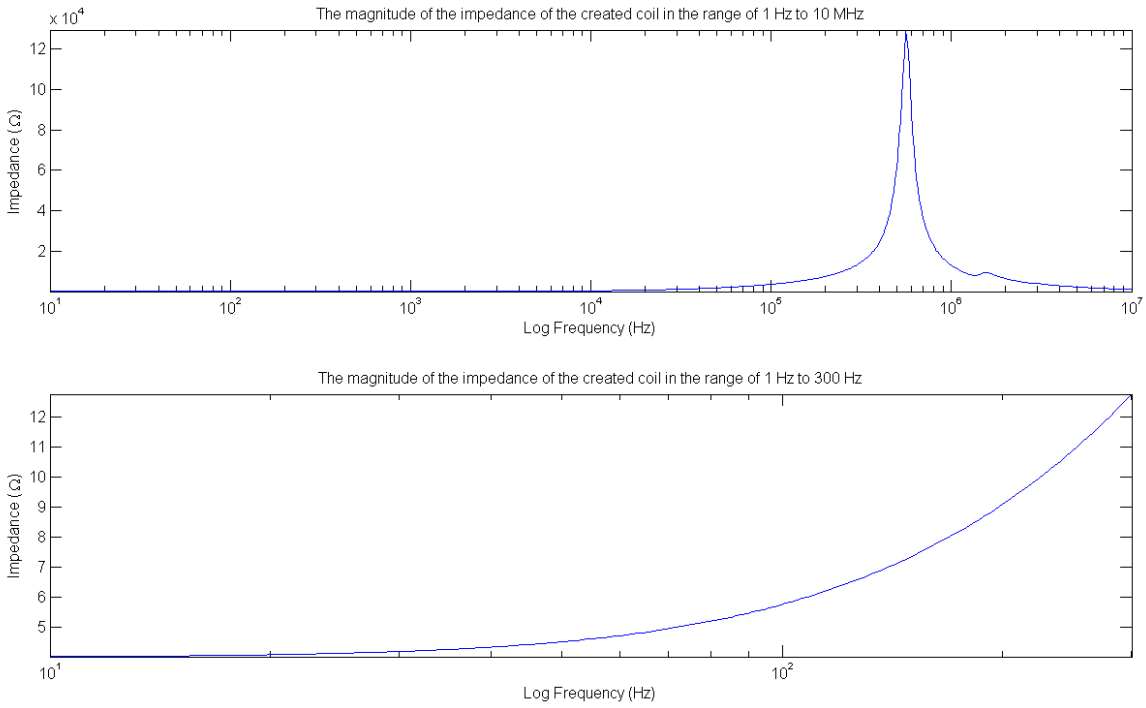


Figure 5-10: Impedance of created coil measured using a Bode 100

Whilst the impedance measured is higher than 8 Ω, the STA 235 power amplifier used to provide the current to the coil has a built in protect feature which, restricts the input signal when the limit level is reached at the output, as stated in the products manual [213]. Despite these slight imperfections, the coil created was simply required to act as a tool to create varied flux densities in order to provide MIVS. Through testing the coil the amplifier's protective circuit was not activated in the ranges used within the experimentation (Chapter 6 and Chapter 7) and therefore the impedance range of the coil has been determined to be suitable for purpose.

5.5.3 B Field Verification

In order to examine the magnitude of the magnetic flux density (B field), emitted by the electromagnetic coil, three methods have been used:

1. Theoretical Approach – Biot-Savart's Law
2. Modelling Approach – FEMM Analysis
3. Experimental Approach – Hall Effect Probe and Linear Actuator

In this section these methods are presented and then cross compared.

5.5.3.1 *Theoretical Approach – Biot-Savart's Law*

Biot-Savart's law is used to calculate the magnetic field on at a point, P, along axis of a circular current [220] the equation of which is shown below.

$$H = I\frac{R^2}{2(R^2+X^2)^{3/2}} \tag{5.3}$$

Where H is the magnetic field strength, R is radius of the coil, I is the current flowing through the wire and X is the distance along the central axis, as shown in Figure 5-11.

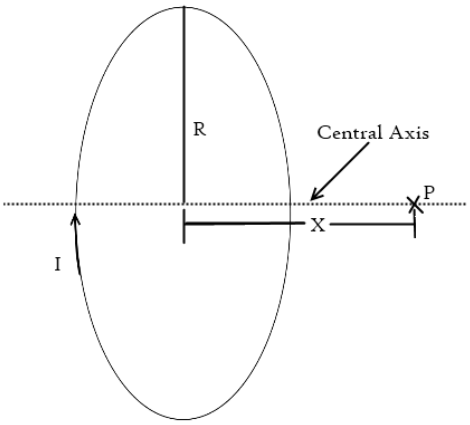


Figure 5-11: Graphical representation of the variables used Biot-Savart's Law

Given that the magnetic fields strength H multiplied by the permeability of free space μ_0 (4πE-7) is equal to flux density, B. The Biot-Savart's equation can be rewritten in the form:

$$B = \frac{\mu_0 * I * R^2}{2(R^2+X^2)^{3/2}} \tag{5.4}$$

Assuming that the wire's thickness is infinitesimally small and that all of the coil's turns are superimposed upon one another; the theoretical flux density of the coil is given by the sum of each of the turns. This is simplified to the multiple of number of turns, as shown in the following equation:

$$B = \frac{\mu_0 * I * n * R^2}{2(R^2+X^2)^{\frac{3}{2}}} \tag{5.5}$$

The theoretical maximum flux density along the central axis is 0.0176 T/A, when X = 0, R = 0.018, n = 504 (the coil's properties) and I = 1 A. To clarify the radius value (R) used

in this calculation was the 'centre to turn centre radius' as illustrated in Figure 5-6. Equation 5.5 was examined using Matlab as a function of *X* (i.e. position along the central axis). The results for which are shown in Figure 5-22 in section 5.5.3.4.

5.5.3.2 *Modelling Approach – FEMM Analysis*

In order to model the magnetic properties of the electromagnetic coil a finite element analysis, FEA, software called FEMM [221] was used. FEA is used in order to numerically approximate a system's characteristics within a set boundary which defines a spatial 'end point' for the stimulation (further reading on the properties and various models of the boundaries are explained by Parfitt in [216]). Examples of where FEA is used are; mechanical stress and strain analysis, magnetic field analysis and heat flow analysis [222]. A brief description of how FEA functions is given by Widas [222] as he discusses its use for stress analysis:

> *"FEA uses a complex system of points called nodes which make a grid called a mesh... ...This mesh is programmed to contain the material and structural properties which define how the structure will react to certain loading conditions. Nodes are assigned at a certain density throughout the material depending on the anticipated stress levels of a particular area. Regions which will receive large amounts of stress usually have a higher node density than those which experience little or no stress. Points of interest may consist of: fracture point of previously tested material, fillets, corners, complex detail, and high stress areas. The mesh acts like a spider web in that from each node, there extends a mesh element to each of the adjacent nodes. This web of vectors is what carries the material properties to the object, creating many elements."*

Two models were created in FEMM, the first was the measured coil (post creation) and the second was the designed coil, both of which are described in section 5.5. The values for the measured coil were rounded as actual measurements for the coil turn width and inner wall thickness could not be accurately established. The dimensions used for both models are shown in Figure 5-12. The models shown are mapped using rotational geometry, which is referred to as an asymmetric problem in FEMM. Unlike 2-D Cartesian geometry, which is referred to as a planar problem in FEMM, the asymmetric problem solution in FEMM incorporates the *z*-axis by rotating a design (in this case the coil) around a central axis; which is illustrated in Figure 5-13.

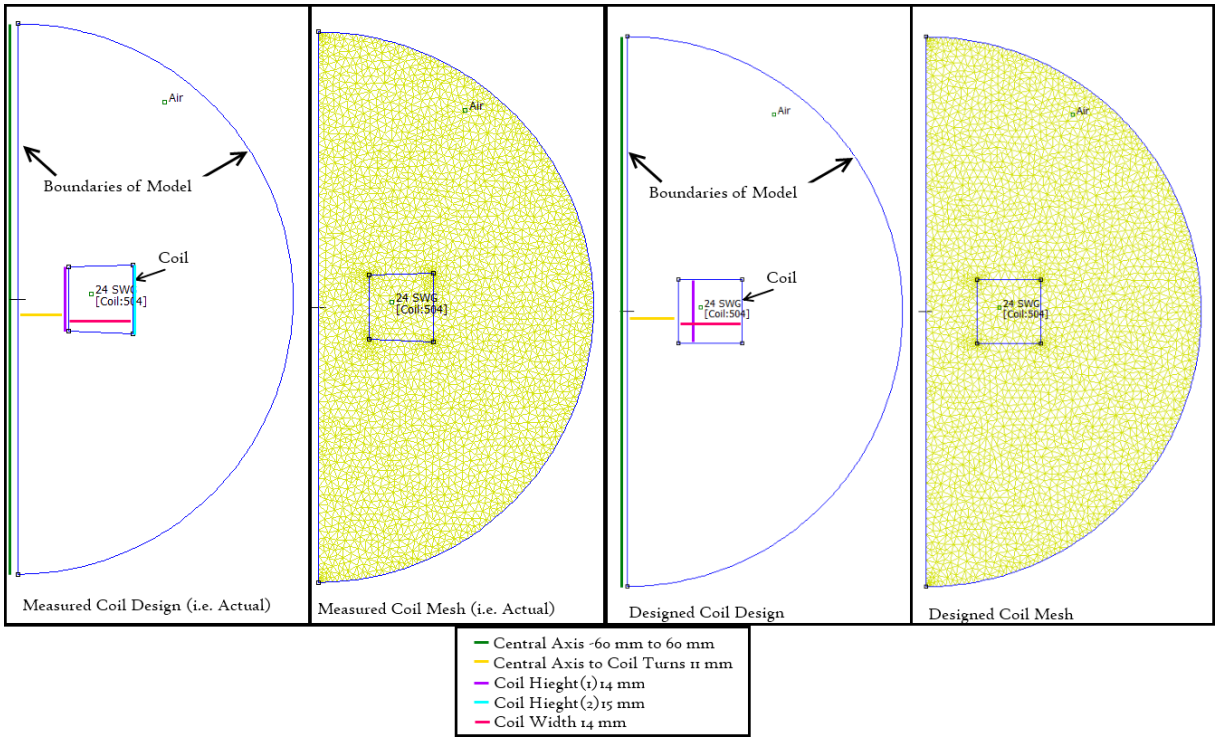


Figure 5-12: FEMM Models used to analyse the created coil

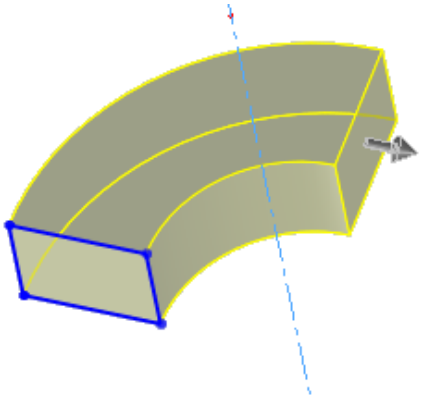


Figure 5-13: Illustration of Asymmetric Problem Solution in FEMM i.e. Rotational Geometry

Once each of the two designs were created, the regions of the two models were defined. As shown in Figure 5-12 there are two regions per model, the first is the coil and the second is air. The coil material used as stated previously was copper wire (24 SWG) the properties of which are predefined within FEMM, as are the properties of air. The coil required an additional property referred to as 'circuits' in FEMM, which defines the current within a region. The current value used was 1 A and the number of turns was defined as 504 as per the coils design. Following definition of the regions, FEA is performed by having FEMM create a mesh (shown in Figure 5-12) and running the analysis; the results of which are shown in Figure 5-14.

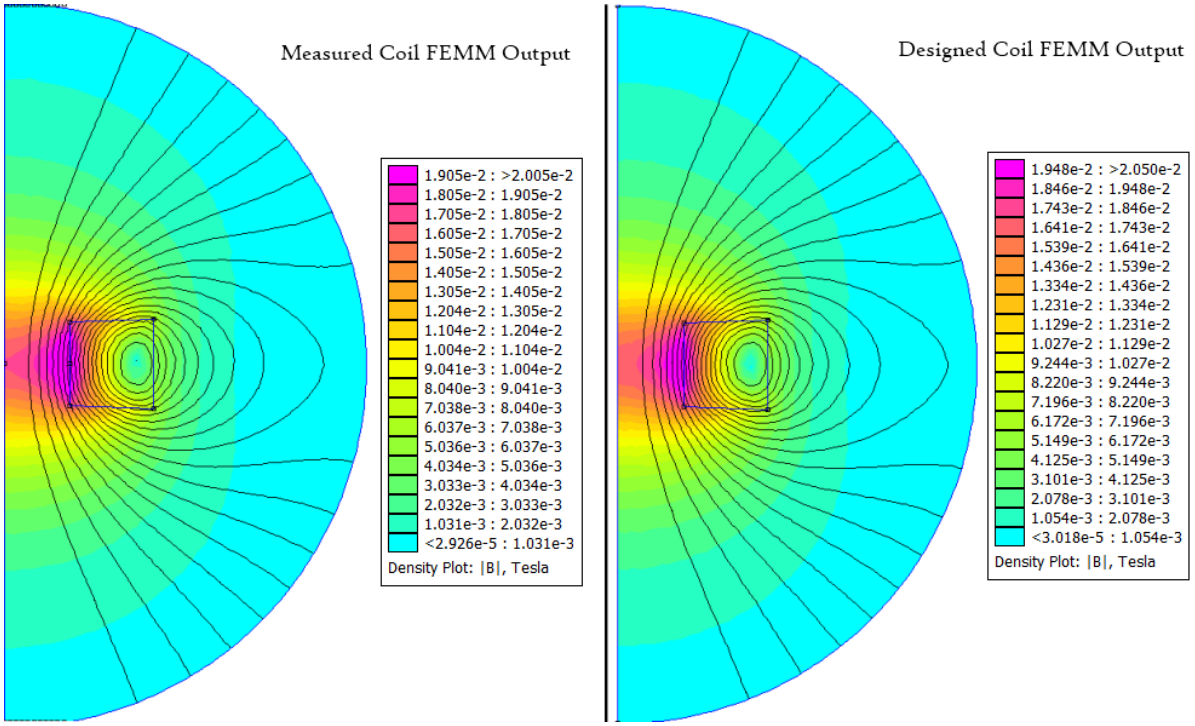


Figure 5-14: FEMM Outputs of Coil Models (as labelled in figure)

Exploring the FEMM output it can be seen that the measured coil model has not only a lower peak value for B field but also a changed B field shape when compared with the designed coil's model. Figure 5-14 shows as predicted that the flux density is maximised at the inner wall of the coil. In order to further analyse this result, Figure 5-15 (Type 1) shows vector measurements taken along the central axis and in millimetre increments parallel from the central axis. A comparison between the two coil types shows that the non-uniform shape of the measured coil has a slightly reduced maximum flux density; 17.21 mT at the centre of designed coil vs 17.11 mT at the centre of the measured coil. This is presumably due to the non-parallel turns not completely coupling, which would cause a reduction in the total B field.

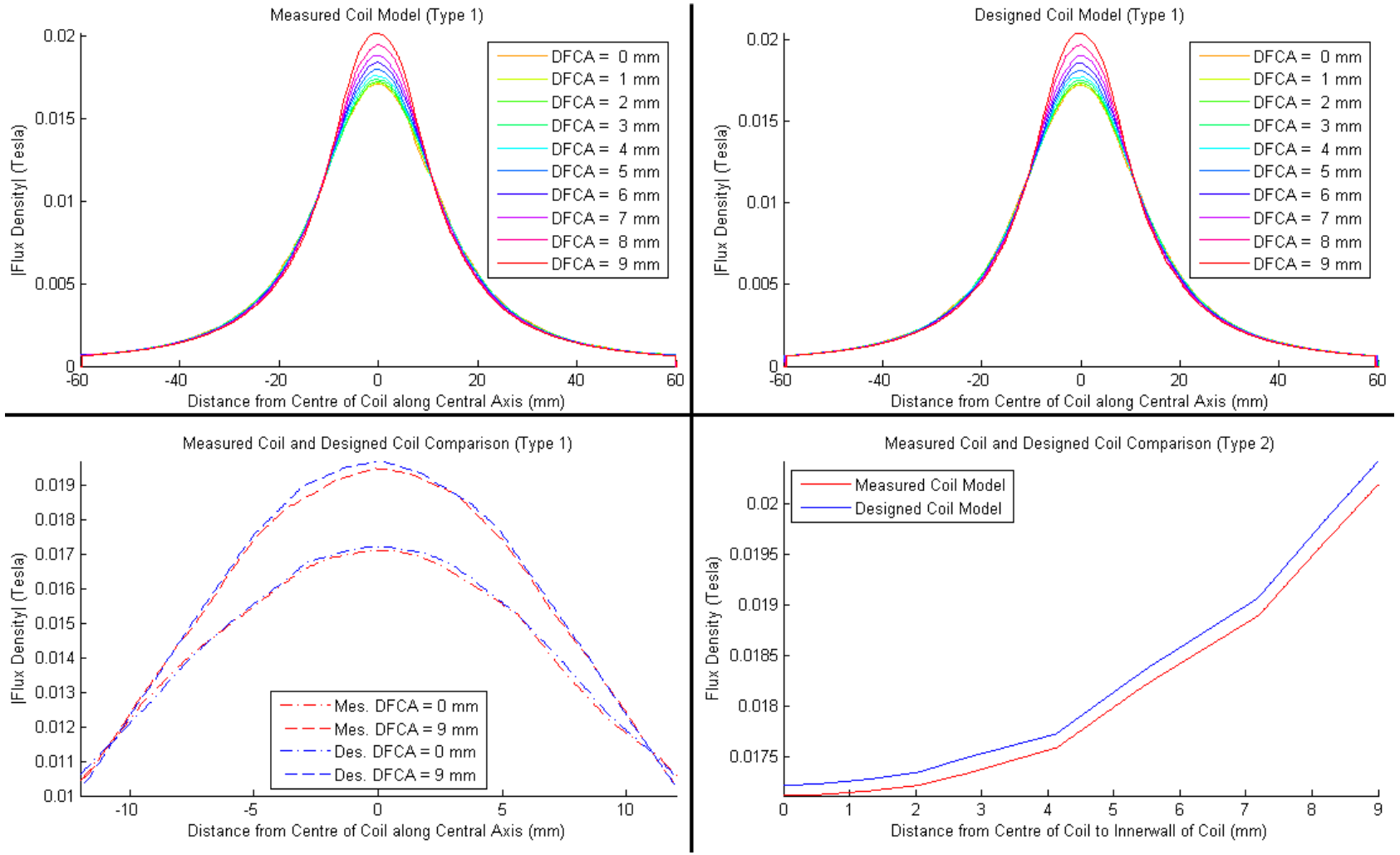


Figure 5-15: FEMM vector analysis. (DFCA – distance from central axis). Type 1 – Central axis and parallel vector measurements. Type 2 – perpendicular vector measurements from centre of coil to inner wall of coil.

Figure 5-15 (Type 2) presents a perpendicular vector measurement from the coil centre to the inner wall of the coil. Both of which are measured to the inner wall of the coil (i.e. 9 mm). This graph clearly shows the slight reduction in flux density between the measured coil model and the designed coil model. A comparison of the two FEMM models to the other approaches for determination of the created coil's B field is shown in Figure 5-22.

5.5.3.3 *Experimental Approach – Hall Effect Probe and Linear Actuator*

This section describes how the flux density of the central axis of the coil was measured empirically. This was preformed from -60 mm to 60 mm along the central axis, where the 0 mm reference point was centre of the coil. In the section, the equipment list is defined, followed by the experimental setup and the experimental procedure.

5.5.3.3.1 Equipment List

A number of instruments and devices were used within this experiment; which are explained along with their purpose (within the context of this experiment) below:

- **The created electromagnetic coil**.
- **Instron® 4206** [223] – A high precision linear actuator which is typically used for mechanical measurements, such as; shear forces compression forces and flexor testing. In this experiment the device was used to control the movement of a Hall Effect probe.
- **CERMAG GMET H001** [224] – A gauss meter along with its axial Hall Effect probe, used to measure the flux density of the coil.
- **Digimess® DC power supply HY3003** [225]– Power Supply used in order to provide a constant 1 A current supply.
- **BETEX 1230 Digital Laser Thermometer** [226] – For accurate temperature measurement of the coil during testing.
- **Common Table-Top Fan** – Used in order to maintain the temperature of the coil.
- **Common Vernier Caliper** – Used to insure the probe was positioned centrally within the coil.
- **Common Set Square** – Used to insure the probe was aligned correctly within the Intron.

A custom piece of hardware was also required as the coil needed to be held in a horizontal position such that the central axis of the coil was aligned vertically within the Instron. Furthermore the coil needed be raised such that the coil's B field recordings would not be affected by the Instron itself. In order to do this a wooden holder was created, the schematics for which are shown in Figure 5-16 (top). This was created by Mr P. Tolson, who is a master workshop technician working at the University of Reading. Figure 5-16 (bottom) is a photograph of the manufactured holder.

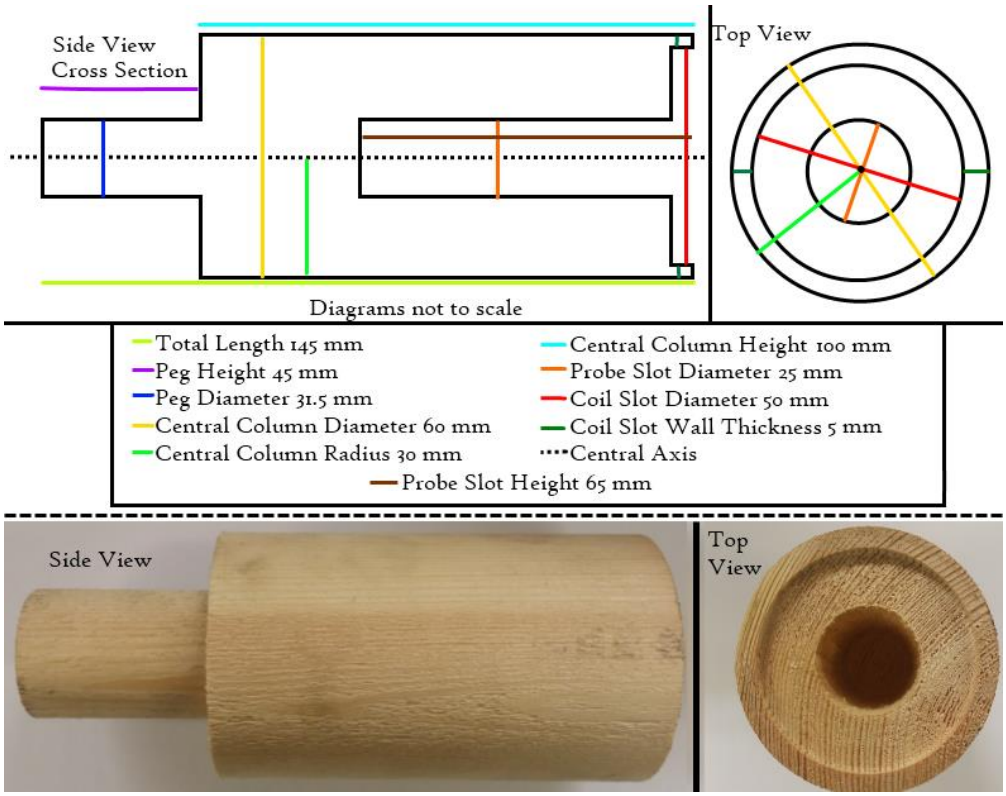


Figure 5-16: Wooden Holder used experimental approach of examining flux density of electromagnetic coil. (Top) – Schematic representation. (Bottom) – Photograph of holder.

5.5.3.3.2 Experimental Setup

1. Both jaws (aka clamp, see Figure 5-17 (2)) of the Instron were removed.
2. The coil was positioned within the holder and the holder was positioned in the Instron's bottom jaw holder (Figure 5-17 (1)).
3. The axial Hall Effect probe was positioned within the Instron's 'jaw', using a set square to ensure its alignment was correct (Figure 5-17 (2)).
4. The Instron's jaw with the now attached Hall Effect probe was repositioned back into the Instron.

5. The Instron was lowered such that the tip of the whole effect probe was positioned within the coil's centre (Figure 5-17 (3)).
6. Multiple length measurements were taken and the Instron's jaw repositioned such that the probe was aligned with the vertical central axis of the coil.
7. The Hall Effect probe's vertical displacement was calibrated by positioning a piece of paper (thickness 0.1 mm) was positioned flat across the top of the coil; the Instron was then lowered such that the probe slightly indented the paper.
8. The probe was then re-calibrated in terms of vertical displacement by -70.1 mm; this position was the test start position; as it was ~60 mm below the centre of the coil.
9. The fan was positioned such central axis of fan was directed at the coil.
10. The coil was connected to the power supply (using standard cable and crocodile clips) and the connections were insulated to prevent electrical shorting (Figure 5-17 (4))).
11. The power supply was turned on as and set supply a 1 A supply.
12. The gauss meter was turned on and set to record mT.

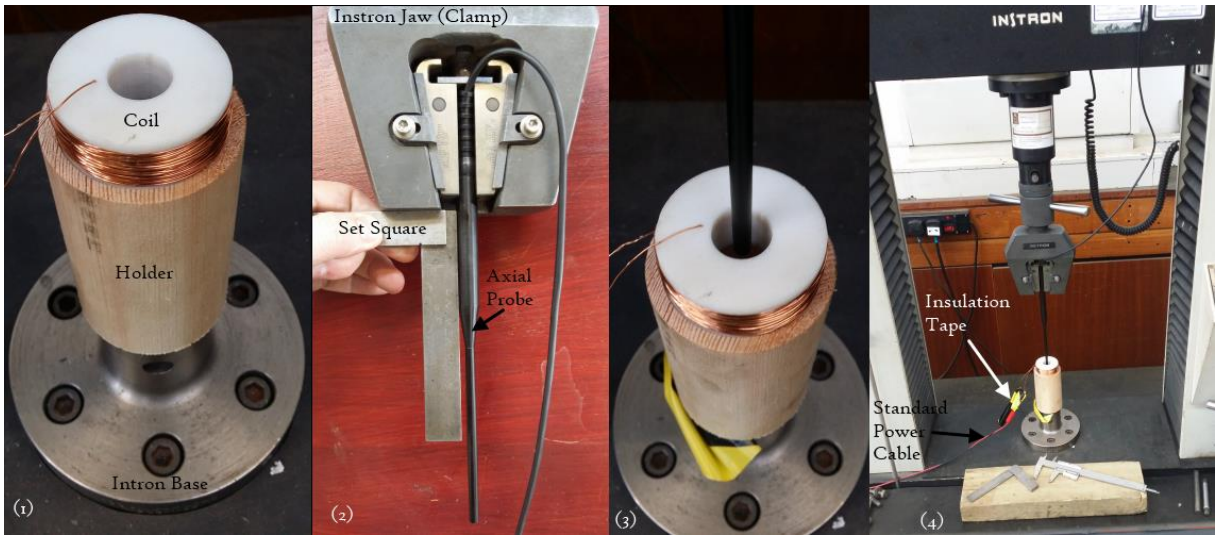


Figure 5-17: Experimental Setup Photographs. (1) – Coil in holder inside of Instron Base. (2) – Axial Probe in Instron Jaw (Clamp), alignment set with set square. (3) Probe Position in Coil. (4) Final Setup.

5.5.3.3.3 Observation Measurement Averaging Guideline

The accuracy of the Hall Effect probe used is +/- 2% or 10 gauss (whichever greatest) as stated in the instruction manual for the device shown in Appendix D. A consequence of this resolution and accuracy meant that observations of the measured B field were not

completely accurate. Furthermore the device, due to this resolution, rarely settled on one particular value for B field and hence observation averaging was conducted in order to assure the best possible measurement was recorded. This averaging was done in two scenarios, when observing measurement fluctuations on the gauss meter, these were:

1. Gauss meter fluctuating between two values - measurement recorded was the most prominent observed value over a ~2 s sample (i.e. the mode value).
2. Gauss meter fluctuating between three values - measurement recorded was the mean value (i.e. the mean value).

5.5.3.3.4 Experimental Procedure

In order to observe the B field along the central axis of the coil the following method was used:

1. Wait for gauss meter (Figure 5-18 (4)) to settle (~1 s), record the value of flux density from the gauss meter in mT, following the guideline set in previous subsection.
2. Alter vertical displacement (i.e. height) of Hall Effect probe by using the jog function on Intron ((Figure 5-18 (1)) to increment 0.1 mm (Figure 5-18 (2)).
3. Ensure current from the DC power supply is 1 A from digital read out (Figure 5-18 (3)).
4. Record temperature using infrared thermometer from wire coil centre using laser alignment at approximately every 100 measurements.
5. Repeat steps 1 – 4 1201 times.

The B field was recorded in both current directions through the coil in order to observe any discrepancies of the coil. However due to the lengthy time taken to conduct the experiment (~ 6 hours) the full sets of measurements were conducted on two separate days. Furthermore due to its demand, health and safety concerning the equipment and security, the access to the equipment was physically restricted; which meant that the experimental setup had to be conducted at the start of each day.

Figure 5-18: Instron Controls (1 & 2), Digimess Power Supply (3), Gauss Meter (4)

5.5.3.3.5 Results

Figure 5-19 presents the observed results from this experiment. While the results for the forward and reverse bias seem in close agreement to one another, certain areas of the graph suggest that this is not the case. Zoomed regions have also been presented in Figure 5-19 to further explore this data. The discrepancies shown in the zoomed regions, e.g. the difference in recordings at the apex in zoomed region two could possibly be attributed to 2 factors. These factors are simply either the experimental setup (as recalibration was performed on the two separate recordings sessions) or the coil's imperfections.

To further examine whether the experimental setup contributed to these discrepancies a third round of recording took place. In this recording session both the forward and the reverse bias was examined along the central axis; however this was focused such that the measurements obtained were only within the coil itself (i.e. ±10.2 mm). Furthermore this experiment followed the same procedures outlined in section 5.5.3.3.4 with one exception. Rather than observing an average result from the Gauss meter (see section 5.5.3.3.3); the maximum and minimum values at each point were recorded, and subsequently the mean of the values at each location were determined. The results from which are presented in Figure 5-20.

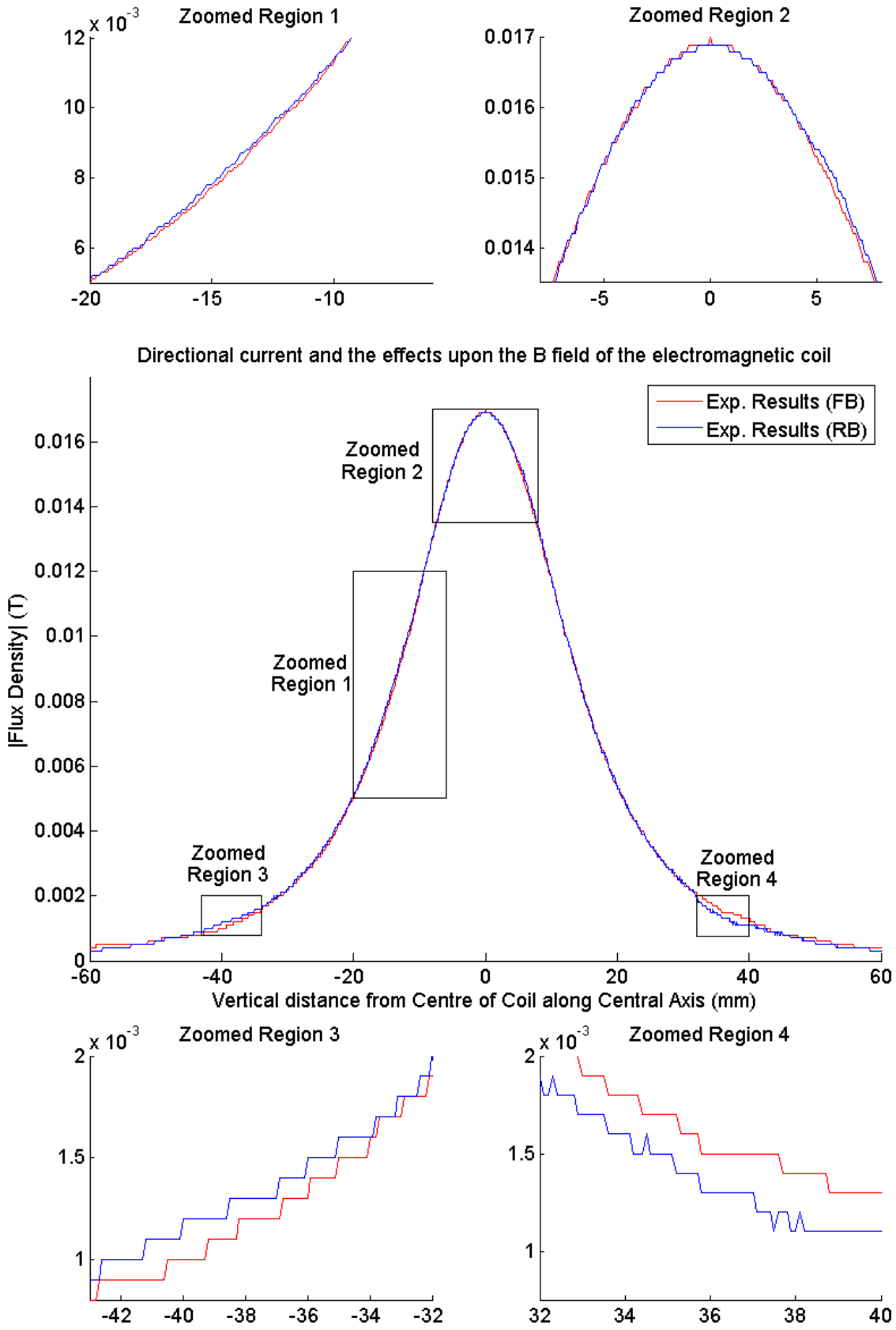


Figure 5-19: Magnitude of B field recordings observed along the central axis of the created electromagnetic coil. Exp. – Experimental, FB – Forward Bias, RB – Reverse Bias.

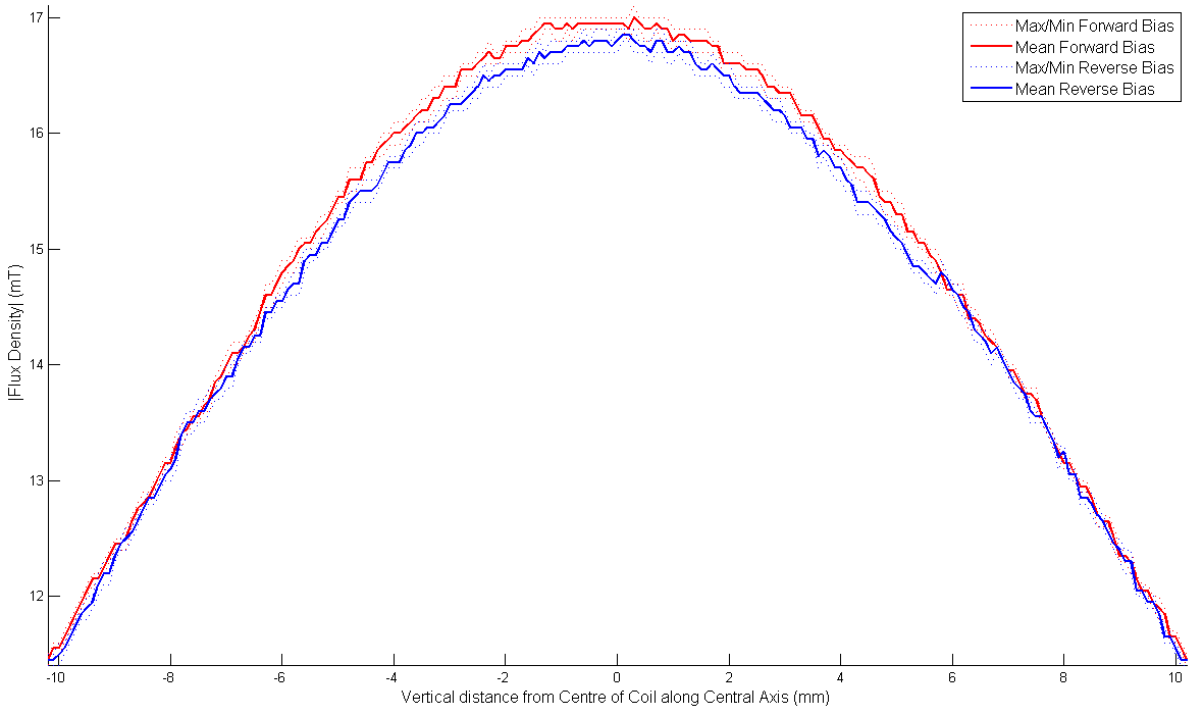


Figure 5-20: The magnitude of B field measurements recorded in the electromagnetic coil's centre along the central axis

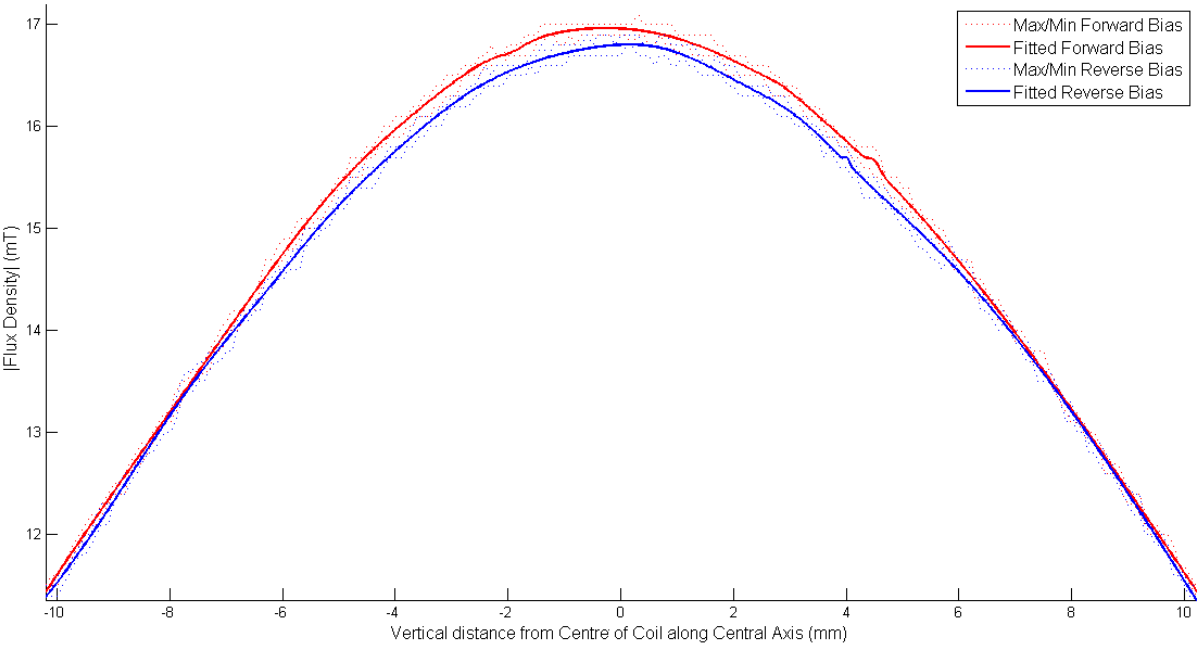


Figure 5-21: Mean result data from Figure 5-20 fitted using the curve fitting toolbox in Matlab.

Figure 5-21 presents the mean results found in Figure 5-20 post being fitted to a Gaussian distribution curve using the curve fitting toolbox in Matlab. The R^2 values for forward and reverse bias are 0.995 and 0.994 respectively. Comparing Figure 5-19 and Figure 5-21 it is clear that there was a small discrepancy that occurred due to the

experimental calibration; which could have been due to a number of factors including; the coil position in the holder not being perfect, the position of the probe not being 100% central, and the holders central axis not being completely vertical.

It is clear from the results presented in Figure 5-20 that the coil created is not perfect; as a perfect coil would respond with the same magnitude of the field regardless of the direction of current. The assumed reason for this difference comes from the inaccurate windings of the coil (described in section 5.5.2.1). As mentioned previously the windings are critical for magnetic coupling, windings that are not completely parallel to the horizontal plane (i.e. perpendicular to the central axis) will not completely summate; as the flux density produced by that turn will be off by an angle.

Whilst this has been considered, this coil, as mention previously, is simply a tool used to create varying magnetic fields in order to provide MIVS. Hence further discussion of this matter is omitted from this thesis as it is not within the context of this research. The results of these observations are shown in Figure 5-22 in comparison with the previous approaches used to determine the B field of the coil.

5.5.3.4 *Comparison of Approaches*

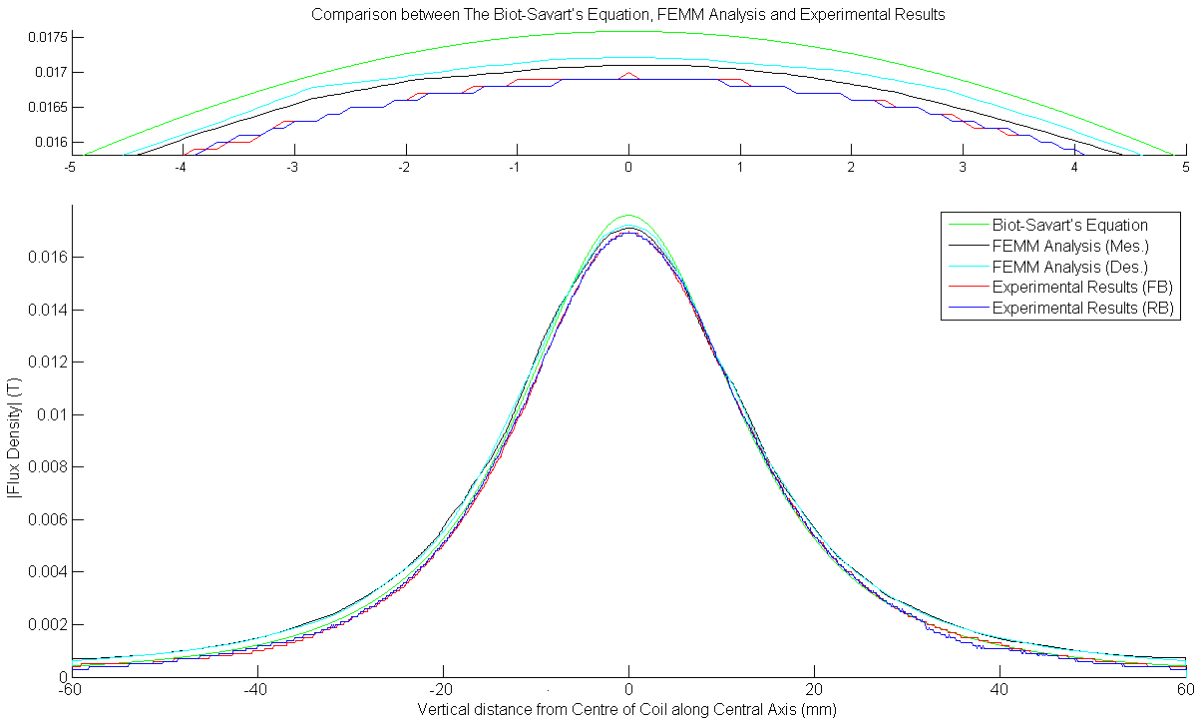


Figure 5-22: Comparisons between three flux density approaches (experimental results 1)

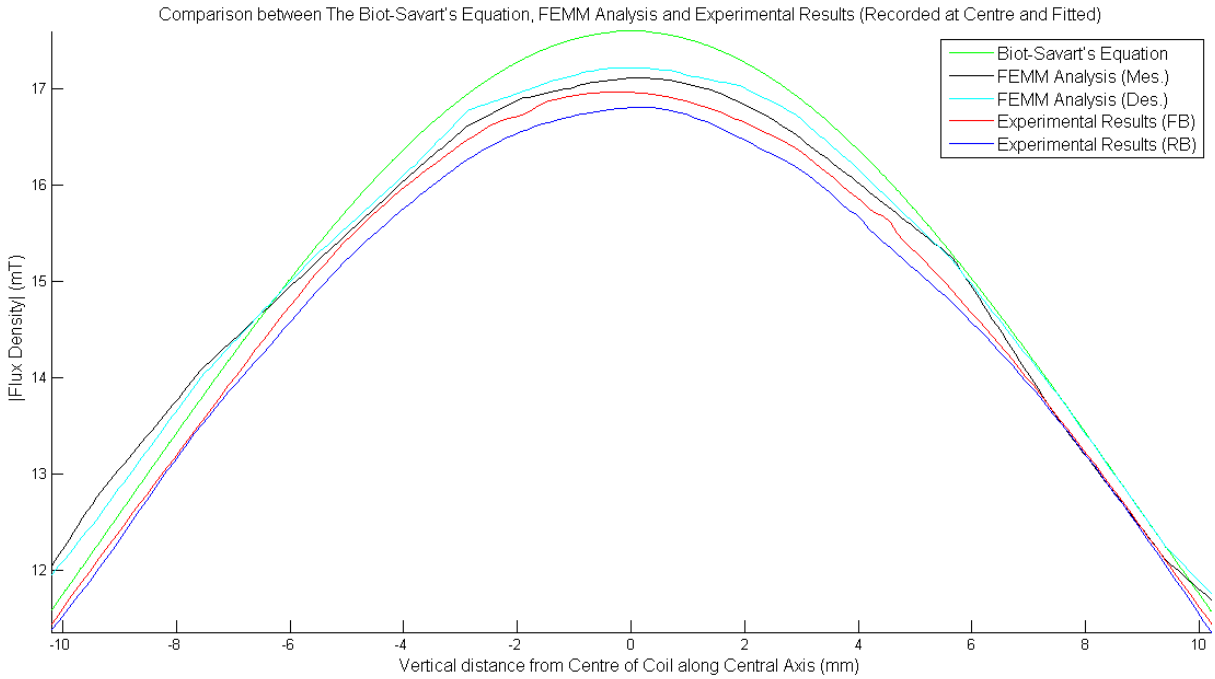


Figure 5-23: Comparisons between three flux density approaches (experimental results 2 fitted)

Approach IDs	Method Of Approach	|B field| at coil centre (mT)
1	Biot-Savart	17.59
2.1	FEMM – Designed coil	17.22
2.2	FEMM – Measured coil	17.11
3.1.1	Experimental – Forward bias 1st measurement	17
3.2.1	Experimental – Reverse bias 1st measurement	16.9
3.1.2.1	Experimental – Forward bias 2nd measurement mean	16.95
3.2.2.1	Experimental – Reverse bias 2nd measurement mean	16.8
3.1.2.2	Experimental – Forward bias 2nd measurement fitted curve	16.96
3.2.3.2	Experimental – Reverse bias 2nd measurement fitted curve	16.8

Table 5-1: Absolute measurements of B field at the coil centre (i.e. x = 0 along the central axis) for each of the approaches used to determine B field of the coil

↓/→	1	2.1	2.2	3.1.1	3.2.1	3.1.2.1	3.2.2.1	3.1.2.2	3.2.2.2
1	100.00	102.15	102.81	103.47	104.08	103.78	104.70	103.71	104.70
2.1	97.90	100.00	100.64	101.29	101.89	101.59	102.50	101.53	102.50
2.2	97.27	99.36	100.00	100.65	101.24	100.94	101.85	100.88	101.85
3.1.1	96.65	98.72	99.36	100.00	100.59	100.29	101.19	100.24	101.19
3.2.1	96.08	98.14	98.77	99.41	100.00	99.71	100.60	99.65	100.60
3.1.2.1	96.36	98.43	99.06	99.71	100.30	100.00	100.89	99.94	100.89
3.2.2.1	95.51	97.56	98.19	98.82	99.41	99.12	100.00	99.06	100.00
3.1.2.2	96.42	98.49	99.12	99.76	100.36	100.06	100.95	100.00	100.95
3.2.2.2	95.51	97.56	98.19	98.82	99.41	99.12	100.00	99.06	100.00

Table 5-2: Percentage differences between different approaches, row and column headers represent the approach IDs from Table 5-1. The colour indicates above (aqua), below (orange) and equals (blue) 100%, the percentages are based such that the row is a percentage of the column.

The results presented in Figure 5-22 and Figure 5-23 show that the real world measurements are in very close agreement to the theoretical approximations. The maximum values for each approach is shown in Table 5-1; which have been cross examined in terms of percentage difference in Table 5-2.

From the percentage differences presented in Table 5-2, the closest approximation for the experimentally measured B field came from the measured FEMM model (described in section 5.5.3.2) is > 98% accurate. This is result is more than suitable for the hardware's application. The possible explanations for the overestimation seen in the theoretical approaches are:

1. Theoretical models do not account for any air gaps for within their approximations.
2. Theoretical models assume perfect uniform flux density and coil winding is present through all wire within the theoretical models.
3. In the case of the FEMM analysis, uniform coil turn layering is assumed. However as described in section 5.5.3.2 this is not the case.
4. In the case of Biot-Savart's law, the assumptions made, (described previously in section 5.5.3.1) does not account for the dimensions of the actual created coil.

However despite the discrepancies in accuracy, the created coil has shown under test condition to be suitable for purpose, as it generates the necessary varied magnetic field required to create MIVS stimulation.

5.6 Surface Magnetism Experimentation

The following experiment was conducted in order to ascertain the surface flux density created by the implanted magnet on the authors index finger pad. The purpose of this experiment was to attempt to approximate the orientation of the author's implanted magnet within his left finger pad. The equipment used within this experiment was as follows:

- **CERMAG GMET H001** [224] – A gauss meter along with its axial Hall Effect probe, used to measure the flux density along the surface of the finger pad.
- **Rice paper** – Used to position the probe, with a ~2 mm Cartesian grid drawn upon it (Figure 5-24).

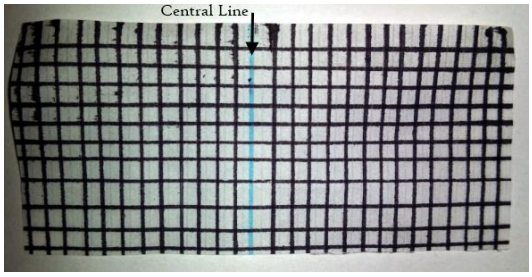


Figure 5-24: Rice paper gird used in surface flux density experiment

The grid was made at 2 mm accuracy as a 1 mm could not be achieved due to the size of the axial probe's tip and accuracy of the probes position. The experiment was set up by simply wrapping the rice paper around the finger and centring the middle of the paper, such that it aligned with the centre of the author's fingertip (Figure 5-25). The rice paper used has a strip of adhesive as standard and this was used in order to affix the paper to the finger.

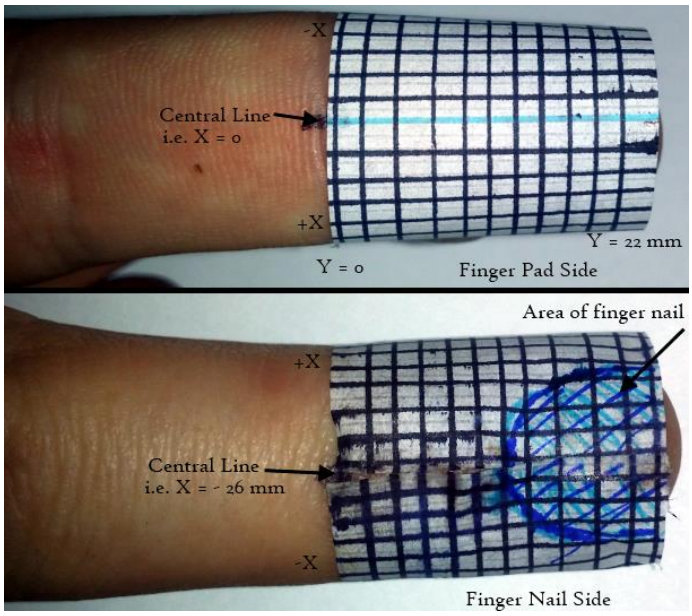


Figure 5-25: The author's fingertips with rice paper grid attached. X and Y values represent the measurement direction.

The recordings were then observed and recorded the mT reading (after ~1 s) at each of the line intersections. This was achieved by lining up the axial probe datum lines to the grid as illustrated in Figure 5-26. In order to obtain consistent recordings the guidelines for observation measurement, outlined in section 5.5.3.3.3, were adhered too throughout this experiment. Furthermore care was taken not to indent the skins surface whilst taking

measurements as this greatly increased the observed value, being that the probe became closer to the magnet itself.

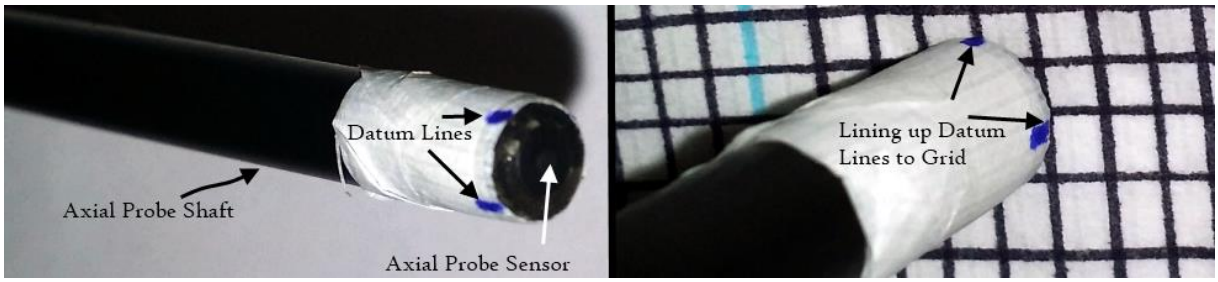


Figure 5-26: Axial Probe Datum Lines and Grid Referencing

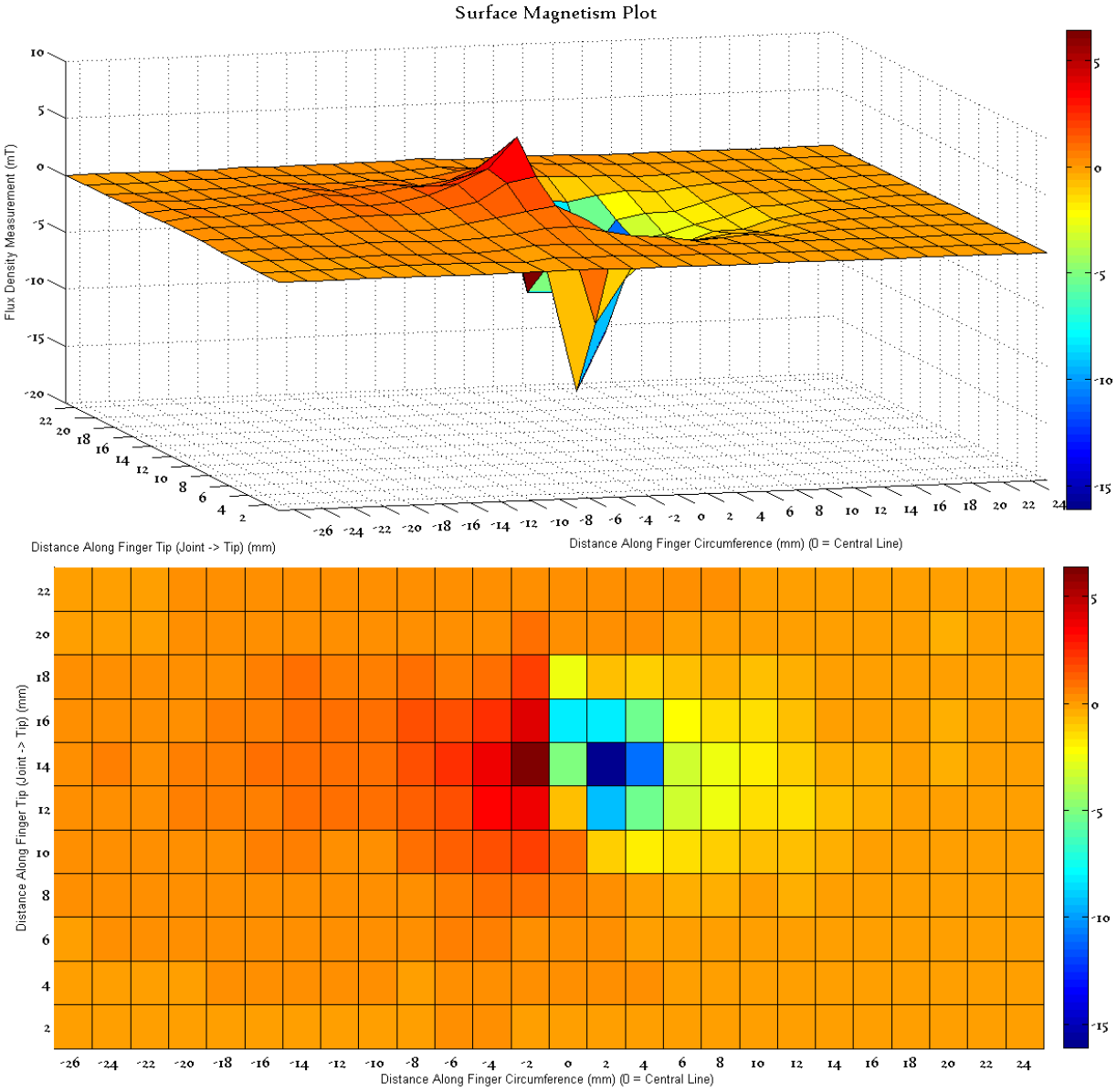


Figure 5-27: Surface plot of Surface Flux Density Experiment in both 2D and 3D

In Figure 5-27:

- The x-axis represents the circumference distance (mm) of the authors fingertip centred upon the centre line (Figure 5-25).
- The y-axis represents the distance (mm) from the joint (i.e. middle and distal phalanx) to the fingertip of the author's index finger (Figure 5-25).
- The z-axis (colour) represents the flux density (mT) recorded value.

The results indicate that the author's implanted magnet's orientation is not horizontal but predictably more vertical, and of orientation similar to that seen in the author's middle finger in his x-ray image (Figure 5-4). To clarify the magnets' poles are split horizontally; i.e. each face of the cylinder is opposite in polarity. This assertion is based around the change in field shown in Figure 5-27, i.e. the results suddenly change polarity from negative to positive at the 0 mm recordings along the circumference. Furthermore the surrounding field recordings in both the positive and negative directions along the circumference display the typical magnetic field drop off.

5.7 Approximation of Force Applied to the Magnet from the Coil (The Flipping Experiment)

5.7.1 Introduction

The experiment described in this section was conducted in order to empirically approximate the force acting upon the magnet from the electromagnetic coil. The magnet tested is an approximately identical magnet to that implanted in the author's fingertips. The idea of the experiment was to relate the current supplied to the coil, to the force required to 'flip' the magnet. A flip in this context refers to the reorientation of the magnet, which is defined as the elevation of the magnet, followed by an 180° rotation along its horizontal axis and finally it's decent (illustrated in Figure 5-28).

As described by Biot-Savart's law (section 5.5.3.1), current applied to a loop of wire $\vec{I}$ (in this case the electromagnetic coil) is proportional to the flux density as a given point along its central axis, $\vec{B}(x)$. Furthermore the vector force $\vec{F}(x)$ applied to a magnet by the coil is proportional to the B field at a point along the central axis. Thus at any given point along the coil's central axis the force applied to the magnet, is proportional to the current applied to the coil, $\vec{I}$.

$$\vec{F}(x) \propto \vec{B}(x) \propto \vec{I} \tag{5.6}$$

The point at which the force applied to the magnet becomes greater than the magnets weight is the flipping point of the magnet. When a large enough B field is generated by the coil (caused by the increase in current intensity provided to it), the opposing magnetic fields (from both the coil and the magnet) create enough of a force to counter the gravitational force acting upon the magnet; at which point the magnet elevates and becomes unstable. In order to realign itself with the direction of the B field from the coil, the magnet flips. This experiment measures the current required to flip the magnet in order to approximate the force applied to the magnet from the coil for a given current.

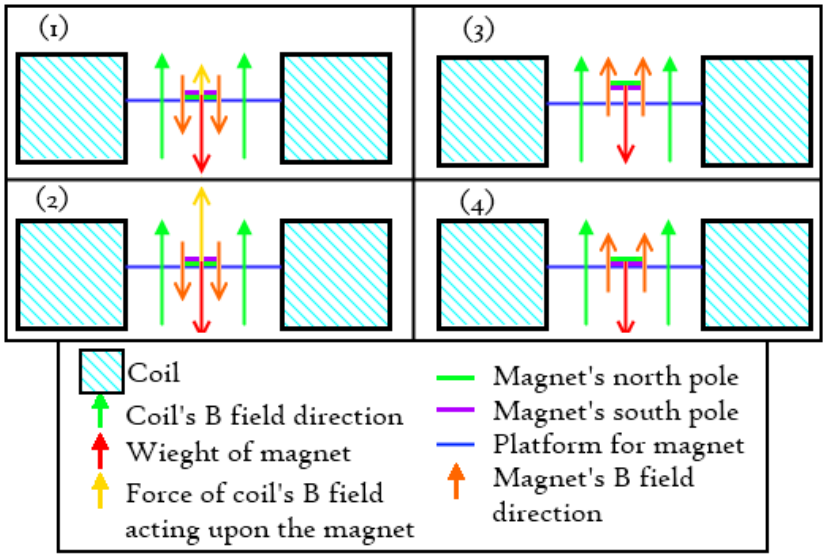


Figure 5-28: Graphical representation of the magnet flipping. (1) The magnet is at rest, force due to gravity (i.e. its weight) is greater than that of the force from the coil's B field interacting with the magnet's B field. (2) The current increases to the point where the force from the coil's B field acting on the magnet is greater than that of the magnet's weight. (3) The magnet elevates and rotates 180° along its horizontal axis in order to align its field with that of the coils. Since the B fields from both the coil and the magnet are now inline the force between them no longer exists. (4) The magnet descends returning to the centre of the coil and rests upon the platform.

As this experiment is measuring the current at the point of 'flipping' of the magnet, the assumption made is that the force created by the interaction of the B fields from the coil and the magnet, is greater than that of the weight of the magnet in order for the flip to occur. These approximations are depicted graphically Figure 5-28 and algebraically in equations 5.7, 5.8 and 5.9.

$$Gravitation\ Force: \overrightarrow{F_1} = m\vec{g} \tag{5.7}$$

$$Force\ of\ Current: \overrightarrow{F_2}(x) \propto \vec{I} \tag{5.8}$$

$$Flip\ Force: \overrightarrow{F_2}(x) > \overrightarrow{F_1} \tag{5.9}$$

where m is the mass of one magnet (4.418E-5 kg), $\vec{g}$ is the gravitation acceleration constant on earth (9.80665 ms^{-2}), $\overrightarrow{F_1}$ is the vector weight of the magnet which equals $4.3326*10^{-4}$ N. $\vec{I}$ is the vector current through the coil and $\overrightarrow{F_2}(x)$ is the force applied to the magnet from the coil at a given point along the central axis.

5.7.2 Equipment List

Within this experiment the following equipment was used:

- **The created electromagnetic coil.**
- **3.4 mm diameter 0.73 mm thick neodymium, 48 MGOe parylene coated magnet.**
- **Thurlby Thandar Insturments, TTi PL154 15 V, 4 A PSU** [227] – Variable current supply.
- **Rapid 955 Digital Multimeter, DMM** – Used to accurately determine the DC value applied through the coil provided by the PSU.
- **Double Pole Double Throw, DPDT switch** – Used in a crossover formation to easily reverse the current direction from the PSU to the coil (see Figure 5-29).
- **Custom Made Pedestals** – In order to vary the platform position (shown in Figure 5-28), varying height pedestals were created. The created pedestals increased in height by 1 mm in the range of 10.5 mm (the coil centre) to 20.5 mm (~ coil edge) (see Figure 5-30 for photograph). The diameter of each coil created was 17.5 mm and printed from ABS plastic using a HP Designjet 3D Printer [215]. As described in section 5.5.2.1 the 3D printer used has a known resolution error, for this reason the pedestals height were not exactly the height intended. The measured heights compared with the designed heights are presented in Table 5-3.
- **The wooden coil holder** (used in section 5.5.3.3.1) – Used in order to ensure that the coils flux density was not affect by the surrounding area.
- **Rice paper** – Used to create a smooth surface on the platform and also for alignment of the magnet such that is was positioned coil's centre. Furthermore the added thickness from the rice paper enabled the pedestal to be held firmly in position.

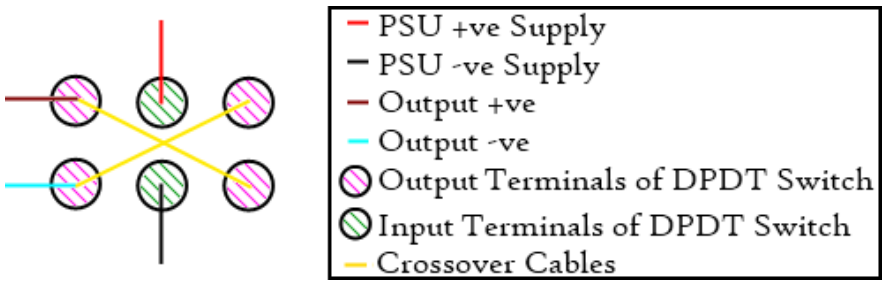


Figure 5-29: DPDT switch in crossover formation

Figure 5-30: The custom made pedestals for the flipping experiment

Designed Height (mm)	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5
Measured Height (mm)	10.8	11.9	12.9	14	15	16	16.8	17.8	18.8	19.8	20.8
Percentage Increase (%Error)	2.86	3.48	3.20	3.70	3.45	3.23	1.82	1.71	1.62	1.54	1.46

Table 5-3: Designed height vs measured height of created pedestals for the flipping experiment

5.7.3 Experimental Setup

The experimental setup was completed in two parts, the electrical setup and the pedestal setup. The electrical setup was completed only once, the pedestal setup was completed after each set of measurements were taken from a particular pedestal. The electrical setup was as follows:

1. The PL154 PSU was connected to the DPDT switch using standard electrical cabling.
2. The negative output of the DPDT when in forward bias configuration was connected to the COM (i.e. the negative terminal) of the 955 DMM, again using standard electrical cabling.
3. The positive output of the DPDT again in forward bias configuration was connected to the coil through standard cabling and a crocodile clip.
4. The mA current measurement terminal from the 955 DMM was connected to the other coil terminal again using standard cabling and a crocodile clip.

A photograph of this setup is shown in Figure 5-31 in both forward and reverse bias. In the left image a forward bias is passing through the coil. This provides a negative B field

when measured from the coils central axis, making the face that is shown the image the south pole of the coil. What can also be observed from the image is the difference in current measurement during forward and reverse bias. Through empirical measurements a 1 mA difference was consistently present; this is due to the location of the DMM within the circuit. The collected results for the reverse bias were all subsequently modified post data collection; i.e. 1 mA was subtracted from the measurement taken.

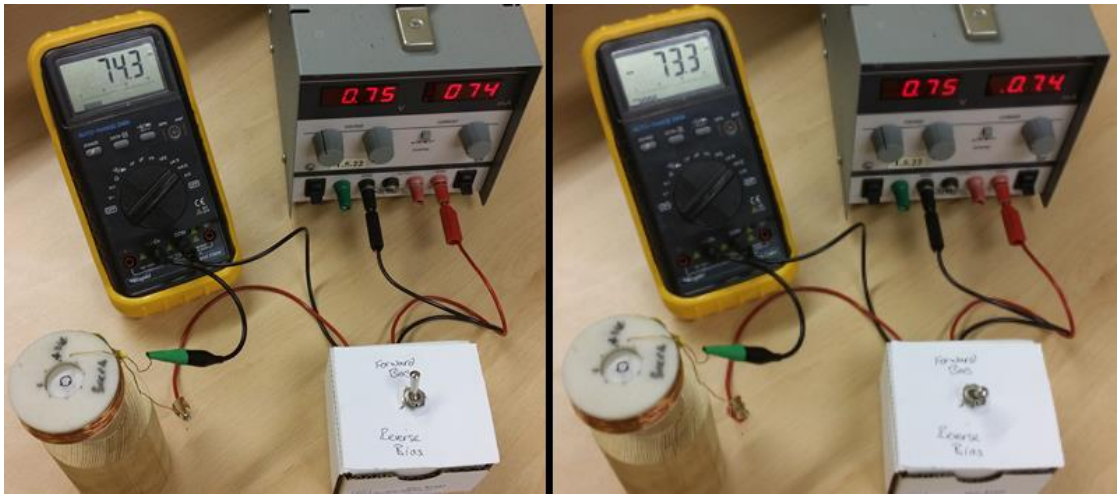


Figure 5-31: Flipping Experiment Electrical Experimental Setup. Left – Current in forward bias. Right – Current in reverse bias.

The eleven pedestals were individually set up as follows:

1. Rice paper was positioned on top of the particular pedestal Figure 5-32 (1, 2).
2. The pedestal and rice paper were then forced through the bottom of the coil. The bottom of the coil is defined here as the face of the coil, such that during forward bias, the measured B field was positive; i.e. the north pole of the coil Figure 5-32 (3).
3. Excess rice paper was then removed from the bottom edge Figure 5-32 (4).
4. The pedestal was forced downwards such that the pedestal was in-line with the outer circumference of the coil Figure 5-32 (5). In this position the platform (shown in Figure 5-28) of the 10.5 mm pedestal was approximately in the coil centre.
5. In order to correctly align the magnet to the coils centre, using a template, a marker was drawn on the rice paper Figure 5-32 (6, 7).
6. The coil was positioned on the wooden holder as shown in Figure 5-31.

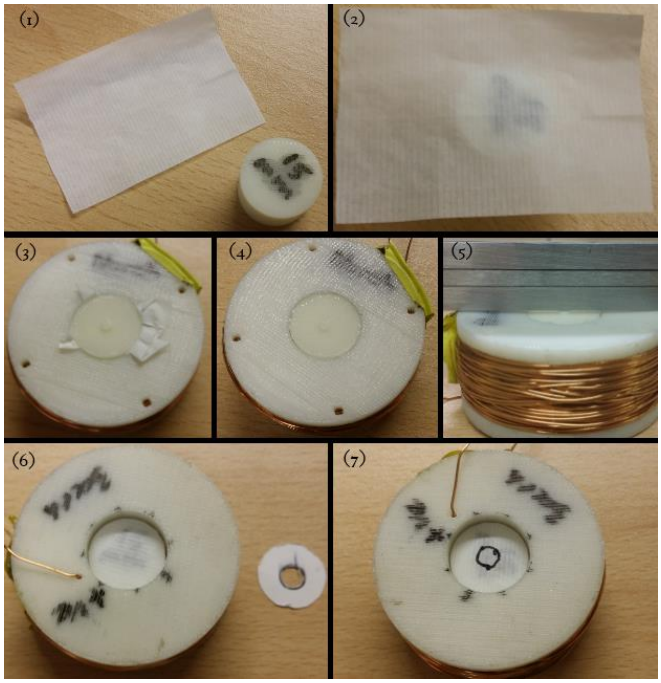


Figure 5-32: Pedestal experimental setup for flipping experiment.

The final step of the experimental setup was to simply mark the magnet on one face as to identify the orientation of the magnet after each flip.

5.7.4 Method

After ensuring the DMM was set to measure current (mA), the iterative method used within this experiment is given below:

1. The PL 154 PSU was switched off and current set by the dial to its minimum position.
2. The magnet was positioned within the centre of the coil (as shown in Figure 5-33).
3. The DPDT switch was orientated such that the direction of flow of current caused an opposite B field in the coil to that of the magnet's B field pointing downwards.
4. The PL 154 PSU was switched on and slowly the current was increased by hand, until the point at which the magnet flipped.
5. At the flipping point the current measured by the DMM was recorded.
6. Points 1 through 5 were repeated 10 times per orientation of the magnet; i.e. 10 positive and 10 negative current values per pedestal.
7. The pedestal was changed following the experimental setup as presented in section 5.7.3 until each of the 11 pedestals had been examined.

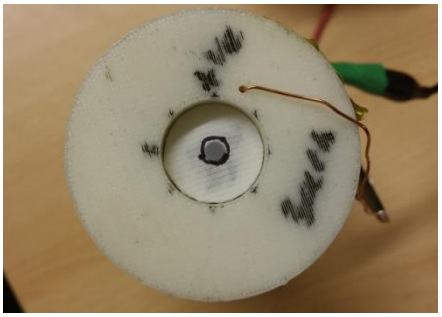


Figure 5-33: Magnet position for flipping experiment

5.7.5 Results and Discussion

The current required to flip the magnet at various pedestal heights in both forward and reverse bias are shown in Figure 5-34.

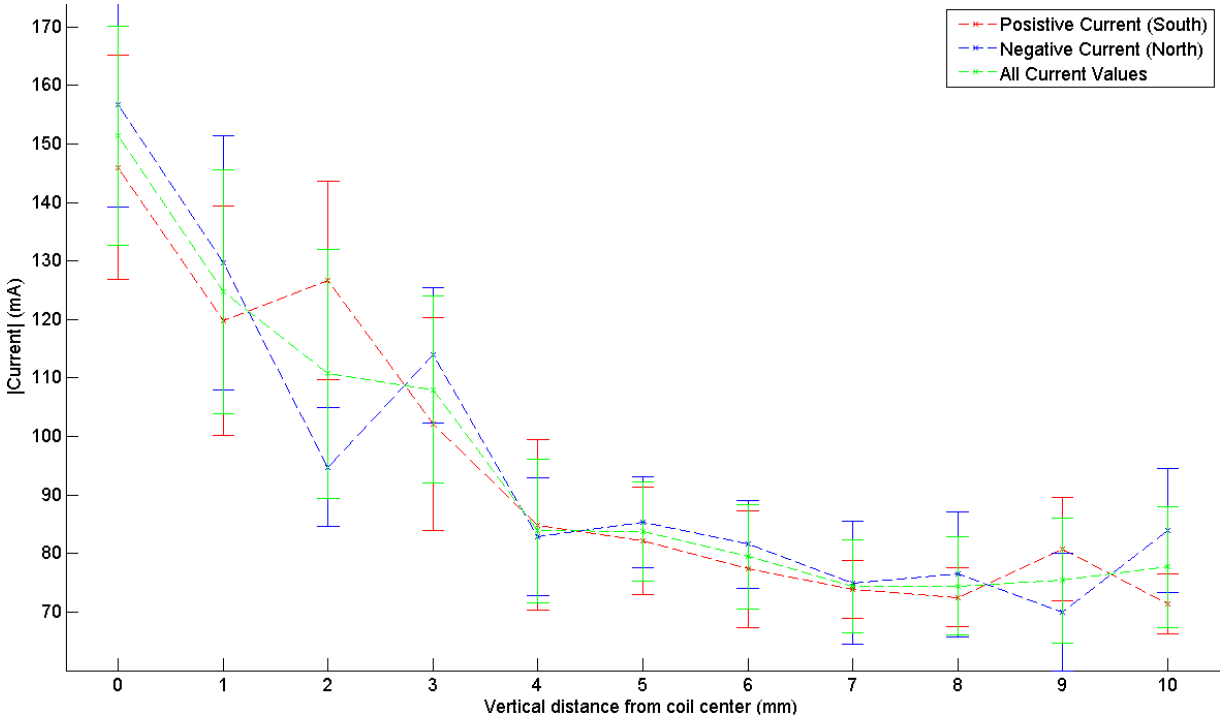


Figure 5-34: The current supplied to the coil in order to flip the magnet, in forward (positive) and reverse (negative) bias, at various heights (i.e. pedestal heights) within the created coil. The error bars shown represent the standard deviation of each of the data sets.

5.7.5.1 *Errors in recorded data*

The differences in the forward and reverse bias current required to flip the magnet can be attributed to a number of factors.

5.7.5.1.1 Position of the magnet within the coil per trial

Whilst the position of the magnet was attempted to be controlled with a marked area on the pedestal; the accuracy of the position per trial was not 100% accurate. As shown in the results from the FEMM modelling (Figure 5-15) the B field of the coil increases in an exponential manner from the coil centre to the inner coil wall. Inaccurate positioning would have an effect on B field, and thus affect the force applied to the magnet. In doing so, the force applied to one side of the magnet would be greater than the other, and rather than flipping the magnet would simply pivot about the weaker force as illustrated in Figure 5-35.

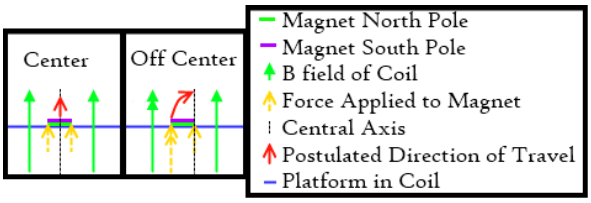


Figure 5-35: Postulated direction of travel of the magnet if positioned out of the coils centre.

5.7.5.1.2 The B field and flux lines of the created coil

The recorded values of the B field within the coils centre are shown in Figure 5-21. As the heights of the pedestals were not perfect B field recordings were recorded on the surface of them using a similar technique shown in section 5.5.3.3. To obtain these recordings the height Instron was finely reduced, such that the probe rested on the pedestals surface. The results for which are shown in Table 5-4.

VDFCC (mm)	0	1	2	3	4	5	6	7	8	9	10
DPH (mm)	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5
|B| field (mT) RB	16.9	16.7	16.3	15.8	15.3	14.6	14	13.2	12.4	11.5	10.7
|B| field (mT) FB	17	16.8	16.6	16.1	15.5	14.9	14.2	13.4	12.6	11.9	11
|B| field (mT) Avg.	16.95	16.75	16.45	15.95	15.4	14.75	14.1	13.3	12.5	11.7	10.85

Table 5-4: Recorded B field measurements on the surface of the pedestals with a current of ±1 A applied through the coil. VDFCC – Vertical Distance from Coil Centre. DPH – Designed Pedestal Height. RB – Reverse Bias (i.e. negative current through the coil, creating a north pole at measurement location). FB – Forward Bias (i.e. positive current through the coil, creating a south pole at measurement location).

These discrepancies shown in the B field of the coil give reason as to why there is a different magnitude of current required to flip the magnet in forward and reverse bias. To clarify the force required to flip the magnet is proportional to the B fields; in order to

match the magnitudes of the B fields, with the discrepancies shown in the coil (due to as previously mentioned, the non-uniform coil windings), the current in each direction would have to attain the same magnitude of B field. Hence which indicates the required increase in negative current is shown at vertical distance between 0 – 1 mm.

As stated previously the non-uniform winding presumably affect the measured B field along the central axis. Based upon this assumption the windings would likely produce a non-uniform B field also. Figure 5-15 (Type 2) shows the FEMM analysis of the measured coil, in this diagram, the flux lines are shown to be symmetrical at the coils centre. However in the case of the created coil, the assumption made, based on the differences in the forward a reverse bias recordings shown in Figure 5-20 is that, the flux lines are not perfectly symmetrical.

This could further provide reason as to why at the result at the 2 mm vertical distance from the centre of the coil shown in Figure 5-34 (recorded with the 12.5 mm pedestal, shown in Table 5-4), is so; potentially this is the point at which the non-uniformity in the flux lines is greatest, and as the vertical distance increases from this point the flux lines predictably become more uniform. This uniformity postulation is reinforced with the results shown between 4 mm and 8 mm. The result shown at 9 mm is likely due to this location now being out of the coil windings, which is thought to be another location as to where the flux lines are non-uniform as they begin to curl around the edge of the coil windings.

The mean current required to flip the magnet at each vertical distance from the coil centre (Figure 5-34), has been multiplied by the B Field recordings presented in Table 5-4 respectively (reverse bias current * reverse bias B field recordings, etc.). This thus provides the B field required at each pedestal height to flip the magnet, the results of which are presented in Figure 5-36 as well as a cross comparison to the mean currents (i.e. the interpolated lines) in Figure 5-34.

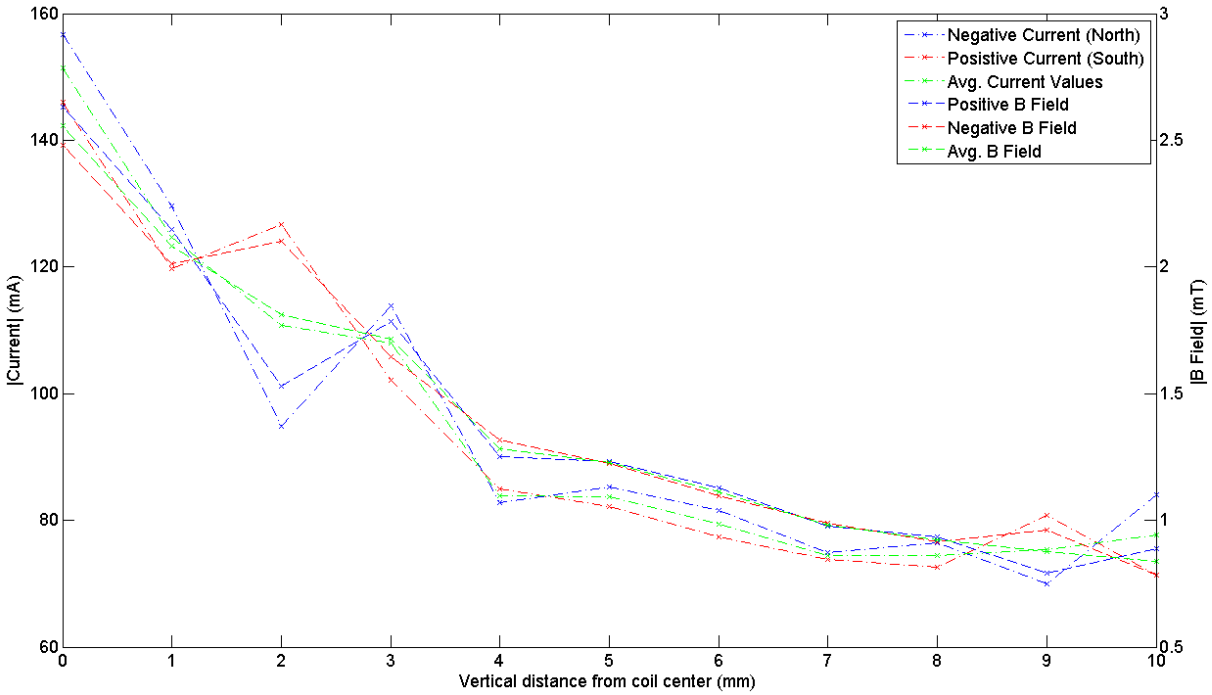


Figure 5-36: The current supplied to the coil and induced B field in order to flip the magnet, in forward (positive) and reverse (negative) bias, at various heights (i.e. pedestal heights) within the created coil.

5.7.5.1.3 Observation Error in Instrument Operation and Measurement Recording

Whilst the previously mention factors affect the measurements recorded, the most prominent factor comes from simply human error. Exploring the methodology used to conduct this experiment there are three main areas at which human error occurs. The first is the previously mentioned position of the magnet within the coil per trial. The remaining two errors that could have occurred are the measurement recording and the fine movement of the current dial on the TTi PL 154 PSU. The current measurement was recorded at the point of flipping, however as stated in section 4.4.2 and explored within the experimentation of this research (section 7.4) the human RT for the visual system differs significantly between objects in the visual focal area and that of the periphery. This coupled with the continuous movement of the current dial suggests that the current recorded was always higher than that needed to flip the magnet.

5.7.5.2 *Proportionality Variable relating Flipping Force and Current*

Equation 5.8 can be rewritten as follows:

$$\frac{\overrightarrow{F_2}(x)}{\vec{I}} \cong K(x) \tag{5.10}$$

where $\overrightarrow{F_2}(x)$ and $\vec{I}$ remained the force acting upon the magnet and the current respectively, $K(x)$ represents the proportionality variable dependent upon the vertical distance along the central axis. The variable $K(x)$ is simply the reciprocal of the results presented in Figure 5-34, multiplied by the coil's force due to gravity (shown in equation 5.7) which as stated previously is 4.3326*10^-4. The results of which are presented in Figure 5-37.

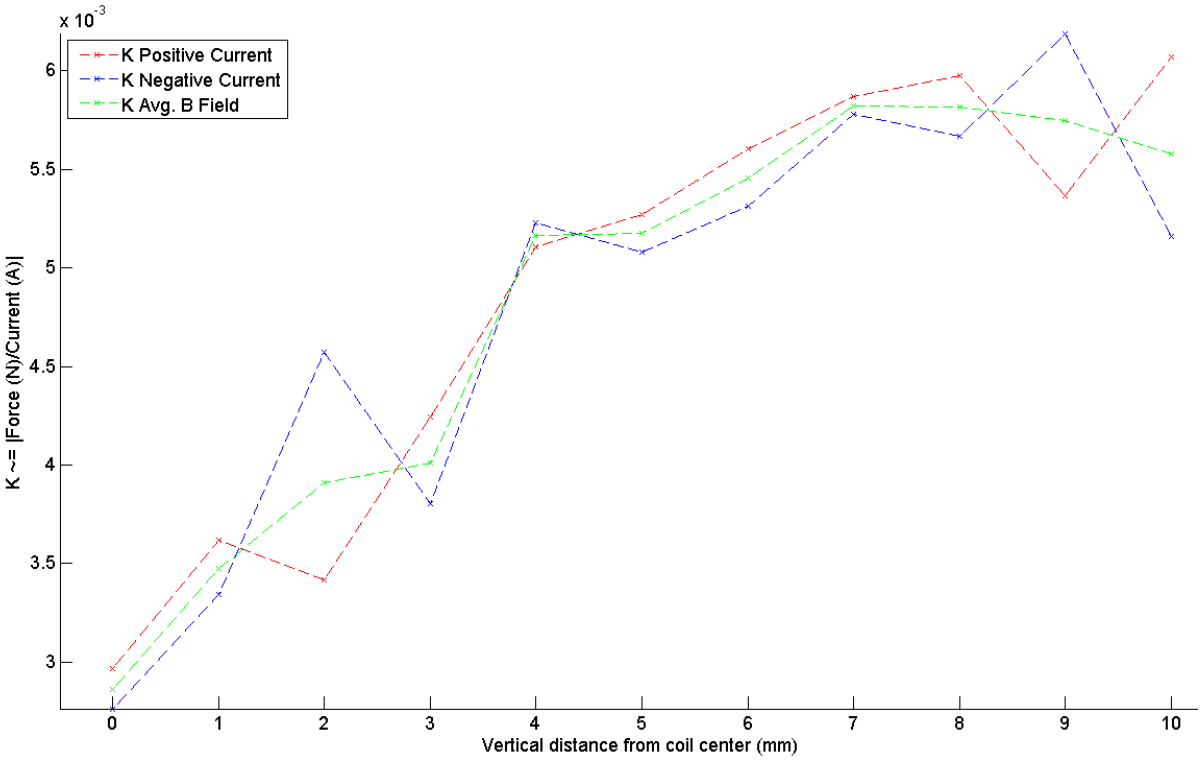


Figure 5-37: The proportionality constant K relating coil's current in forward (positive) and reverse (negative) bias, at various heights (i.e. pedestal heights) within the created coil, to the force required to flip the magnet. N.B. Current is presented in Amps.

The aim of this experiment was to approximately determine the minimum force required for stimulation due to the movement of the magnet (i.e. MIVS). Taking an average of the proportionality variable presented in Figure 5-37, K ≈ $4.6*10^{-3}$. As an example the author required the current through the coil to be 0.884 mA (RMS) with a 200 Hz sine wave in order to perceive stimulation. This was found using the amplitude detection methodology explained in section 7.5.2 and the results of which are presented in section 8.2.2. From the approximate K value obtained from this flipping magnets experiment, the estimated force required for the author to perceive a 200 Hz sinewave is estimated at ~$4*10^{-6}$ N. This result is smaller than the results obtained by Israr *et al.* [148]

who presented absolute intensity RL of $2.7*10^{-4}$ N. This is presumably due to the increase in inertial force from the surface skin tension in comparison to the soft tissue inertial force.

Whilst the factors shown in section 5.7.5.1 would have affected the recordings, the aim of this experiment was to attain an indication of the approximate force applied to the magnet in respect to the current supplied to the coil. This experiment has been conducted in order to approximate the outcome of the amplitude detection experiment (section 7.5.2) in terms of force. In order to accurately measure this force a proposed method would be to use a fine linear newton meter attached to a long Perspex rod and a magnet attached to the rod. Positioning the magnet a various points long the central axis and using a computer to control a PSU record the data from the newton meter. This would accurately measure both the current supplied to the coil and the force of the interaction. This method is further proposed in section 10.6.5.2 as future work for this research.

5.8 Summary

This chapter covers many topics regarding; SMIs, , the custom electromagnet coil constructed in order to generate the MIVS stimuli, as well as various experimentation which has been conducted surrounding these areas. In order to summarise this chapter these topics are individually discussed below.

- **A Brief History of Magnets & Their Medical Uses** – This section outlined the history of magnets from their conception and discussed their use within modern technology further focusing in on their use within orthodontics. Within this section is a brief review of research conducted in order to determine the cytotoxicity effects of neodymium magnets. Of the research reviewed there are contrasting results as to these effects, future work within for this research will aim to determine the cytotoxicity of SMIs (discussed in section 10.6.4).
- **The Author's SMIs** – This section briefly outlined the rationale for the author's SMIs with regards to; the magnets' dimensional properties and profile, their material properties and the choice of location for each of them. The section furthered by outlining the methodology as to the implantation procedure itself.
- **Explantation** – This section described five known cases to the author of individuals who have undergone the explantation procedure of SMIs, in which each individual

explains their reasons for doing so. Of the five cases described within the section, the author provides his personal views with respect to precautionary guidance advice regarding SMIs. Further summary of this section can be found in 5.4.4.

- **Stimulation Coil Creation** – This section described the device created in order to provide MIVS; which has been used throughout the experimentation presented in Chapter 6 and Chapter 7. This section began by describing the design process and rationale, and furthers by evaluating the created coil's B field both empirically and theoretically. As discussed within the analysis of the B field results and through observation of the coil itself, the coil windings are not entirely uniform. Whilst this non-uniformity slightly affected the B field generated by the coil; the coil itself has been merely used as a tool throughout the experimentation, to which it performed as desired. The measured magnitude of the B field created coil's centre was ~16.9 mT when provided with a 1 A DC current.
- **Surface Magnetism Experimentation** – This section discussed an experiment conducted in order to determine the orientation of the authors implanted magnet within his left index finger pad. This has been achieved through analysis of multiple superficial B field measurements on the dermis surrounding the implant. Through observation of the experimental results the estimated orientation of the magnet is vertical, such that the cylindrical face of the magnet is perpendicular to the surface of the skin.
- **Approximation of Force Applied upon the Magnet from the Coil (The Flipping Experiment)** – This section presented an experimental approach conducted in order to give indication as to the approximate force which is applied to the magnet from the created electromagnetic coil. The result of which has been used to approximate the results of the amplitude detection experiment (section 7.5.2) in terms of force. With the use of the author's experimental results from the amplitude detection experiment conducted within this research (described in section 7.5.2); the estimated force required for the author to perceive the MIVS stimuli, is ~$4*10^{-6}$ N.

Chapter 6 – Initial Investigation

6.1 Introduction

The main aim of this research is to ascertain any perceptual benefits of subdermal magnetic implants, SMIs to superficially attached magnets, with a further aim to utilise MIVS as form of human machine interface for situations such as high stress scenarios in driving automotive vehicles as described in section 3.3.3. In order to determine any perceptual benefits a variety of perception based experimentation has been conducted.

The initial investigation described in this chapter provides preliminary perceptual experiments regarding the thresholds (section 4.3.1.1) of vibrotactile perception using MIVS. Whilst research relating to vibrotactile thresholds has been examined by a variety of authors, as stated previously, to the author's knowledge, no such research has been conducted in this area using MIVS and SMIs as the form of stimulation.

The experiments described here are preliminary experiments self-conducted by the author using MIVS upon his SMI located in his index finger pad. The experiments conducted aim to determine the frequency discrimination threshold (i.e. frequency DL) and temporal gap detection threshold (i.e. temporal gap RL) of the author using this MIVS method.

The force used in order to provide this MIVS was generated using the custom made stimulation coil, and powered using an IMG STA-235 professional audio amplifier [213] (as previously described in section 5.5). By using computer generated signals of varying frequency, length and amplitude to the coil, different MIVS are perceived. It is this variation in perception that will be used to create the human machine interface for application purposes.

Both experiments conducted used non-adaptive psychometric methods otherwise known as classical methods (section 4.3.1.2). This chapter presents the experimental setup

and introduces each experiment individually in terms of its method, rationale, results and discussion. The knowledge gained from these initial investigations ultimately aided in the rationale and methodology for the participant experimentation presented in Chapter 7.

6.2 Experimental Setup

The two experiments in this initial investigation used the same experimental setup, which is described as follows.

6.2.1 Setting up the PC and Power Amplifier

In order to power the electromagnetic coil (described in section 5.5) a power amplifier was used. The one chosen was (as stated previously) the IMG Stage Line STA-235 stereo professional audio amplifier [213]. This received input from the test signals generated from a PC. The test signals varied per test and are described in terms of properties in each of the experiment sections within this chapter. In order to connect the amplifier and the PC, the lineout/headphone socket from the PC audio card was connected to the input of the amplifier, via a standard shielded audio cable. The left channel output of the amplifier was directly connected to the electromagnetic coil using standard electrical cabling, as shown in Figure 6-1.

Precautions were taken with the audio output from the PC with respects to unwanted noise, such as operating systems alerts tones. Software based volume mixers are generally provided to all modern PC operating systems, which displays all audio outputs that are currently connected to the PCs mixer. Using this volume mixer only the wanted audio output i.e. the stimulation signal, was outputted. To prevent crosstalk noise the audio cable from the PC to the power amplifier was kept far away from any mains power cables, as this could have induced an unwanted 50 Hz signal from the mains power supply. A photo of the setup is shown in Figure 6-1.

Figure 6-1: Power Amplifier, Audio Input Cable, Electromagnetic Coil and Power Leads for the Coil

In order to ensure that the author was comfortable with the strength of the B field (i.e. force) emitted from the electromagnetic coil, the power output from the amplifier was subjectively set using the volume dials as seen in Figure 6-1. This was done by the author being subjected to a 10-second 200 Hz sine wave signal, during which time he adjusted the power output using the dial on the front of the amplifier. The signal was produced using Matlab. The amplitude of the generated signal was set to 1, and the volume mixer was set to maximum.

6.2.2 Finger/Hand position for the author for EMF stimulation

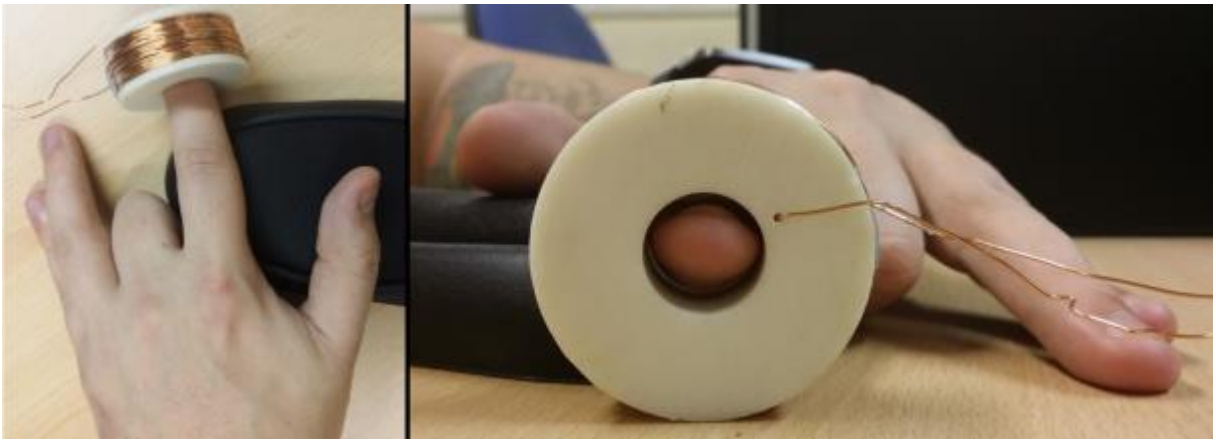


Figure 6-2: Author hand (left) and Finger (right) position within the electromagnetic coil

During each experiment within the initial investigation, the author used his index finger to receive the MIVS. In order to ensure that only his index finger was stimulated,

as opposed to both his index finger and his middle finger, his hand was orientated in a similar position to that shown in Figure 6-2 (left). In order to ensure that the movement of the magnet was not dampened, the author kept his fingernail in contact with the top of the inner face of the coil. Figure 6-2 (right) shows a front view of the coil with approximate position of the author's finger within the coil.

6.3 Frequency Discrimination

6.3.1 Introduction and Rationale

Frequency discrimination is a standard thresholding experiment that has been conducted by many authors with regards to vibrotactile stimulation; the review of which is presented in section 4.4.5. The aim of the experiment was to determine the frequency difference limen, DL of the author using MIVS. The initial purpose of which was to use the determined threshold for the creation of alert signals that vary in frequency in order to relay information.

Within this experiment 4 baseline (aka standard) frequencies were used. These are 20 Hz, 50 Hz, 100 Hz and 200 Hz, and were chosen in order to cross reference previous research results conducted in this area (section 4.4.5). A baseline frequency in this context is the frequency at which the minimum changes are positively measured from. For example, an individual may with frequency DL of 4 Hz at a baseline of 20 Hz, would be able to distinguish between 20 and 24 Hz. In order to obtain this threshold the experiment conducted used the method of constant stimuli with a 1AFC same-different task paradigm (section 4.3.1.2).

However within this experiment frequency was not only variable. The waveform of the input signal was also tested as a variable to determine if a waveform affects frequency DL. The three waveforms selected were sine, square and sawtooth. This was postulated as a possible factor that could be altered in created varied tactile signals by Goff in 1967 [161]. Whilst waveform alteration has been tested in frequency discrimination experiments (as discussed in section 4.4.5), to the authors knowledge the waveforms tested here are, novel for this task. The hypothesis behind testing these particular waveforms is that the complex waveforms (square and sawtooth) will alter the frequency DL at lower frequency baselines (20 and 50 Hz), due to their harmonic properties.

Square and sawtooth waveforms as describe by Fourier's theorem are comprised from the addition of multiple component sine and cosine signals, known as harmonics. The first harmonic of a periodic signal is referred to as F_0. F_0 is equal to 1 over the time period of the signal. It is also referred to as the fundamental frequency. Within a sine wave there is only one harmonic, whereas square waves and sawtooth waves have multiple harmonics see Figure 6-3.

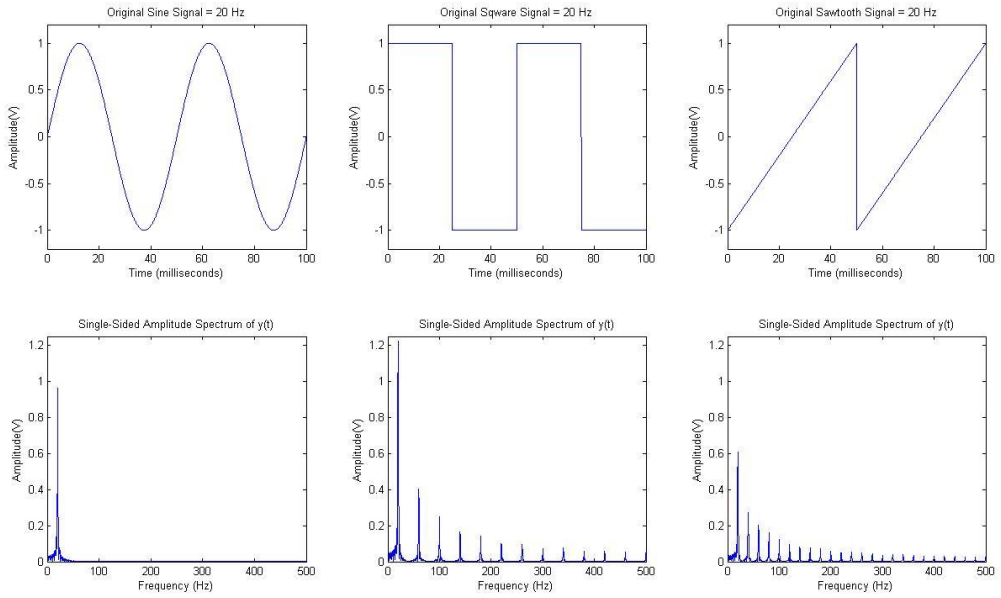


Figure 6-3: Time Domain and Frequency Domain representations of a Sine, Square and Sawtooth Signal with a Frequency (F_0) 20 Hz

The rationale behind testing multiple waveforms is that not only the fundamental frequency will be transferred to the dermis but the harmonics will be as well. This in turn at lower frequencies should not only stimulate the RA1 receptors but the RA2 receptors, due to the receptors frequency response range (described in section 4.2.1). This in turn is hypothesised to increase the ability to discriminate frequencies at lower frequencies (i.e. 20 and 50 Hz) and not the higher ones (100 and 200 Hz).

After completing the experimental setup and following the finger hand placement guidelines outline in section 6.2, the experiment was conducted following the method described in the following section.

6.3.2 Method

As stated previously the method is based on is the method of constant stimuli using a 1AFC same-different task paradigm, as discussed in section 4.3.1.2. As 4 baseline frequencies were examined along with three waveforms, in total this experiment consisted of 12 tests.

Tests are grouped by baseline frequency. Each test's trial consists of a signal being passed to the electromagnetic coil, perceived by the author through MIVS. The signal passed consists of two, 1 second signals with a 300 ms gap between them.

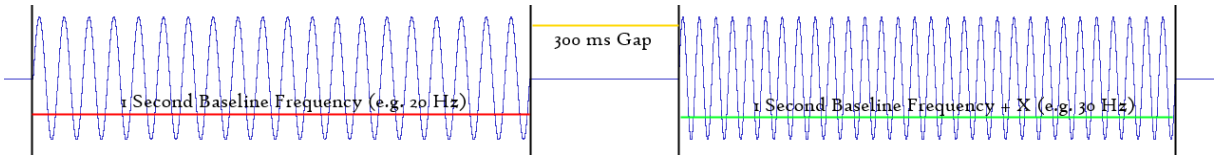


Figure 6-4: Frequency Discrimination Signal Example

The first signal contains the baseline frequency and the second signal the baseline frequency plus X, Figure 6-4 shows for a graphical representation of a trial signal. The lists of X values for each of the baseline frequencies are shown in Table 6-1. After each trial, the author has to decide whether signal 2 was the same or different in terms of frequency to signal 1, i.e. a 1AFC same-different task. After which point the response is documented, noting 0 for same and 1 for different (i.e. higher).

	Baseline Frequency (Hz)			
X Value Count	20 (Baseline + X)	50 (Baseline + X)	100 (Baseline + X)	200 (Baseline + X)
1	0 (20)	0 (50)	0 (100)	0 (200)
2	4 (24)	5 (55)	25 (125)	25 (225)
3	8 (28)	10 (60)	50 (150)	50 (250)
4	12 (32)	15 (65)	75 (175)	75 (275)
5	16 (36)	20 (70)	100 (200)	100 (300)
6	20 (40)	25 (75)		
7		30 (80)		
8		40 (90)		
9		50 (100)		

Table 6-1: Baseline Frequencies and the number/values of threshold frequencies that were tested

Each test consisted of ten times the number of X values (shown in Table 6-1) for a given baseline frequency, as summarised in Table 6-2. For example for the baseline frequency 20 Hz, using the sine waveform, there were 6 X values, so there were 60 trials for that particular baseline. In total there were 180 trials for the 20 Hz baseline.

Baseline Frequency (Hz)	20	50	100	200
Number Of X Values	6	9	5	5
Test Trial Number per Waveform	60	90	50	50
Total Trial Number	180	270	150	150
			Total Trials	750

Table 6-2: Trial Number Breakdown for the Frequency Discrimination Test

Each test signal was created using Matlab and exported as wav files. A playlist of these wav files was then randomly generated such that the author did not know the order in which they were played. After each test was completed the order of the wav files was then noted down.

The experiment was conducted using an open source media player called, VLC. For clarification the step by step method for each of the 12 tests, (4 baseline frequencies, each with 3 waveforms) was as follows:

1. The random stimulation signal containing the baseline frequency signal and the comparison signal (baseline + X) was transmitted into the authors finger.
2. The author decided signal 2 was the same or different in terms of frequency to signal 1, recording 0 for same and 1 for different (higher) in a list.
3. Steps 1 and 2 were repeated the appropriate number of times for the baseline, e.g. 90 trials for a 50 Hz baseline (Table 6-2).
4. The order of the random playlist was recorded.
5. The list from step 2 was cross-referenced with the order of play from step 4 and each frequency comparison was expressed as a percentage of difference.

6.3.3 Results and Discussion

The results from each of the 4 baseline frequencies, 20 Hz, 50 Hz, 100 Hz and 200 Hz are presented as the mean result for each X value in Figure 6-5, Figure 6-6, Figure 6-7 and Figure 6-8 respectively. The tables of raw data recorded can be found in Appendix F.

Each diagram presents the 'percentage of higher response' vs. X (i.e. the frequency change). Solid, straight interpolation lines are used to show the progression of each waveform as frequency changes. Limited trial numbers per frequency change prevented accurate psychometric functions, PFs to be fitted to this data. Despite this, approximations of the underlying PFs are noticeable and have been illustrated as dashed lines within each graph; each was created using the logistical regression function in SPSS.

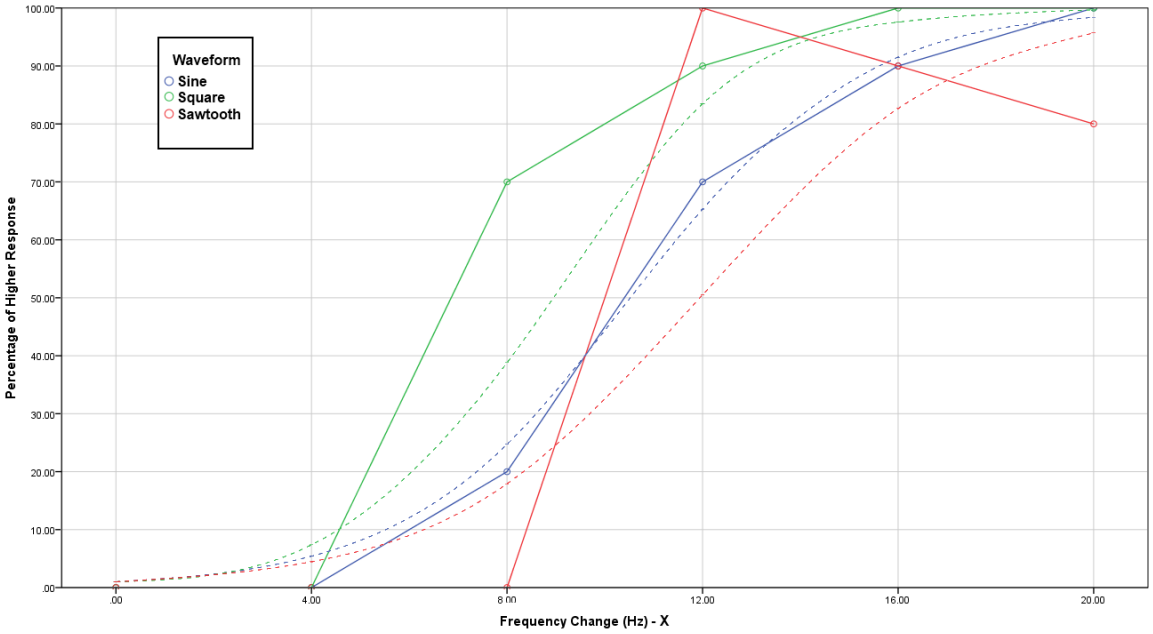


Figure 6-5: 20 Hz Frequency Discrimination results for varying waveform

Figure 6-5 presents the results of the 20 Hz (baseline) frequency DL experiment. The raw data shown suggests that the square waveform enables the greatest frequency discrimination (for the author at 20 Hz); which furthermore suggests that both the square and sawtooth waveforms enable greater frequency discrimination when compared to sine (observed at the DL threshold of 50%). An example of where the limited trial number affects the fitting of a psychometric function is shown in the sawtooth waveform approximation. This is due to the perceptual responses (from the author) at 16 and 20 Hz, and the instantaneous change from 0 % at 8 Hz to 100 % at 12 Hz. It is expected with increased trials that both 16 and 20 Hz would tend towards 100% where 8 and 12 Hz would tend towards the central area.

Figure 6-6 displays the results of the 50 Hz (baseline) frequency DL experiment. Similarly to the 20 Hz results the data suggests that square and sawtooth waveforms enable greater frequency discrimination over sine (in the case of the author). As opposed to the results of the 20 Hz experiment, the sawtooth waveform at this frequency baseline enabled the greatest frequency discrimination threshold when observed at a percentage accuracy of 50%. With an increased trial number it is expected that the results of the square and sine waveforms from 25 Hz onwards would further tend towards 100%.

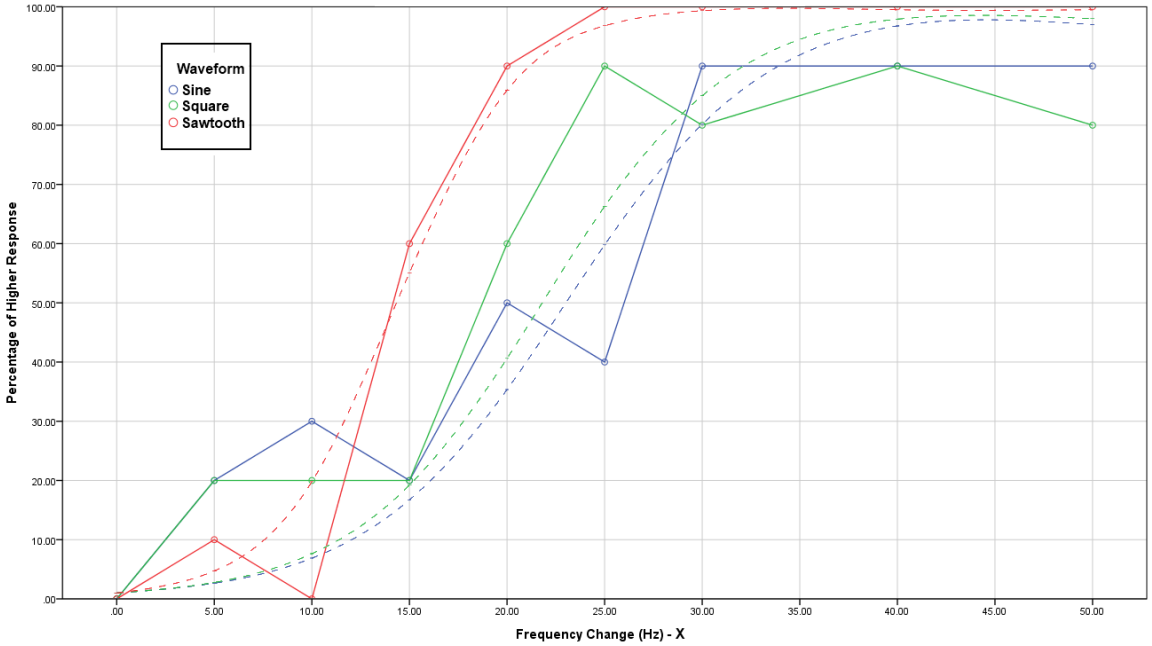


Figure 6-6: 50 Hz Frequency Discrimination results for varying waveform

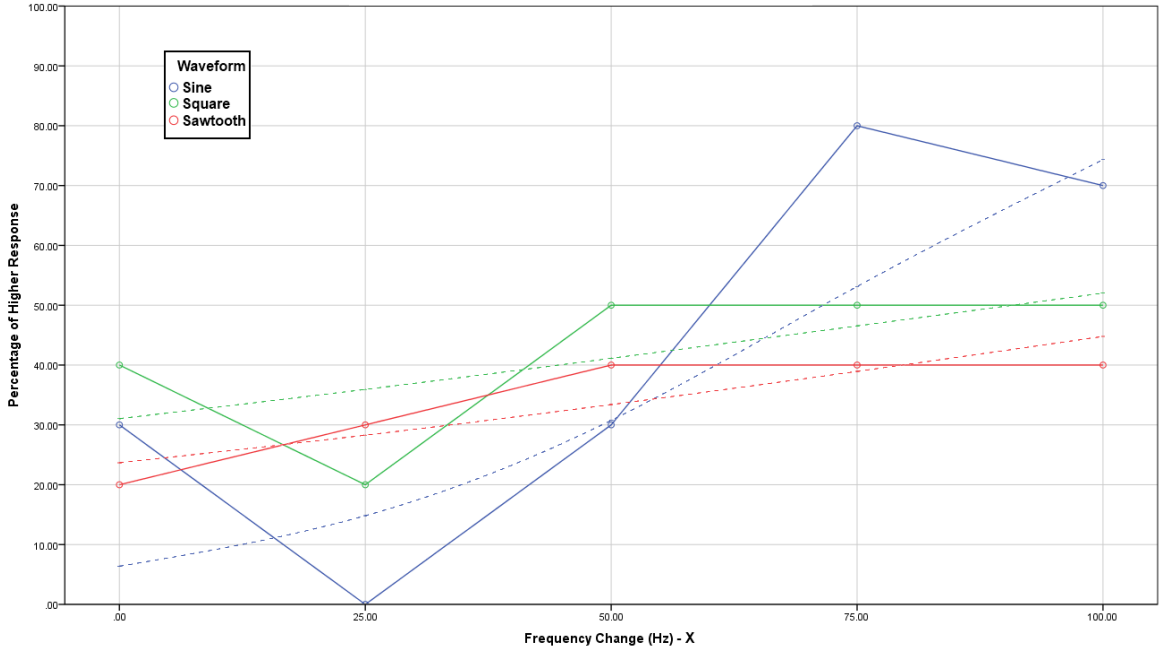


Figure 6-7: 100 Hz Frequency Discrimination results for varying waveform

Figure 6-7 presents the results from the 100 Hz (baseline) frequency DL experiment. It is clear from these results that this task for the author proved to be rather complicated. A possible rationale for these results would come from the overlapping of the susceptible frequency range of the rapidly adapting mechanoreceptors; i.e. the Meissner corpuscle and Pacinian corpuscle. The optimum receptive range for the Meissner corpuscle is 20-40 Hz

though it has a range of 10-200 Hz. The optimum range for the Pacinian corpuscles is 200-300 Hz and its range is 40-800 Hz (see Table 4-2).

The magnet is implanted within the skin of the finger pad; however no correct measurement for its depth has been established. The depth of the dermis is estimated to be ~2.4 mm [228]. The knowledge of the implant procedure explained in section 5.3.3 has led to the assumption that the magnet lies below the dermis; which also means the vibration from the MIVS is travelling through the cutaneous mechanoreceptors in the opposite way to standard tactile stimulation. This crossover in frequency range, along with the magnets position in the dermis, could potentially being to explain confusion in perception.

Similar observations have previously been seen by Sherrick; 'Goff (1967) [161] reviewed Sherrick (1952) by stating "... that frequency discrimination is poor above 100 Hz and relatively good below 100 Hz"'.

This experiment is similarly repeated in section 7.5.2 with both implanted and superficial participants. The results of which will potentially identify whether or not the location of the magnet affects an individual's ability to discriminate frequency at the 100 Hz baseline.

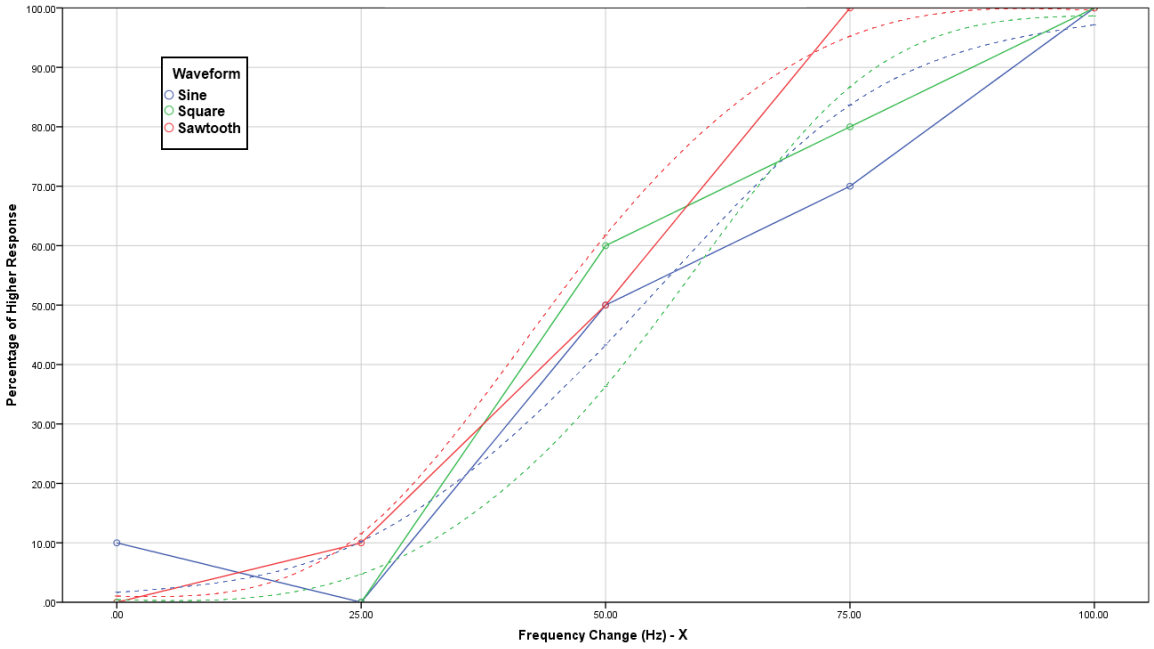


Figure 6-8: 200Hz Frequency Discrimination results for varying waveform

Figure 6-8 presents the results from the 200 Hz (baseline) frequency DL experiment. Within this graph the frequency discrimination variation between waveforms is minimal. At the 50% point of recognition the square waves, shows the greatest discrimination. DL values are also often recorded at the 75% perceptual values. In which case, purely from the raw data, the sawtooth waveform appears to give the greatest frequency discrimination.

The hypothesis for these tests was that multiple waveforms would alter frequency discrimination thresholds as defined in section 6.3.1. The results indicate an increase in frequency discrimination capabilities at lower frequencies as predicted. However as these observations are based on straight interpolation lines and not the actual underlying PFs, this analysis is purely speculative.

The approximated Weber fractions in Table 6-3 were not determined at 100 Hz as there was no indication that the test was completed properly. Comparing these results to that obtain by previous authors, the Weber fractions values here are higher than that of Goff [161] and Mahns *et al.* [145] (see section 4.4.5). The Weber fractions obtained by Mahns *et al.* were: 0.32, 0.19 and 0.14 for the 20 Hz, 50 Hz and 200 Hz respectively. However these were obtained using a 2AFC experiment. Altering the test methodology (section 4.3.1.2) has been empirically shown to alter perceptual thresholding experiments, similar to the continuous vs gated pedestal point discussed in section 4.4.4.

		Baseline Frequency		
Waveform	**Data Line**	**20 Hz**	**50 Hz**	**200 Hz**
Sine	**Interpolated Line**	0.53	0.41	0.25
	Fitted PF	0.6	0.46	0.27
Square	**Interpolated Line**	0.35	0.38	0.25
	Fitted PF	0.45	0.44	0.28
Sawtooth	**Interpolated Line**	0.49	0.28	0.23
	Fitted PF	0.525	0.29	0.21

Table 6-3: Approximated Weber fractions from 20 Hz, 50 Hz and 200 Hz Frequency DL experiment taken at the 50% DL value

Though the values are larger than that presented by Mahns *et al.* [145], the trend shown is similar; i.e. as the baseline frequency increases the Weber fraction tends to decrease. Further testing using this 1AFC same different task paradigm to obtain the DL, would benefit from the following:

- A finer resolution in terms of frequency change.
- A larger number of trials per frequency change.

This experiment requires repetition with a number of participants in order to validate the hypothesis that waveform affects frequency DL. With a large trial number the time take to perform this experiment for each participant would be unfeasible; hence the QUEST method (see section 4.3.2) has been chosen in order to obtain this threshold (as described in Chapter 7).

6.4 Temporal Numerosity Discrimination With Respect to Temporal Gap Detection

6.4.1 Introduction and Rationale

The concept of sending concatenated vibration signals (further referred to as a pulses) to relay information is frequently used in applications such as mobile phones, where text messages, emails, social media etc. can be relayed this way. For instance a user may have 1 pulse for text messages, 2 pulses for emails and a continuous vibration for an incoming call. Each type of message can be assigned a different number of pulses. This allows the user to perceive what type of information has been received without having to visualise the data.

The aim of the TGD experiment is to determine the minimum time required among a varied number of short concatenated pulses, such that an individual can perceive the correct number (i.e. TND). This experiment assumes that as the time between concatenated pulses tends towards zero there is a point at which the overall signal is perceived as continuous.

The purpose of which is to provide stimulation that fulfils each of the generic criteria for a tactile alert mentioned in the chapter introduction, i.e. can be easily recognised, rapidly perceived and varied in intensity. Thus enabling a personalised varied intensity stimulus set which is recognisable to the user. Seeing that the test aims to reduce the overall signal length, the rapidly perceived requirement is fulfilled also.

Furthermore this experiment aims to determine the factors which affect the correct perception of transmitted concatenated pulses. The factors tested are as follows: pulse number (3, 4 and 5), frequency of pulse (20 Hz and 200 Hz) and pulse length. Pulse length is a variable due to the length in time required for a single period of the two different frequencies; i.e. 20 Hz having a period of 50 ms, and 200 Hz having a period of 5 ms, these

values are shown in Table 6-4. The reason for testing the two frequencies is to compare the perceptual effects of the two vibratory mechanoreceptors (the Meissner and Pacinian corpuscles) with regards to the perception of time. As discussed in section 4.4.7 increasing frequency has been shown previously to reduce the TGD threshold.

The values of separation time between the pulses (which this experiment aims to determine) were estimated without apriori knowledge and determined after exploratory experimentation. Initially both 20 Hz and 200 Hz had the same list of separation times, that is 25 ms and multiples of 25 ms up to 200 ms. However it soon became apparent that there were specific regions for both frequencies at which the correct number of pulses was recognisable.

In total there are 8 groups of TGD tests as part of this experiment. These groups are defined as a combination of both pulse number (2, 3, 4 and 5) and frequency (20 Hz and 200 Hz). Part 1 of the method describes the test procedure for the 3, 4 and 5 pulses. Part 2 describes how the experiment the procedure for the 2 pulses tests. The experimental setup is presented in section 6.2.

6.4.2 Method – Part 1

The number of trials for the three 20 Hz tests is 252, and the number of trials for the three 200 Hz tests is 154. These trial numbers are set such that each pulse length is tested against each separation time for the given frequency (see Table 6-4).

The variables for each of the stimulation signals are: pulse number, pulse length, frequency of pulses and the separation time between these pulses; which are displayed in Figure 6-9 labelled as $Y_{(1\text{-}5)}$, $Y_{(1\text{-}5)}$ length (ms), $Y_{(1\text{-}5)}$ frequency and Tx respectively. The waveform for the pulses was square, and each were created and exported as wav files using Matlab.

Within each test, pulse number, pulse length, and the frequency of the pulse remained a constant; the separation time was the test variable. The pulse numbers used were 3, 4 and 5 and the two frequencies were used 20 Hz and 200 Hz. Pulse length and separation time varied dependent upon the frequency shown in Table 6-4.

Stimulation signals for each test are again randomised in a playlist and each test is conducted using VLC. During a trial of each test, the author answered the same question,

how many pulses did you feel? Each answer is then recorded and once each test is complete the order of the playlist is recorded also.

	Frequency of Pulses (Hz)			
	20		200	
Count	Pulse Lengths (ms)	Separation Times (ms)	Pulse Lengths (ms)	Separation Times (ms)
1	50	5	25	5
2	100	7.5	50	7.5
3	150	10	100	10
4	200	12.5	150	12.5
5	250	15	200	15
6	300	20	250	20
7	350	25	300	25
8	400	30	350	50
9	450	35	400	75
10	500	40	450	100
11	1000	45	500	125
12	1500	50		150
13	2000	75		175
14	2500	100		200
15		125		
16		150		
17		175		
18		200		

Table 6-4: Pulse Lengths and Separation Times for 3, 4 and 5 Pulse TGD Experiment

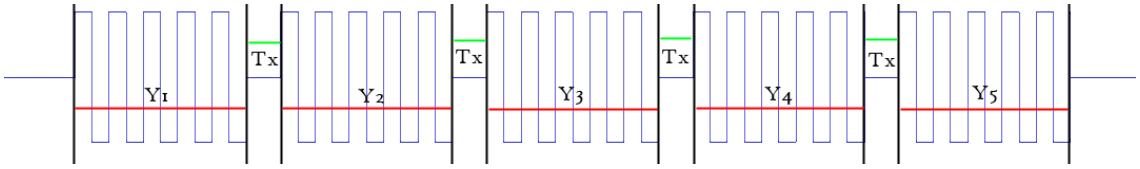


Figure 6-9: Stimulation Signal Example for Gap Time Discrimination Task

For clarification a step-by-step method for each test is given below:

1. The random stimulation signal is transmitted to the authors' fingertip via MIVS.
2. The author records how many pulses he felt. If a decision could not be made, step 1 is repeated a maximum of two times.
3. Steps 1 and 2 were repeated the appropriate number of times for the particular test, e.g. 198 for the 4 pulse, 20 Hz test.
4. The order of the random playlist is recorded.
5. The lists from step 2 and step 4 are then cross-referenced in order to create the table of results (for an example of this, see the raw data shown in Appendix G).

6.4.3 Results and Discussion – Part 1

Figure 6-10 presents the results for the 3, 4 and 5 pulse TGD experiments for both 20 and 200 Hz; each are displayed as surface plots generated using Matlab. It should be noted that the y axis, displaying the separation times (ms) of each test are not to scale. The x axis of both plots displays the pulse length of each signal. All graphs and raw data tables for this experiment are shown in full scale in Appendix G.

The colour of each block represents the perceived pulse number at that particular point, referencing the colour map on the right. For example on the 5 pulse 20 Hz experiment, the author perceived 4 pulses, with a separation time of 50 ms and each pulse being 450 ms.

With the exception of the 50 to 150 ms pulse lengths, the results of 20 Hz pulses suggest a negative regression as pulse length increases, in terms of the correct number of pulses being perceived. This regression trend is found within the 200 Hz graphs, which suggest a strong negative regression in the lower pulse lengths (i.e. 25 – 250 ms).

The results of the 200 Hz TGD tests suggest that the author required an increase in separation time in order for him to correctly discriminate the correct number of pulses. For example looking pulse length 250 ms shows the author was correct at discriminating two pulses with a separation time of 7.5 ms. However required 20 ms and 15 ms to correctly perceive 4 and 5 pulses respectively.

Results presented by Philippi *et al.* in 2008 [180] (reviewed in section 4.4.7) showed that individuals required an increase in SOI, (i.e. the separation time between pulses) as pulse number increased. This result is comparable with the results found in this experiment. Observing the 200 Hz, 3, 4 and 5 pulse results using a 25 ms pulse length (shown in Figure 6-10), the separation times recorded for correct perception were 125 ms, 150 ms and 175 ms respectively.

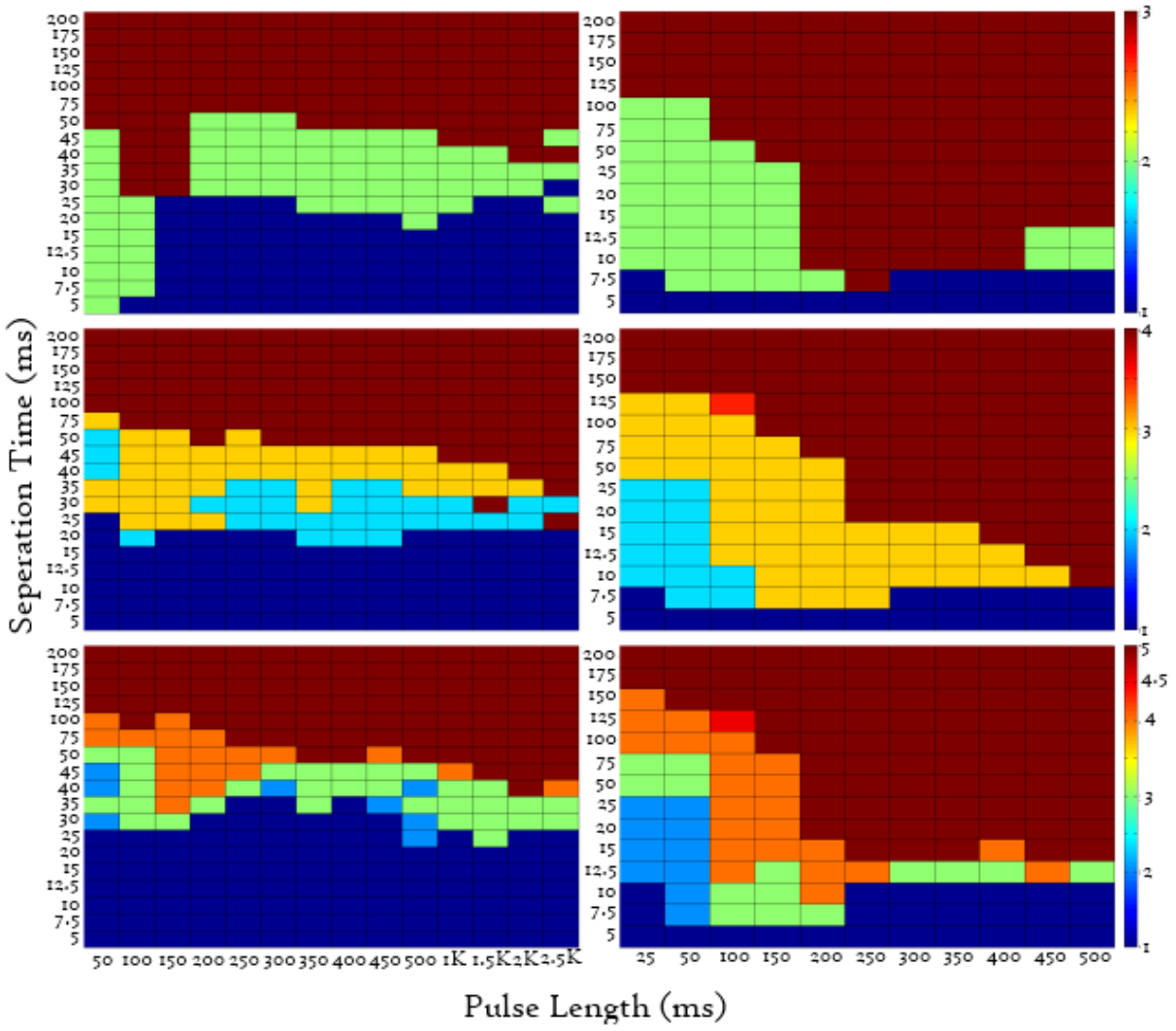


Figure 6-10: Results of the TGD in the initial investigation Part 1. The Left Column displays 20 Hz and the right column displays 200 Hz. Each row 1, 2 and 3 presents the results for the 3, 4 and 5 pulses respectively. The colour represents the number of pulses the author reported feeling.

Although this experiment has a large number of trials, it is still unclear in a lot of the cases as to where the exact threshold of separation times of the various pulse lengths lie. An example of this can be seen in the 50 ms pulse length at 20 Hz showing 5 perceived pulses at 125 ms separation time. However at 100 ms separation time the perceived number of pulses were 4. To rectify these ambiguities this experiment would need to be run using smaller separation time intervals (e.g. 2.5 ms). This however would dramatically increase the number of trials required for this particular test. As this experimental procedure would be very time demanding it has been deemed unfeasible for the participant experimentation (Chapter 7) and has been left open for future work.

6.4.4 Method – Part 2

The methodology used for the 2 pulse TGD experiment is based around a yes/no experiment, the concept of which has been presented in section 4.3.1.2. The 2 pulse TGD experiment is also tested at both 20 Hz and 200 Hz. However the number of trials varied from the part one method as each separation time for each pulse length is repeated 10 times (Table 6-5).

The results gathered from the 3, 4 and 5 pulse TGD experiments, gave indication as to the approximate location of the absolute threshold with respect to the 2 separate frequencies. Again pulse length and frequency of pulse remained a constant, and separation time was the only variable per test. The waveform of the pulses was again square.

	Frequency (Hz)		Total
	20	200	
Number of Tests Per Frequency	6	11	**17**
Trails Per Test with repeated values	150	130	**28**
Trial Per Frequency	900	1430	**2330**

Table 6-5: Number of Trials summary for the 2 Pulse TGD Experiment

	Frequency of Pulses			
	20 Hz		200 Hz	
Count	Pulse Lengths (ms)	Separation Times (ms)	Pulse Lengths (ms)	Separation Times (ms)
1	250	0	25	0
2	300	5	50	5
3	350	7.5	100	7.5
4	400	10	150	10
5	450	12.5	200	12.5
6	500	15	250	15
7		20	300	20
8		25	350	25
9		30	400	30
10		35	450	35
11		40	500	40
12		45		45
13		50		50
14		55		
15		60		

Table 6-6: Pulse Lengths and Separation Times for 2-Pulse TGD Experiment

Each test conducted followed the same pattern. Firstly the stimulation signals were created using Matlab. The stimulation signals constructed consisted of a combination of 2 pulses and a random separation time within that frequency group (see Table 6-6 for the

list of pulse lengths and separation times used). For example, one simulation signal that was applied used the following parameters: frequency 20 Hz, pulse length 300 ms and separation time 35 ms. The number of pulses (Y number) is restricted to 2. The value of the pulse lengths (Y Length) are shown in Table 6-6 along with the separation time values (Tx).

As before each of the tests were conducted using a randomised playlist and VLC. Each trial of each test, consisted of the author being subjected to a stimulation signal, after which he answered the same question, did you feel 2 pulses, yes or no? For clarification a step-by-step method of each test is given below:

1. The random stimulation signal is transmitted to the authors' fingertip via MIVS.
2. The author determined whether or not he perceived two pulses or one long pulse. These responses were recorded as a list, denoting 1, for yes (i.e. 2 two pulses) and 0, for no (i.e. 1 pulse).
3. Steps 1 and 2 were repeated the appropriate number of times for the particular test, e.g. 150 for the 450 ms pulse length test at 20 Hz.
4. The order of the random playlist is recorded.
5. The lists from step 2 and step 4 are then cross-referenced in order to create the table of results (for an example of this, see the raw data shown in Appendix H).

6.4.5 Results and Discussion – Part 2

This section presents the results for the 2 pulse TGD experiment. All plots within this section were created using SPSS. The raw data collected for these experiments are given in Appendix H. Figure 6-11 shows the results of the 20 Hz experiment. The solid interpolation lines show the progression of the raw data, and the dashed lines show an approximation of the underlying PFs that accompany each pulse length. These were generated using the logistic regression function in SPSS. For clarity the 200 Hz results are shown in 2 separate figures. Figure 6-12 and Figure 6-13 display the raw data and the approximated underlying PFs respectively.

The y-axis in Figure 6-11, Figure 6-12 and Figure 6-13 presents the percentage of trials where the author stated that he felt 2 pulses. The x-axis displays the separation time between two pulses, and the colours indicate the various pulse lengths tested. For

example, in Figure 6-12, the red line on the far left shows the raw data of the 250 ms pulse length.

The raw data in Figure 6-11 (20 Hz) shows that as the pulse length alters the percentage at which 2 pulses were reported varies with separation time. The raw data suggests the minimum separation time between 2 pulses was found, to be with a pulse length of 250 ms, when looking at the 50% rate of '2 pulses' (i.e. yes). The data suggests that as pulse length increases the separation time required for correct perception increases also, with the exception of the longest pulse length tested i.e. 500 ms.

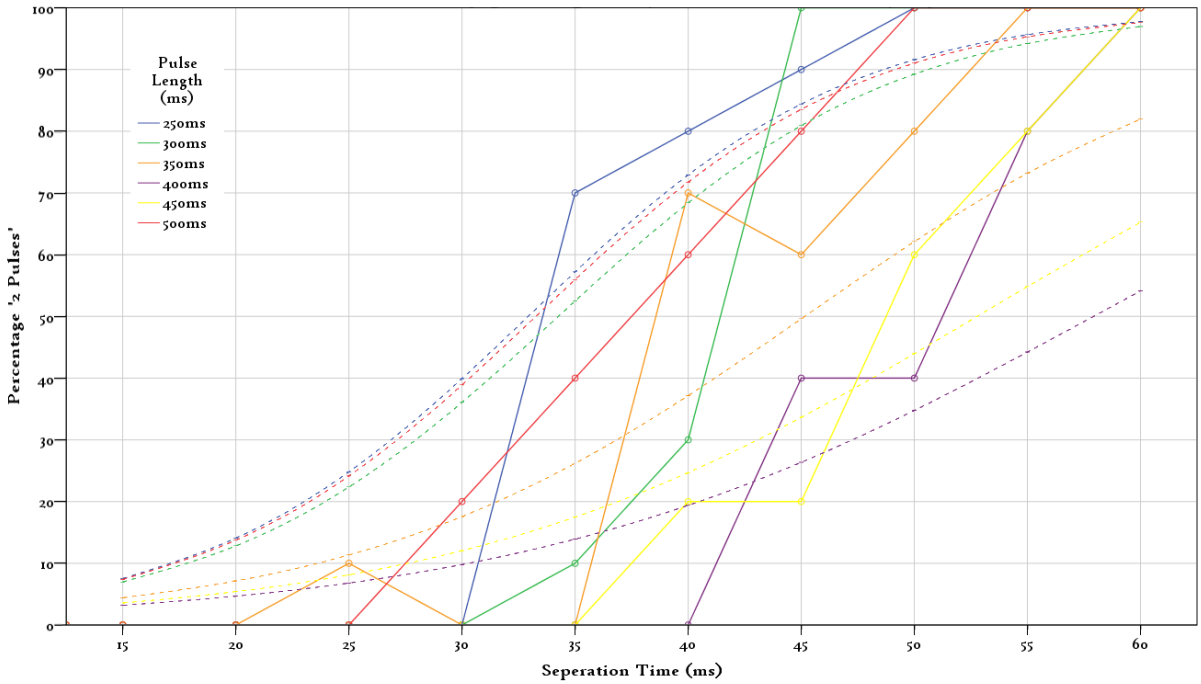


Figure 6-11: 2 Pulse Absolute Threshold for TGD varying Pulse Length and Separation Time with 20 Hz Squarewave Pulses

The PFs presented are approximation. To ascertain the true PFs would require a larger trial number as well as an increase in the separation numbers post 60 ms. In the cases of both the 400 and 450 ms pulse lengths, the 100% correct response (i.e. 2 pulses) was found at 60 ms and which caused logistic fitting function to not converge to the top asymptote. Furthermore in the case of the 350 ms pulse length, the 100% perception was only found at 2 values again causing the fitting function to not converge properly.

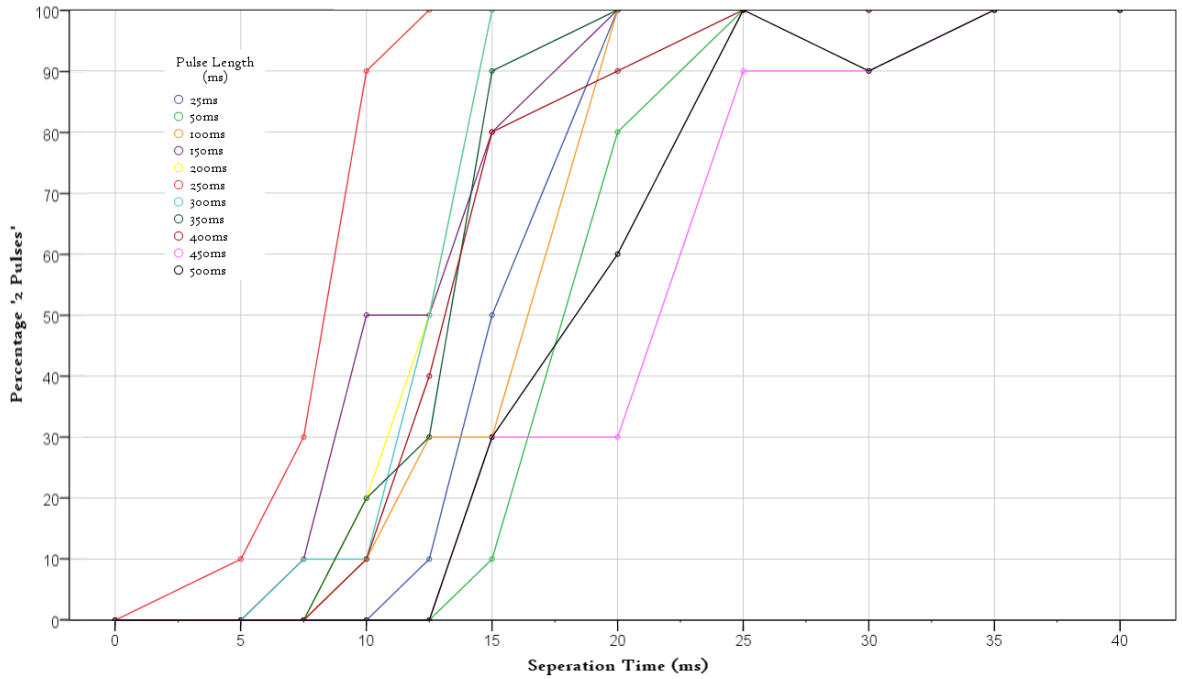


Figure 6-12: 2 Pulse Absolute Threshold for TGD varying Pulse Length and Separation Time with 200 Hz Squarewave Pulses

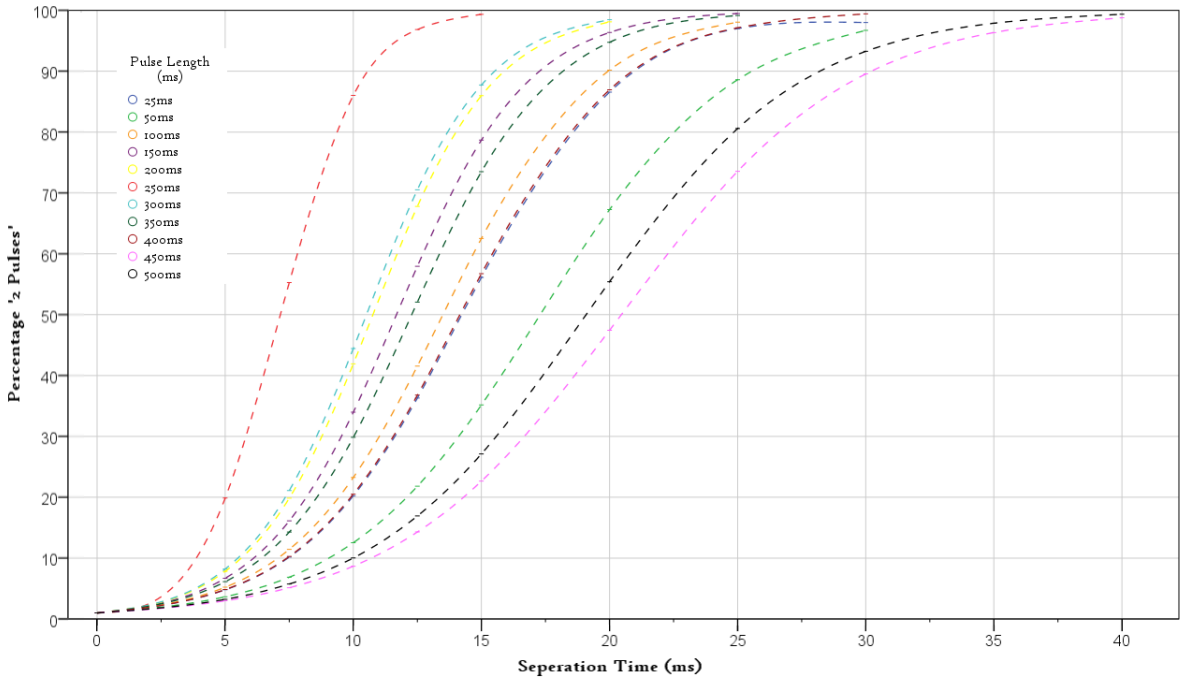


Figure 6-13: 2 Pulse Absolute Threshold for TGD varying Pulse Length and Separation Time with 20 Hz Squarewave Pulses (Displaying approximate PFs only)

Figure 6-12 (200 Hz) displays similar results to that of Figure 6-11. As the pulse length varies, the separation time varies for correct detection of the 2 pulses. Similarly to the 20 Hz results, the author required a progressively larger separation time using 200 Hz, as the

pulse length increases from 250 ms, again with the slight deviation at 500 ms. The lower pulse lengths i.e. 25 ms – 200 ms seem to show a decrease in separation time required for correct perception as pulse length increases, again with the exception of the extreme i.e. 25 ms. In other words, the raw data shows that 50, 100, 150 and 200 ms pulse lengths require decrementing separation times, 17.5, 16.25, 12.5 and 12.5 ms respectively to correctly perceive 2 pulses (which are taken as approximations at 50%).

These observations are further shown in the approximations of the PFs, Figure 6-13. Although these PFs are not the true underlying PFs, these illustrations indicate that the pulse length variation causes a change in the slope of the PFs. However as these tests again are based on a limited trial number this synopsis of the results is speculative.

Bresciani and Ernst in 2007 [186] (reviewed in section 4.4.7) presented results that showed a reduction in separation time was required as frequency increased in order for their participants to correctly determine 2 pulses. This result is comparable to that shown in this experiment, observing the 250 ms pulse length of both the 20 and 200 Hz tests; the separation times required at the JND value (i.e. 50% correct response) was ~34 ms and ~8 ms respectively (as approximated from the interpolated lines of the raw data).

6.5 Summary

Two experiments conducted on the author are presented. These were performed as an initial investigation prior to the participant experimentation, Chapter 7. The two experiments that are discussed are the frequency discrimination, varying both frequency and waveform and TGD which varied in frequency, pulse length and concatenated pulse number.

Initial results seem to indicate that waveform does have an effect (in the case of the author) on the ability to discriminate frequencies. Furthermore the 100 Hz (baseline) proved to be challenging, for the author, in terms of his ability to correctly discriminate a change in frequency. An explanation as to why this occurred could be due to the frequency ranges of the mechanoreceptors (further explained in section 6.3.3).

Within the TGD experiment conducted, the results indicate that the author was affected by a number of factors in his ability to correctly determine the number of pulses

to which he was stimulated with. These factors were: the frequency of the pulses, the pulse length and the number of concatenated pulses.

In order to validate the findings of this initial investigation requires repetition from a larger sample. Therefore participants were required to conduct the experiments; however the methodologies require alteration for two main reasons. Firstly, the methods used in the initial investigation would have required a prohibitive amount of the participants' time. Secondly, the experimental technique required standardisation and consistency; as opposed to the exploratory approach seen within this chapter. The methodologies adopted for the participant experimentation are presented in Chapter 7.

Chapter 7 – Participant Perceptual Experimentation

7.1 Introduction

This chapter describes the methodology of the experimentation used to quantify the perceptual benefits of SMIs. This pilot study required participants to undergo multiple perceptual tests. The experimental setup, rationale and methods are accompanied with the data analysis techniques used for each of the perceptual tests. The tests conducted are: simple reaction time, amplitude detection, amplitude discrimination, frequency discrimination, temporal numerosity discrimination, TND, with respect to temporal gap detection, TGD, and temporal discrimination (as discussed in section 4.4). The psychometric method chosen for all of the experiments mentioned, asides from the simple reaction time test, is QUEST (described in section 4.3.2).

The rationale of each experiment includes how the data to be collected is intended for use in real-world applications. For example, the amplitude detection experiment aims to determine the minimum power required for electromagnetic coils such that the participants are able to perceive the electromagnetic field. Within real-world applications power efficiency is often key to the success of a device.

Two participant groups were used within the study; implanted and non-implanted (referred to as superficial). Implanted participants varied with age, sex and implant location. Predominantly fingertip implants were chosen for the study; however one participant was implanted on the left lateral of the left palm. See Figure 7-1 (right) for image of approximate location.

Superficial participants had matched identical grade magnets attached to the surface of the dermis with adhesive. The adhesive chosen was Cyanoacrylate, most commonly

known as 'superglue'. Superficial participants were matched for age, sex and implant location with an implanted counterpart.

Similarly to the initial investigation (Chapter 6) the majority of the stimulation used within this chapter came from MIVS. The experimental setup used within this chapter is also similar to that detailed in section 6.2. However the experimental setup did require some alterations in order to accommodate certain participants which are further discussed in section 7.3.

As this pilot study involved human participants, multiple ethical considerations needed to be adhered too. This project thus had to be granted ethical approval by the University of Readings' Research and Ethics Committee. Documentation of the project proposal are given in Appendix A.

7.2 Participant Testing

7.2.1 Participant Selection & Ethical Considerations

The initial ethical proposal for this pilot study included the implantation of the magnet as part of the project. This was to ensure that the implant methodology, position and the date of implant could have been controlled. The proposal received positive medical advice (see Appendix A Project 10 – Information Sheet – Risk of Experimentation – Ref: Dr. Boulos), however due to strict university guidelines with regards to health and safety and particularly liability this was deemed difficult to achieve.

Prior to the conception of the study, informative presentations were given on this research. These seemed to have a profound effect as they captured the interest of numerous audience members. Each of which wanted to be part of the research and openly expressing willing to undergo the implant procedure. These individuals' interests were the realisation that a participant study could be conducted. The difficulties faced in conducting this study without the implantation included, hugely affected this study in terms of participant number and control variables (such as implant date and location of implant).

Regardless of this setback the project proposal had to be altered. This involved removing the implantation from the scope; meaning only participants whom had already had the implant could be part of the study. The final ethical submission is shown in

Appendix A and approval by the University of Readings' Research and Ethics Committee was granted for this project on 19/11/12.

After approval the search began by browsing transhumanist forums and social media websites, along with conversing with body modification artists. The majority of people with the implant that were found, were unfortunately located outside of the UK, as highlighted by the results of the survey described in section 2.3. This imposed a financial problem as transporting participants to the UK was not within the budget of the project. Unfortunately this meant that participant number was limited.

The knock on impact of the lengthy ethical process (10 months) and participant search for this project dramatically affected the speed at which quantifiable data could be attained to support this research. The criteria for the participants' inclusion in this research are outlined below.

7.2.1.1 *Inclusion Criteria for Implanted Participants*

- Magnetic Implant Required - Preferably within the fingertip for reasons discussed in section 5.3.
- Must be within reasonable travel distance from the University of Reading, UoR.

7.2.1.2 *Inclusion Criteria for Superficial Participants*

- Participant had to be a matched to an implanted participant in the study fitting two criteria:
    1. Approximate Age
    2. Gender
- Must be within reasonable travel distance from the UoR.

7.2.1.3 *Exclusion Criteria*

- Individuals with any tactile disorders (e.g. tactile defensiveness).
- Individuals with pacemakers or any medical device affected by EMF.

7.2.2 Study Details

This section outlines the three studies conducted on participants within the context of the experiments presented in this chapter. The three studies conducted are explained individually below and were named: the main study, the 3-month study and the single subject unique study, SSUS. In total 7 implanted, 7 superficial and 1 unique participants

took part in this pilot study. A summary of the participant information is given in Table 7-1.

7.2.2.1 *The Main Study*

The main study consisted of 7 implanted and 7 superficial participants. As stated previously the main aim of this study was to ascertain any perceptual benefits to SMIs when compared with superficially attached magnets. In order to keep biological similarity between participants, each implanted participant was matched for approximate age and sex with a superficial counterpart.

The participants' details are shown in Table 7-1 and those chosen for the main study were all except for O1RI. The table also identifies which candidates were matched in the 'Pair No.' column. Each of the participants within this main study completed all of the participant experiments, which are all explained later in sections 7.4 and 7.5. Two of the implanted participants also took part in the 3-month study, I4RM and I5RM, which is further explained in the following. The results used for them, within the context of the main study, were their final recordings (i.e. month 3).

7.2.2.2 *The 3-Month Study*

The 3-month study was conducted in order to ascertain if there were any perceptual changes over the healing months post implantation. Two participants, I4RM and I5RM took part in this study. The 3-month study was conducted on the following experiments; reaction time, frequency discrimination, temporal discrimination, amplitude discrimination and amplitude detection explained in sections 7.4, 7.5.2, 7.5.5, 7.5.3 and 7.5.2 respectively. Unfortunately due to a vital methodology alteration after the 3-month study began, it was not possible to conduct the TND with respect to TGD experiment. The methodology and rationale for the TND with respect to TGD experiment can be found in section 7.5.7.

7.2.2.3 *The Single Subject Unique Study, SSUS*

The SSUS was conducted in order to establish whether prior tactile training would affect a participant's performance within the experiments. The unique participant chosen for this study was a blind gentleman. The assumed tactile training comes from the participant using sensory substitution devices such as brail readers from a young age. Wan *et al.* in 2010 [168] (discussed in section 4.4.5) presented a study which suggests that

congenital blindness does significantly improve an individual's ability to perform a vibrotactile frequency DL task. This participant conducted all experiments that were in the main study. However his visual condition prevented him from completing the light and light periphery reaction time experiments (section 7.4). The results obtained were Z-Score tested to compare him to the implanted and superficial group's results.

Unique ID	Implanted Superficial Unique	Member of which Study?	Pair No.	DOB	Test Date Start	Implant date MM/YYYY	Age At Test Date	Gender	Location
I1LI	I	M	1	23/3/1977	31/7/2013	04/2013	36	M	LH IF
I2LP	I	M	2	23/7/1973	9/4/2013	12/2012	39	M	LH LLP
I3LI	I	MS	3	2/2/1989	13/8/2013	04/2013	24	M	LH IF
I4RM	I	MS & 3M	4	10/10/1987	21/5/2013	04/2013	25	M	RH MF
I5RM	I	MS& 3M	5	26/4/1990	14/5/2013	04/2013	23	M	RH MF
I6LR	I	MS	6	10/1/1985	14/3/2013	01/2011	28	M	LH RF
I7LR	I	MS	7	26/6/1991	27/3/2013	08/2012	21	F	LH RF
O1RI	U	SSUS	0	5/11/1990	12/7/2013	N/A	22	M	RH IF
S1LI	S	MS	1	14/1/1977	1/8/2013	N/A	36	M	LH IF
S2LP	S	MS	2	3/2/1974	9/7/2013	N/A	39	M	LH LLP
S3LI	S	MS	3	8/1/1989	8/8/2013	N/A	24	M	LH IF
S4RM	S	MS	4	16/3/1988	19/6/2013	N/A	25	M	RH MF
S5RM	S	MS	5	24/3/1989	7/5/2013	N/A	24	M	RH MF
S6LR	S	MS	6	2/12/1984	8/3/2013	N/A	28	M	LH RF
S7LR	S	MS	7	29/1/1991	19/7/2013	N/A	22	F	LH RF

Table 7-1: Participant Summary. I – Implanted, S – Superficial, MS – Main study, 3M – 3-Month Study, M – Male, F – Female, LH – Left Hand, RH – Right Hand, IF – Index Fingertip, MF – Middle Fingertip, RF – Ring Fingertip, LLP – Left Lateral Palm.

7.3 MIVS Participant Experimentation Experimental Setup

This section outlines the experimental setup for the MIVS within the context of the participant experimentation. Within this section, the methodology for attaching the magnets to the superficial and unique participants, the hand placement for the electromagnetic coil and the method for subjectively setting the output level of the power amplifier used within the QUEST based experiments, are all explained. Furthermore factors such as fatigue of candidates are also discussed.

7.3.1 Attaching the Magnet for Superficial Participants

In order to receive the MIVS the superficial participants and the unique participant required magnets to be attached to their skin. The choice of adhesive was made

empirically after trialling various adhesives. The first of which was a product called spirit gum, produced by the company Snazaroo [229]. This is a commonly used body adhesive used in special effects, for securing latex body augmentations during entertainment performances. This product however was not deemed suitable for the testing procedure as the induced vibrations caused a failure in its adhesive properties.

The adhesive chosen was Cyanoacrylate, which is better known as superglue is produced by multiple manufactures. The manufacturer chosen was Loctite as it was readily available and the particular product chosen advertised a flexibility element. Health and safety was considered when selecting this product. The following quote is taken from the international chemical assessment of Cyanoacrylate performed by Cray in 2001 [230]:

"Human data indicate that liquid Methyl Cyanoacrylate, MCA and Ethyl Cyanoacrylate, ECA are not skin irritants as a result of single exposure. There are indications from human studies that repeated exposure can result in skin irritant effects. Eye irritancy has been observed in humans exposed to liquid Cyanoacrylate adhesives."

The absolute minimum amount of adhesive was used in order to reduce the risk of irritation. Any discomfort felt by any participant during and post the experimentation was asked to be reported immediately. Any discomfort from testing and/or adhesive would have been immediately referred to Dr Boulos for medical attention (see Appendix A – Project 10 – Information Sheet – Risk of Experimentation – Ref: Dr. Boulos) or NHS out of hours services if he was not available. No cases of discomfort were reported during any experiment.

The superficial participants that where matched for implanted participants whom had their implants in their fingertips, each had the magnets attached using Cyanoacrylate, as central on the surface of the dermis of the matching fingertip. The SUSS participant did not have an implanted counterpart so in this case the fingertip chosen was the right hand index fingertip. This particular participant was right handed and the index finger has the greatest number of mechanoreceptors (section 5.2); as this was seen as the optimum location for the MIVS. An example of the attachment position for the fingertip is shown in Figure 7-1 (left).

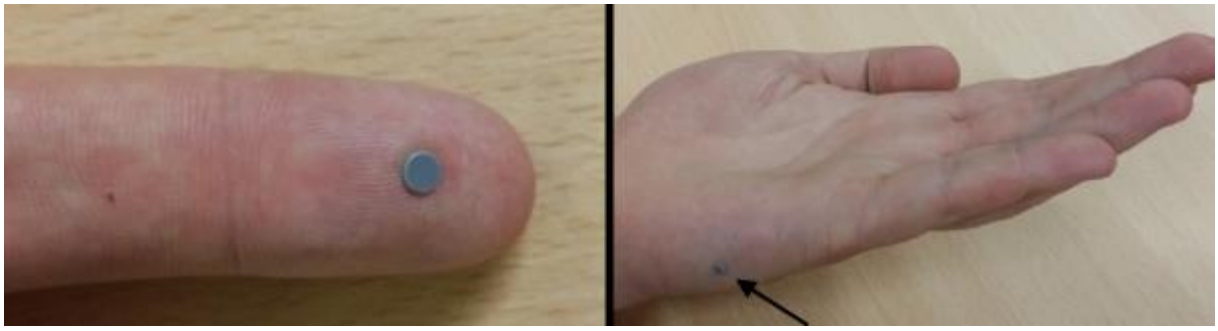


Figure 7-1: Example of superficially attached magnet locations at the fingertip (left) and the left lateral side of the left palm (right, see arrow)

The single superficial participant that was matched with the participant whose magnet is implanted within the dermis of the left lateral side of his left palm, had his magnet attached (again using Cyanoacrylate) in an approximately identical position, shown in Figure 7-1 (right).

7.3.2 Finger/Hand Placement for MIVS

The perceptual tests in the experiments that follow required the participants to use the stimulation coil described in section 5.5. To ensure movement of the magnet was induced from this stimulation and not dampened or prevented by contact with the coil, certain instructions were given to participants. Participants with magnets located upon or inside the dermis of the fingertips (13/15 of the total participants) were instructed to keep their fingernail in contact with the top of the inner face of the coil. As illustrated in Figure 7-2 (left).

Figure 7-2: Fingertip location in coil (left) and Palmside hand location above the coil (right)

Participants with magnets positioned on or within the dermis of the left lateral side of the left palm (2/15 of the total participants) were instructed to keep their magnet directly

over the central axis of the coil. These particular participants had to keep their hand elevated above the face of the coil in order to reduce contact dampening. The separation distance between the dermis and the face of the coil was kept to a minimum, which generally amounted to 0.5 – 1 mm. An example of the positioning is shown in Figure 7-2 (right).

In order to comply with health and safety regulations (Appendix A) and to assure participant comfort throughout the experiments; gel pads were used to support and maintain the participants hand and finger placement throughout the experiments. Examples of which can be seen in within Figure 7-2 (right) and Figure 7-3.

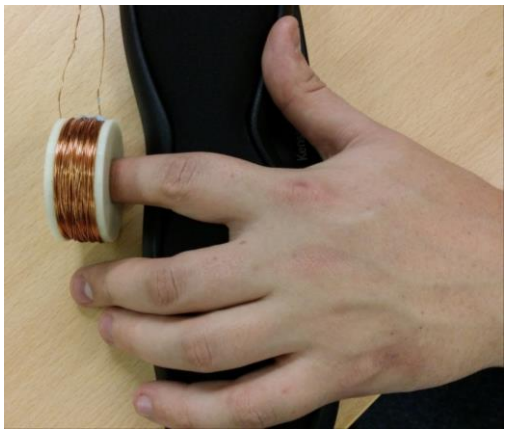


Figure 7-3: Hand Position on Gel Pad Example

Due to the authors two implant locations (index and middle fingertips in his left hand) his hand position for the experimentation is detailed in section 6.2.2.

7.3.3 Subjectively Setting the Amplitude for the Power Amplifier Used in the QUEST based testing

Section 6.2.1 described the setup of the PC and the power amplifier for the initial investigation experimentation as well as the method used for setting the subjective amplitude. The same setup is within the QUEST based experimentation (section 7.5). However the QUEST experimentation requires two subjective power amplifier settings. The additional setting is necessary for the amplitude detection experiment (further discussed in section 7.5.2).

The methodology for obtaining the first subjective voltage is identical to that done by the author (explained in the concluding paragraph of section 6.2.1). To clarify participants were each subjected to a 10 second 200 Hz sine wave signal (via the electromagnetic coil)

and adjusted the dial on the power amplifier such that the vibrotactile stimulus was comfortable for them.

The first stimulation signal was created in Matlab and had no pre-multiplier upon its creation i.e. it had a simulated maximum amplitude of 1 and minimum of -1. The second subjective power setting was set in a similar fashion; however the generated signal had a pre-multiplier of 0.5 i.e. the simulated signal's amplitude is between 0.5 and -0.5.

UID	Subjective Amplitude 1 (mA)		Subjective Amplitude 2 (mA)	
	20 Hz	200 Hz	20 Hz	200 Hz
I1LI	556	256	3128	1593
I2LP	880	455	1992	1032
I3LI	543	277	787	412
I4RM	424	156	1098	564
I5RM	666	329	1627	838
I6LR	555	282	865	447
I7LR	426	153	1986	374
O1RI	548	262	1229	640
S1LI	1527	787	2001	1036
S2LP	2512	1270	1780	918
S3LI	1314	680	1987	1020
S4RM	1848	913	1945	1020
S5RM	1541	788	2174	1113
S6LR	1846	915	2260	1179
S7LR	672	344	2320	1192

Table 7-2: Subjective amplitudes recorded as RMS current values across the stimulation coil

The subjective amplitude settings for each participant are given as RMS current values read across the created stimulation coil (section 5.5) in Table 7-2. These measurements were taken using a TTi 1705 True RMS Programmable Multimeter [218] which was the same device used in section 5.5.2.2.

7.3.4 Fatigue Considerations and Participant Availability

Prior to commencing an experimental session each of the participants were asked whether they were fatigued and were asked to stop if they were. No fixed breaks set throughout the experimentation. However in order to ensure that no long-term potentiation effects occurred and that the participants were comfortable, frequent breaks were taken which were governed by the participant's needs.

Due to the large amount of time required for these experiments (~6-8 hours) to be completed, some participants chose to complete the experimentation over either one or two sessions. This unfortunately could not be controlled as participants obviously have

prior occupational and personal engagements. It must be stressed however that participants choosing to take multiple sittings completed all of the tests within each of the six experiments before ending the session.

7.3.5 Summary of MIVS Setup for all Experiments

For convenience the following points are a summary of what each participant had to follow in terms of experimental setup:

1. Section 6.2.1 – The setup of the power amplifier and electromagnetic coil.
2. Sections 6.2.2 & 7.3.2 – The finger and hand placement within the coil for the author and remaining participants respectively.
3. Section 7.3.3 – The setting of the subjective amplitudes for all participants.
4. Section 7.3.1 – The method for attaching the magnets to all superficial and unique participants.
5. Section 7.3.4 – Participant fatigue and availability.

7.4 Reaction Time, RT

7.4.1 Introduction

Within the context of this research RT is an important factor to establish. As discussed in the introduction to the initial investigation experimentation (section 6.1), the real world application of this research is aimed at high stress scenarios. Incidents such as automotive rear-to-end collisions can often be attributed to the reduction of the drivers RTs, which could be caused by the multitude of distractions that occur within modern vehicles.

As described in section 4.4.2 changes in RTs depend on a number of factors. Within this research simple RTs were measured on 4 stimulus modalities: audio, MIVS, light in the visual focal area and light in the visual peripheral area. The purpose of conducting the simple RT test was too experimentally examine MIVS in comparison to audio and visual stimulations.

This section describes the experimental setup and methodology used to determine the simple RTs of the participants in all of the studies described in section 7.2.2. Furthermore this section discusses the procedure for removing outliers and data analysis techniques used to analyse data collected.

7.4.2 Experimental Setup

The experimental test equipment to determine the simple RT time was custom made. The schematic for the hardware is shown in Figure 7-4 and Table 7-3 shows the descriptions of the components used.

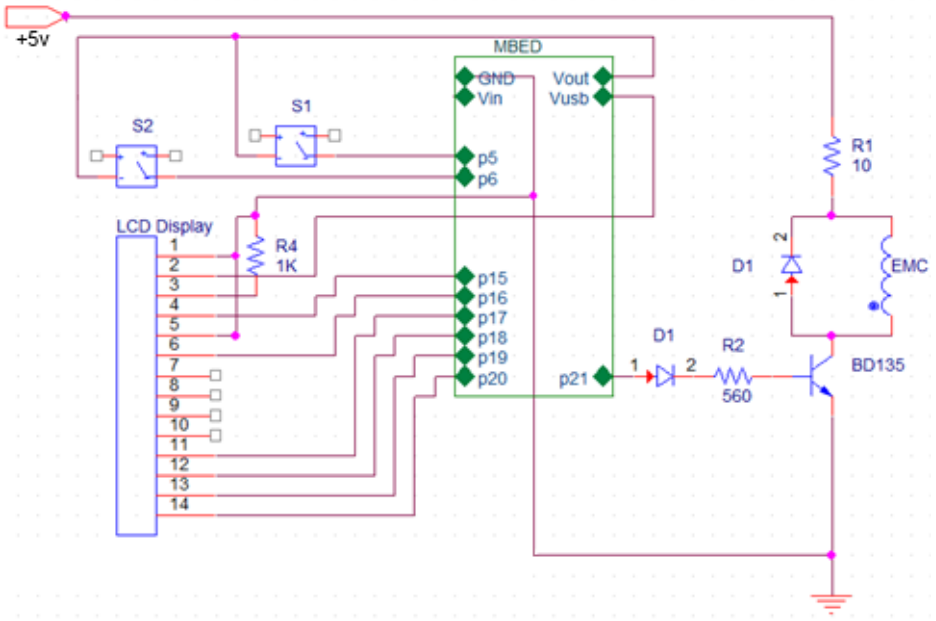


Figure 7-4: Circuit Diagram of Reaction Timer

Component	Description	Variable	Variable Description
R1	10Ω Resistor		
R2	560Ω Resistor		
R3	100Ω Resistor		
R4	1 KΩ Resistor		
BD135	NPN Power Transistor		
D1	20 V Diode		
EMC	Electromagnetic Coil/Speaker		
SW1	Start Button		
SW2	Stop Button		
LCD Display	3 V LCD Display	1	Ground
LCD Display	3 V LCD Display	2	Positive Voltage Input
LCD Display	3 V LCD Display	3	Contrast Pin
LCD Display	3 V LCD Display	4	Register Select
LCD Display	3 V LCD Display	5	Read/Write
LCD Display	3 V LCD Display	6	Enable
LCD Display	3 V LCD Display	7:10	D0:D3 - Not Connected
LCD Display	3 V LCD Display	11:14	D4:7 - Data Bit 4:7
MBED	Mbed NXP LPC1768	GND	Ground
MBED	Mbed NXP LPC1769	Vin	4.5 - 14 V +Ve Input Powered Via USB
MBED	Mbed NXP LPC1770	Vout	5 V Output
MBED	Mbed NXP LPC1771	Vusb	3.3 V Regulated Output
MBED	Mbed NXP LPC1772	p5, p6	Digital Input
MBED	Mbed NXP LPC1773	p15:p21	Analogue Input

Table 7-3: Figure 7-4 Circuit Diagram Component Descriptions

The microcontroller used was an mbed NXP LCP1768, which uses a C/C++ online compiler. The product is an off-the-shelf microcontroller specifically produced for prototyping. This ensured that the creation of the hardware was kept simple and enabled the rapid production of the experimental setup.

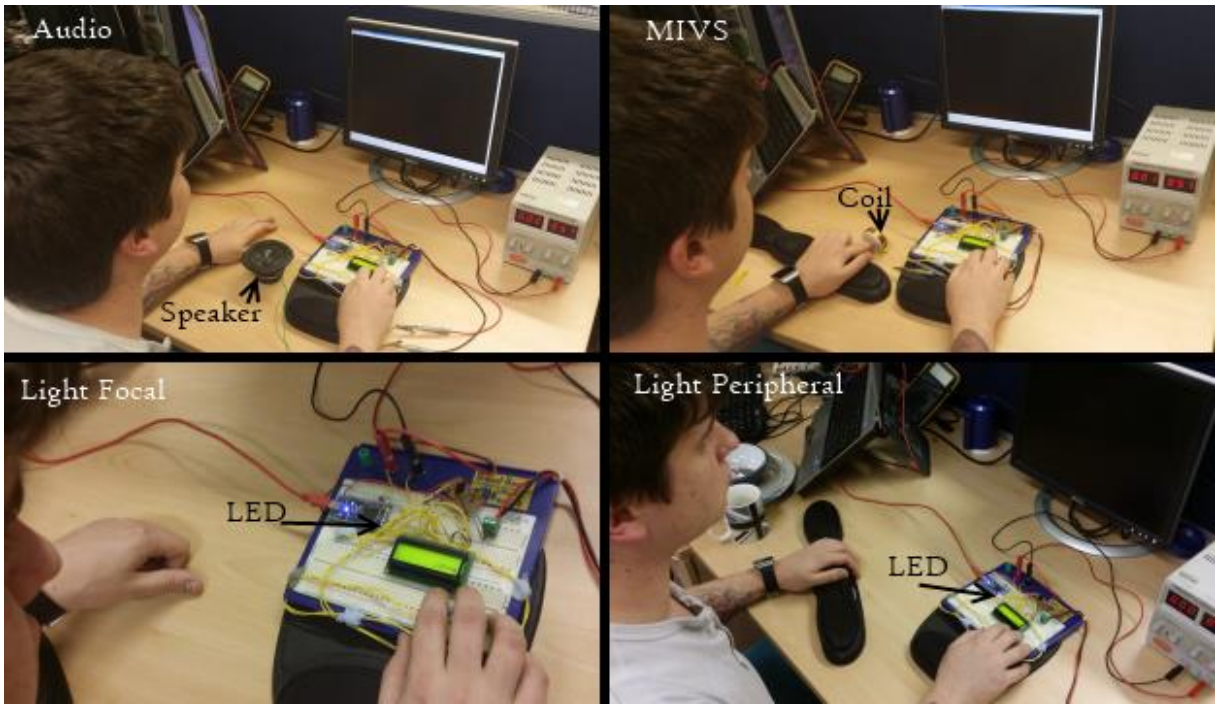


Figure 7-5: RT experimental setup photographs

As mentioned the four stimuli tested in the context of this experiment were: audio, vibrotactile (MIVS) and light in both the focal and peripheral areas of the vision system. The stimuli were presented to the participants using the following methods:

- **Audio** – 200 Hz squarewave signal using an Audax HT080Go 8 Ω Impedance Speaker.
- **MIVS** – 200 Hz squarewave signal using the electromagnetic coil described in section 5.5.
- **Visual** – 2 mm surface mount Light Emitting Diode, LED on the mbed NXP LCP1768.

The speaker for the audio stimuli was positioned ~30 cm in front of the participant on the desk. The electromagnetic coil was positioned at a comfortable location for the participant, dependent upon the location their implant or superficially attached magnet. The LED was positioned ~40 cm in front of the participant. The participants were instructed to stare directly at the LED for the visual focal area RT and to look forward so

the LED was ~45° below their visual focal area for the peripheral test. Photographs of the setup for each of the stimuli are shown in Figure 7-5.

The 5 V+ supply was provided using a Digimess Direct Current DC HY3003 Power Supply [225]. This voltage was adjusted subjectively to alter the intensity and volume of the MIVS and auditory stimuli. A Liquid Crystal Display, LCD display was used to show the status of the test. The code used for the mbed board is shown in Appendix D. In order to ensure that the RTs recorded were not affected by the initialisation of the Pulse Width Modulation (PWM) signal; a separate code was made. This code timed the initialisation time of the (PWM) signal i.e. the time taken to generate the signal for the electromagnetic coil and the speaker which was consistently 9μs and is negligible in terms of an RT.

To ensure no human error was made in obtaining the results from the LCD display, the mbed board was linked to a PC. The RTs were sent from the mbed board (with an added comma for csv file creation) to a piece of software called TeraTerm, which is an open-source terminal emulator.

7.4.3 Test Procedure

Prior to the participants commencing the RT experiment, the experimental setup had to be completed sections 7.3.5 and 7.4.2. Each of the RT tests was conducted using the same procedure, only varying the stimulus per test. The method used was as follows:

1. The microcontroller was connected to the PC via USB and TeraTerm was initialised to receive data, which caused the LCD to display Figure 7-6 (top).
2. Each participant was instructed to press S1, 'the start test button' (shown in Figure 7-4), which caused the LCD to display Figure 7-6 (middle).
3. Each of the participants were instructed to press S2, 'the stop/reset button' (shown in Figure 7-4) as soon as they perceived the stimulus in question. This caused the LCD to display their recorded RT, an example of which is shown in Figure 7-6 (bottom). This reaction time was thus recorded by TeraTerm.
4. After each test each of the participants were instructed to press S2 to reset the system, this then displayed Figure 7-6 (top) again.
5. Steps 2-4 were repeated 44 times per stimulus.

6. The recorded data collected by TeraTerm was screened for outliers (see section 7.4.4) and saved.

Figure 7-6: RT LCD Outputs: test start (top), interim (middle), output example (bottom)

To avoid the participants becoming aware of the stimulus onset, there was a random 1 – 3 s time gap between S1 being pressed and the stimulus onset. An example of the signal for the audio and the MIVS stimulus is shown in Figure 7-7. E1 represents the participant pressing the S1 button, T1 represents the random time gap (1 – 3 s), E2 the stimulus was presented, T2 was the participants' reaction time to the stimulus and E3 represents the participant pressing the S2 button.

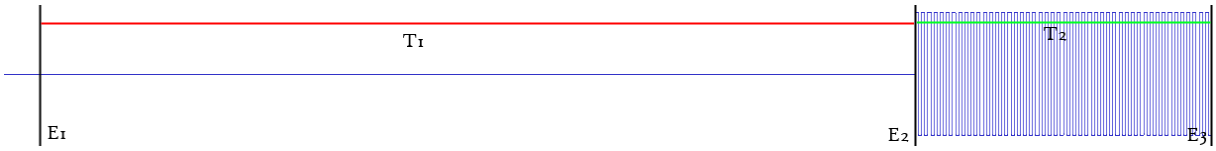


Figure 7-7: RT Signal Example, E1 – Pressing of S1, T1 – Random Time Gap (1-3 s), E2 – Stimulus onset, T2 – Reaction Time, E3 – S2 Pressed.

7.4.4 Outlier Removal

The data collected are screened for outliers prior to saving. Outlier removal occurs in two situations. Firstly, on a trial when a participant clearly misses the stimuli. Secondly, the code has a known flaw, if S2 is pressed in quick succession after S1 it can on rare occasions output a time of 0.000000. Both of these situations are unwanted and hence the data has been removed.

7.4.5 Data Analysis & Null Hypothesis Statements

Reaction time data typically has a distribution that is not Gaussian. A typical RT distribution rises rapidly on the left and has a long right tail. This has been referred to as an ex-Gaussian as it has a Gaussian component with an exponential component also, which forms the long right positive tail as discussed by Whelan in 2008 [231]. The equation below defines the ex-Gaussian distribution function as defined by Lacouture and Cousineau in [232]:

$$f(x|\mu,\sigma,\tau) = \frac{1}{\tau}\exp\left(\frac{\mu}{\tau}+\frac{\sigma^2}{2\tau^2}-\frac{x}{\tau}\right)\Phi\left(\frac{x-\mu-\sigma^2/\tau}{\sigma}\right) \quad (7.1)$$

"In this equation, the exponential function (exp) is multiplied by the value of the cumulative density of the Gaussian function symbolized by Φ. The resulting ex-Gaussian function has three parameters, μ, σ and τ. The two first parameters (μ and σ) correspond to the mean and standard deviation of the Gaussian component. The third parameter (τ) is the mean of the exponential component."

In order to run statistical analysis on this data the ex-Gaussian distribution mean was used. Lacouture and Cousineau in 2008 [232] released a tutorial paper as to how to fit an ex-Gaussian distribution to RT data. Within the paper they also provide a link to a toolbox for Matlab called DISTRIB, this toolbox was used to fit the participant's data to the RT data. An example of the fitted distribution is presented in Figure 8-2. The data used in the fitting per participant was the middle 20 trials taken from each participant's data that were recorded per stimuli. Indeed the first few trials can be considered as training on the stimuli and the equipment which ultimately would have an effect upon RT. The end trails can be affected by fatigue, again affecting RT. Thus the middle trails were used in the analysis.

Post exploratory analysis of the data collected, SPSS has been used to fit statistical models to the main study (section 7.2.2) in order to examine a number of hypotheses:

1. Hypothesis – Implant Type
    - H_0 Implanted = Superficial
    - H_1 Implanted ≠ Superficial
2. Hypothesis – Participants (included as random effect, not individually examined)
    - H_0 All Participants will equal each other
    - H_1 All Participants will not equal each other

3. Hypothesis – Sensory Modality
    - H_0 Audio = EMF = Light in the focal = Light in the periphery
    - H_1 All Sensory Modalities will not be equal to each other

The 3-month study (see section 7.2.2) only contained 2 participants and thus will remain purely exploratory. The SSUS (as previous described in section 7.2.2.3) will be analysed against the responses from the main study using Z-Scores to determine best group fit.

7.5 QUEST based Perceptual Experimentation

7.5.1 Introduction

In order to evaluate the perceptual benefits and or detriments of participants with implanted magnets in comparison with participants whom have had magnets superficially attached, five perceptual thresholding experiments (similarly to those presented in Chapter 6) have been conducted:

1. Amplitude Detection
2. Amplitude Discrimination
3. Frequency Discrimination
4. Temporal Discrimination
5. Temporal Numerosity Discrimination, TND with respect to Temporal Gap Detection, TGD

The first four experiments are all based around the 2IFC paradigm, which is discussed in section 4.3.1.2. The TND with respect to TGD experiment is based around a 5AFC. The reason for this change in trial methodology is to adapt the experiment to an application scenario; which is further discussed in section 7.5.7. However the methodology behind each of the experiments is identical in that they each will use the adaptive thresholding method known as QUEST, which is explained in section 4.3.2 and the rationale for this choice is discussed in section 4.3.1.4.

Each of the experiments has their own particular aim. However they all share the common aim to relay information via the vibrotactile sense. The results of the experiments enabled the creation of optimised vibrotactile stimulation signals that fulfil the three generic criteria: to be rapidly perceived, to be easily recognised, and to include an intensity weighting e.g. level of importance. With the exception of amplitude

detection, each of the experiments are categorised by their fulfilment of these criteria as summarised in Table 7-4.

Experiment	Generic Criteria for Vibrotactile Stimulation Signals		
	Speed Of Stimulation	Recognition Accuracy	Intensity Weighting
Amplitude Discrimination		✓	✓
Frequency Discrimination		✓	✓
Temporal Discrimination	✓	✓	✓
Temporal Gap Discrimination	✓	✓	✓

Table 7-4: Categorisation of the experiments by generic criteria for vibrotactile stimulation

The QUEST method is designed to determine a threshold-estimation at a correct-response rate that is predefined by the user. In these experiments there are two correct-response rates chosen. The first was 82%, which was use for the frequency discrimination task only. Other adaptive methods have similar correct-response rates as their outcome; this rate will enable a better comparison to previously literature in this area (reviewed in section 4.4.5). For example the weighted staircase method (discussed in section 4.3.1.4), investigated by García-Pérez [104] reliably outputs a correct response rate of 80.35% and 83.15% with ratios of 0.5488 and 0.7393 for the 1 up/2 down and 1 up/3 down methods respectively. Furthermore this was recommended as suitable rate by Dr. N. Holmes, University of Reading, UoR, who has vast experience in the use of the QUEST method.

The second correct response rate chosen is 95%. The remaining experiments are each aimed at determining thresholding values for application purposes, whereby the desired change in stimulus has to be accurately identified to relay information. Frequency change may also be used to relay information. However the author found that using frequency as a variable of intensity is more complex to comprehend than changes in time and amplitude. This assertion is based on undocumented prior self-conducted experimentation.

This section provides the: introduction, rationale, methodology, data analysis techniques and null hypothesis statements, for each of the QUEST based experiments. To avoid repetition only two methodologies are given, as the methodologies for the first four tests were practically identical (excluding the stimulation signal and question asked).

7.5.2 Amplitude Detection - Introduction & Rationale

The amplitude detection experiment was conducted in order to determine the minimum amplitude required such that the participants could perceive it (i.e. intensity RL, see section 4.3.1.1). As previously discussed, unlike the other QUEST-based experiments the aim here was not to aid the creation of an information signal, but to determine the minimum power required for the stimulation signals.

Two tests are completed as part of this experiment. The two frequencies examined are 20 Hz and 200 Hz; the sine waveform was used. The effect of frequency on amplitude detection experiments has been examined by multiple authors and is discussed in section 4.4.3.

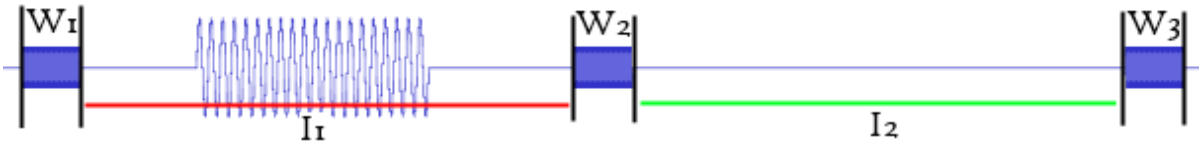


Figure 7-8: Example stimulation signal from the Participant Amplitude Detection task using QUEST

An example of the stimulation signal is represented in Figure 7-8. The signal contains three warning tones, W1, W2 and W3, which are used to separate out the two intervals (I1 and I2). Unknowingly to the participants one interval always remained without a signal, this was deemed the simplest method to fit the amplitude detection experiment to a 2IFC paradigm. After each trial the participants are asked "Which signal has the largest amplitude (I1 or I2)".

The experiment algorithm reduces the amplitude of the simulated signal until the minimum threshold is established. In order to not over stimulate the participants through the tests, the amplitude of the simulated signal begins at 0.5 (i.e. a range of 0.5 to -0.5). If the range was between 1 and -1 the trial number required to find the minimum threshold would potentially over stimulate the participants and inevitably increase the absolute threshold. The amplitude on the power amplifier thus has to be set to a comfortable level for the participants at the beginning of the test. Hence this experiment requires its own subjective amplitude setting per participant as described in section 7.3.3.

7.5.3 Amplitude Discrimination - Introduction & Rationale

The aim of the amplitude discrimination experiment was to determine the minimum increase in amplitude such that the participant can tell there is a difference (i.e. intensity DL, see section 4.3.1.1). The purpose of this discrimination task is to explore the plausibility of relaying information to an individual by varying signal amplitude. Similarly to the amplitude detection experiment, two tests were completed with frequencies 20 Hz and 200 Hz using sine waveform. Multiple authors have examined frequency as a variable for amplitude discrimination, as discussed in section 4.4.4.

Frequency however was not the only variable in this experiment. As stated previously the amplitude for all of the participants' experimentation was individually set in order to ensure participant comfort using the volume controller on the power amplifier (section 7.3.3). Thus the simulated baseline (i.e. reference) amplitude is set to 0.5 (i.e. range of 0.5 to -0.5). If the simulated baseline amplitude range was set between 1 to -1, the simulated threshold amplitude would be greater than the subjective amplitude setting (section 7.3.3). The method for normalization of the data collected is discussed in the data analysis section 7.5.8.2.

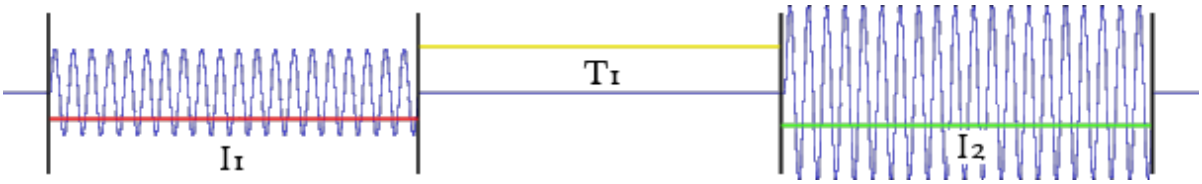


Figure 7-9: Example stimulation signal for the Participant Amplitude Discrimination task using QUEST

A visual representation of an example stimulation signal used can be seen in Figure 7-9. The time between the two signals, T1 = 1.5 s, is kept constant throughout all trials. After each trial the participants are asked "Which signal was the highest in amplitude? (I1 or I2)"; which means the trial paradigm is a 2IFC.

7.5.4 Frequency Discrimination - Introduction & Rationale

A frequency discrimination experiment was conducted as part of the initial investigation experimentation (section 6.3). Fundamentally the only difference between the participant experimentation and the initial investigation is the methodology of obtaining the threshold. The initial investigation used a 1AFC same-difference paradigm (section 6.3.2) and the participant experimentation uses a 2IFC trial paradigm with the

QUEST method of thresholding. The participant experimentation uses the same main variables as the initial investigations frequency discrimination experiment: the baseline frequencies and waveforms, which are reminded in Table 7-5.

The difference being that the QUEST method is used, the discrimination frequency is adaptively found. This ensures test consistency and reduced the time taken to complete the test by the participants. The aim of the experiment is identical to the aim stated in the initial investigation (section 6.3.1) which is to determine the minimum change in frequency at which an individual can determine there is a difference (i.e. the frequency DL of each participant).

Baseline Frequencies (Hz)	Waveforms
20	Sine
50	Square
100	Sawtooth
200	

Table 7-5: Variables for the Participant Frequency Discrimination task

Twelve tests are conducted as part of this experiment; i.e. each baseline frequency is tested with each waveform listed in Table 7-5. An example of stimulation signal is shown in Figure 7-10, (which is again similar to the initial investigation stimulation signal). The respondents are now asked "which frequency was the highest? (I_1 or I_2)", i.e. a 2IFC trial paradigm. The separation time between the two intervals, T_1 = 1.5 s, remains constant throughout all of trials.

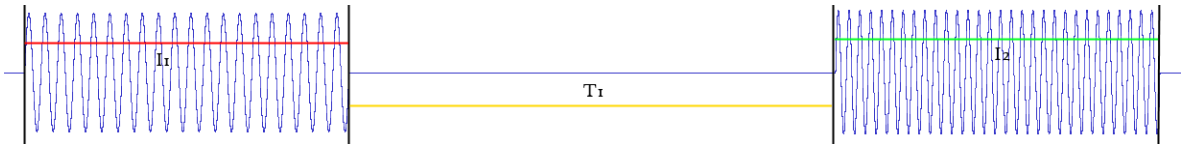


Figure 7-10: Example stimulation signal from the Participant Frequency Discrimination task using QUEST

Altering the frequency of a signal affects its power. In order to ensure that this power change does not provide indication to the participant of the correct response; the amplitude of the first harmonic in the magnitude spectrum for each interval is matched to one another using a floor to ceiling algorithm (Appendix I). This algorithm alters the time domain amplitude of the simulated signal such that the resulting magnitudes of the first harmonics are identical.

7.5.5 Temporal Discrimination - Introduction & Rationale

The aim of the temporal discrimination experiment is to determine the minimum increase in time such that the participant can tell the difference (i.e. temporal DL, see section 4.3.1.1). The purpose of this experiment is to explore the idea of relaying information to an individual by varying the length of the vibrotactile stimulation signal.

As before two tests are completed with frequencies 20 Hz and 200 Hz using sine waveform. The baseline (i.e. reference) time is 500 ms.

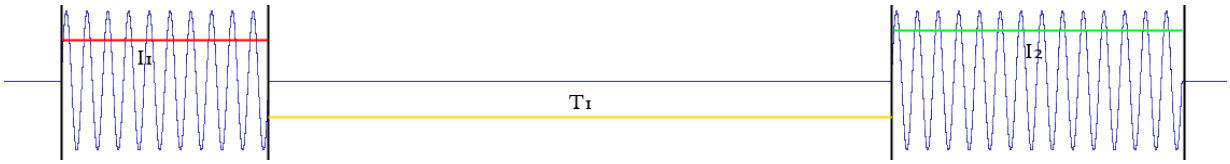


Figure 7-11: Example stimulation signal from the Participant Temporal Discrimination task using QUEST

Figure 7-11 shows a visual representation of an example stimulation signal used within this experiment. Once the participant was presented with the stimulation signal they are asked "Which signal was the longest? (I1 or I2)", i.e. a 2IFC trial paradigm. As before the time between the two signals, T1 = 1.5 s, is kept constant throughout all trials. To clarify one of the intervals is always 500 ms, and the other is 500 ms +X ms, where X ms is the discrimination threshold that the QUEST method is used to determine.

7.5.6 Methodology for the Frequency, Temporal & Amplitude Discrimination and Amplitude Detection Experimentation using QUEST

As stated previously, the methodology for the frequency discrimination, temporal discrimination, amplitude discrimination and amplitude detection experiments is very similar. Only the stimulation signal used and question asked are different.

Following the experimental setup outlined in section 7.3.5. The test procedure commenced using Matlab along with the psychophysics toolbox which contains the QUEST functions. The QUEST procedure requires multiple variables to operate. In order to simplify this process a Matlab GUI was created which has the function statements pre-embedded. The custom made GUI used is shown in Figure 7-12.

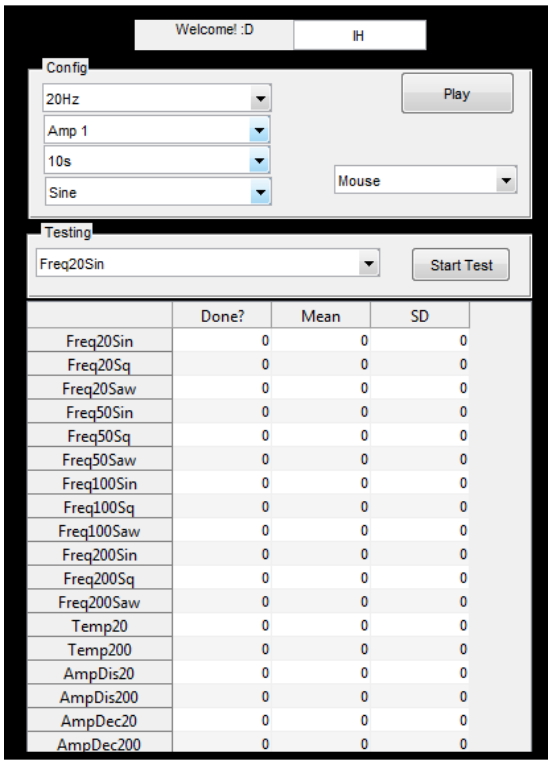


Figure 7-12: The Custom made GUI for the 2IFC QUEST based tests

Each participant is asked for their initials for identification, which have subsequently been replaced with unique identification codes (UIDs), see Table 7-1 for participant information. The initials shown in Figure 7-12 are those of the author for illustrative purposes.

Below the initials box is the 'config' area, this enabled the setup of the power amplifier (see section 7.3.3) to be done simply, as it can generate multiple predefined signals using the dropdown menus. Also within this area is a method of input menu. Each participant has the option of using the mouse or the keyboard (Figure 7-13) to answer the questions (Table 7-6) per trial.

Test Number	Experiment Type	Question
1-12	Frequency Discrimination	Which frequency was the highest?
13-14	Temporal Discrimination	Which signal was the longest?
15-16	Amplitude Discrimination	Which signal was the highest in amplitude?
17-18	Amplitude Detection	Which signal has the largest amplitude?

Table 7-6: Experiment Questions asked during the 2IFC experiments to the participants

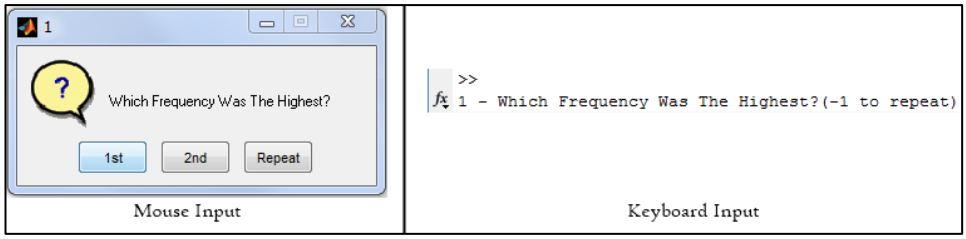


Figure 7-13: Examples of the methods of input for the use

The testing section is used to select the test which the participant is about to conduct. The table within the GUI displays the output of the QUEST tests (mean and STD), and whether the participant has completed that particular test or not.

Table 7-7 displays lists the 18 tests conducted using the 2IFC trial paradigm, the variables used and the experimentation to which the test belongs. Once a test has been selected the QUEST function commences, which requires the following variables to be initialised (as defined in section 4.3.2):

- β = 3.5
- λ = 0.01
- γ = 0.5
- **Estimated mean** = The threshold estimation (Table 7-7)
- **Estimated STD** = The threshold estimation (Table 7-7)
- **Range** = Two times the threshold estimation (Table 7-7)
- **Correct-response rate** = QUEST Threshold Percentage (Table 7-7)

The trials for each experiment arranged into a matrix, further referred to as the trial matrix. The trial matrix ensures that the correct response for each trial is presented within each interval an equal number of times. For example, the 20 Hz sinewave frequency discrimination test, askes the participant to identify which interval (Figure 7-10) has the highest frequency. One of the intervals has the 20 Hz sinewave signal (referred to as the baseline), and the other (correct) interval has the 20 + X (i.e. the threshold) Hz sinewave signal (referred to as the target). The trial matrix randomises which interval the baseline and target signals are in.

Test	Experiment Type	Stimulation Signal Frequency (Hz)	Threshold Estimation	Stimulation Signal Lengths (ms)	Stimulation Signal Waveform	Separation Time Between Signals (ms)	Simulated Signal Amplitude	QUEST Threshold Percentage (%)	Subjective Amplitude Setting Number
1	Freq. Dis.	20 (Baseline)	10 Hz	1000	Sine	1500	1	82	1
2	Freq. Dis.	20 (Baseline)	10 Hz	1000	Square	1500	1	82	1
3	Freq. Dis.	20 (Baseline)	10 Hz	1000	Sawtooth	1500	1	82	1
4	Freq. Dis.	50 (Baseline)	25 Hz	1000	Sine	1500	1	82	1
5	Freq. Dis.	50 (Baseline)	25 Hz	1000	Square	1500	1	82	1
6	Freq. Dis.	50 (Baseline)	25 Hz	1000	Sawtooth	1500	1	82	1
7	Freq. Dis.	100 (Baseline)	50 Hz	1000	Sine	1500	1	82	1
8	Freq. Dis.	100 (Baseline)	50 Hz	1000	Square	1500	1	82	1
9	Freq. Dis.	100 (Baseline)	50 Hz	1000	Sawtooth	1500	1	82	1
10	Freq. Dis.	200 (Baseline)	50 Hz	1000	Sine	1500	1	82	1
11	Freq. Dis.	200 (Baseline)	50 Hz	1000	Square	1500	1	82	1
12	Freq. Dis.	200 (Baseline)	50 Hz	1000	Sawtooth	1500	1	82	1
13	Temp. Dis.	20	100 ms	250 (Baseline)	Sine	1500	1	95	1
14	Temp. Dis.	200	100 ms	250 (Baseline)	Sine	1500	1	95	1
15	Amp. Dis	20	0.1 (MA)	1000	Sine	1500	0.5 (Baseline)	95	1
16	Amp. Dis.	200	0.1 (MA)	1000	Sine	1500	0.5 (Baseline)	95	1
17	Amp. Dec.	20	0.5 (MA)	1000	Sine	25 (WT)	Aim	95	2
18	Amp. Dec.	200	0.5 (MA)	1000	Sine	25 (WT)	Aim	95	2

Table 7-7: Summary of each test the Participants completed using the 2IFC paradigm. Multiple abbreviations are used within this table. Freq. Dis. = Frequency Discrimination. Temp. Dis. = Temporal Discrimination. Amp. Dis. = Amplitude Discrimination. Amp. Dec. = Amplitude Detection. MA = Matlab Amplitude (i.e. generated signal amplitude). Baseline aka standard is used to define where the difference threshold (i.e. DL, see section 4.3.1.1) is measured from. WT = Warning Tone (25 ms, 200 Hz, Sinewave, 0.25 MA). Aim – as the aim of the Amplitude Detection experiment was to determine the minimum amplitude of the signal required for participants to perceive it, the signal amplitude was continually altered in tests 17 & 18.

The number of trials per test is 44. The first four trials are training trials enabling the participant to become familiar to the test and the stimulation. The remaining 40 trials are adapted by QUEST to subjectively find the participant's threshold dependant on which experiment they are conducting. To avoid collecting acquiescent data the participants have the option to repeat the stimulation signal once per trial.

For clarification the iterative process used for each of the 18 tests (Table 7-7) is listed below:

1. Check the trial matrix in order to find the order of the intervals i.e. interval 1 – the baseline and interval 2 – target, or vice versa.
2. Determine the target threshold value for the trial by using QuestQuantile function (section 4.3.2).
3. Using the information from the two previous statements use the appropriate (test dependant) 'Create and Play' function in order to stimulate the participant. This statement further explained below.
4. Ask the participant the appropriate question for the test (see Table 7-6).
5. Check answer to trial against the actual answer.
6. If trial number is greater than 4 (the training trials), update QUEST with a correct or incorrect response using the UpdateQuest function (Psychophysics Toolbox).
7. Save trial information to the Data Matrix (shown in Appendix J).
8. Repeat 1 - 7, until trial number 44 is complete, then save the Data Matrix and final QUEST estimation of threshold (in terms of mean and STD) to file.

The 'Create and Play' functions are individual to each experiment. Each of these functions generates the simulated signal for each trial and outputs the signal using the sound function in Matlab. The variables for these functions are shown in Appendix J and the values used per test are shown in Table 7-7.

The amplitude detection and amplitude discrimination target values (i.e. the Matlab generated signals amplitude X) were set at 1000 times their actual values when using QUEST to estimate the thresholds for these experiments. A minor issue with the QUEST function (found when creating the software), is that it doesn't operate correctly with small numbers. To correct for this the targets values were subsequently divided by 1000 within the 'Create and Play' functions for these two experiments. As stated

previously in order to avoid the power of the signal affecting the participant's response in the frequency discrimination task, an algorithm was used to match the signals amplitude (see section 7.5.2).

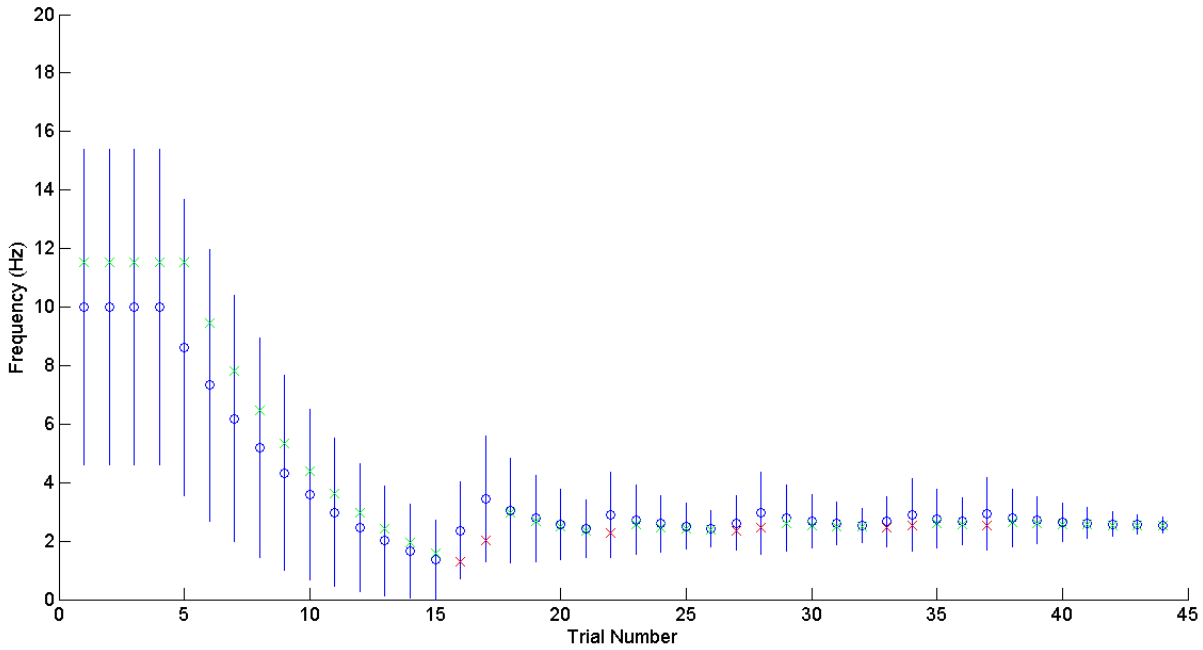


Figure 7-14: Example of a completed QUEST experiment, 20 Hz Sine Frequency Discrimination. The × shows the value tested on that particular trial. The y-axis measures frequency change, above 20 Hz, e.g. trial 1, ~11.5 Hz, refers to 1 trial signal containing the baseline 20 Hz and a 31.5 Hz signal also.

Figure 7-14 shows an example of a complete QUEST output graph running the 20 Hz sine frequency discrimination task. The y-axis shows the threshold frequency and the x-axis shows the trial number. The blue circles of the mean of the QUEST PDF at each trial, the blue vertical lines show the standard deviation of the QUEST PDF at each trial and the x on each line shows the threshold which was tested on that particular trial. The green x indicates the participant responded correctly to the trial, the red x indicates the participant responded incorrectly to the trial. The QUEST output of this particular example is a mean threshold estimate of 2.5484 Hz with a standard deviation of 0.2614.

7.5.7 Temporal Numerosity Discrimination With Respect to Temporal Gap Detection

7.5.7.1 Introduction & Methodology Rationale

A TND with respect to TGD experiment was conducted as part of the initial investigation, section 6.4. Within the context of the participant experimentation the

methodology and variables used had to be altered due to the length of time taken to complete the previous method. The aim of the experiment remains the same i.e. determine the minimum time required between a varied number of concatenated signals (referred to as pulses) such that an individual can still perceive the correct number of pulses (temporal numerosity). Again this is based on the same as previously stated assumption that as the time between pulses tends to zero there will be a point at which the pulses are perceived as continuous.

Similarly to the 2IFC based QUEST methodologies explained previously the QUEST function is used to estimate the participants' threshold. However for this experiment four QUEST functions are interleaved. Each function determines the thresholds of TGD with respect to the number of pulses 2, 3, 4 and 5 individually.

After each trial the participants are asked 'how many pulses did you feel (1, 2, 3, 4 or 5)?' hence choosing a 5AFC method for this experiment. If the participant perceived a continuous signal rather than a number of pulses, (i.e. the gap time is so small that individual pulses can't be perceived) then the participants are instructed to denote a 1 pulse. In order to ensure that there is an equal probability of presenting 1, 2, 3, 4 or 5 pulses per trial, a '1' pulse has been created. However as a single pulse (e.g. 250 ms, 200 Hz) is considered to be too recognisable, the '1' pulse is randomly set to be 1, 2, 3, 4 or 5 concatenated pulses with no gap in between (i.e. continuous), as shown in Figure 7-15.

Each of the five pulse numbers ('1', 2, 3, 4 and 5) are presented 44 times. As before the first four trials of each of the four QUEST functions are training sets, i.e. the gap time between the pulses does not alter. The gap time for the remaining 40 trials is adaptively altered by each of the individual QUEST functions to determine the four separate thresholds. Therefore in total there were 220 trials per test. Three tests which vary the pulse frequency and pulse length are shown in Table 7-8, each using a sine waveform. Table 7-8 also displays the threshold estimates for each test, which are necessary for the QUEST function.

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

Table 7-8: TGD 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.

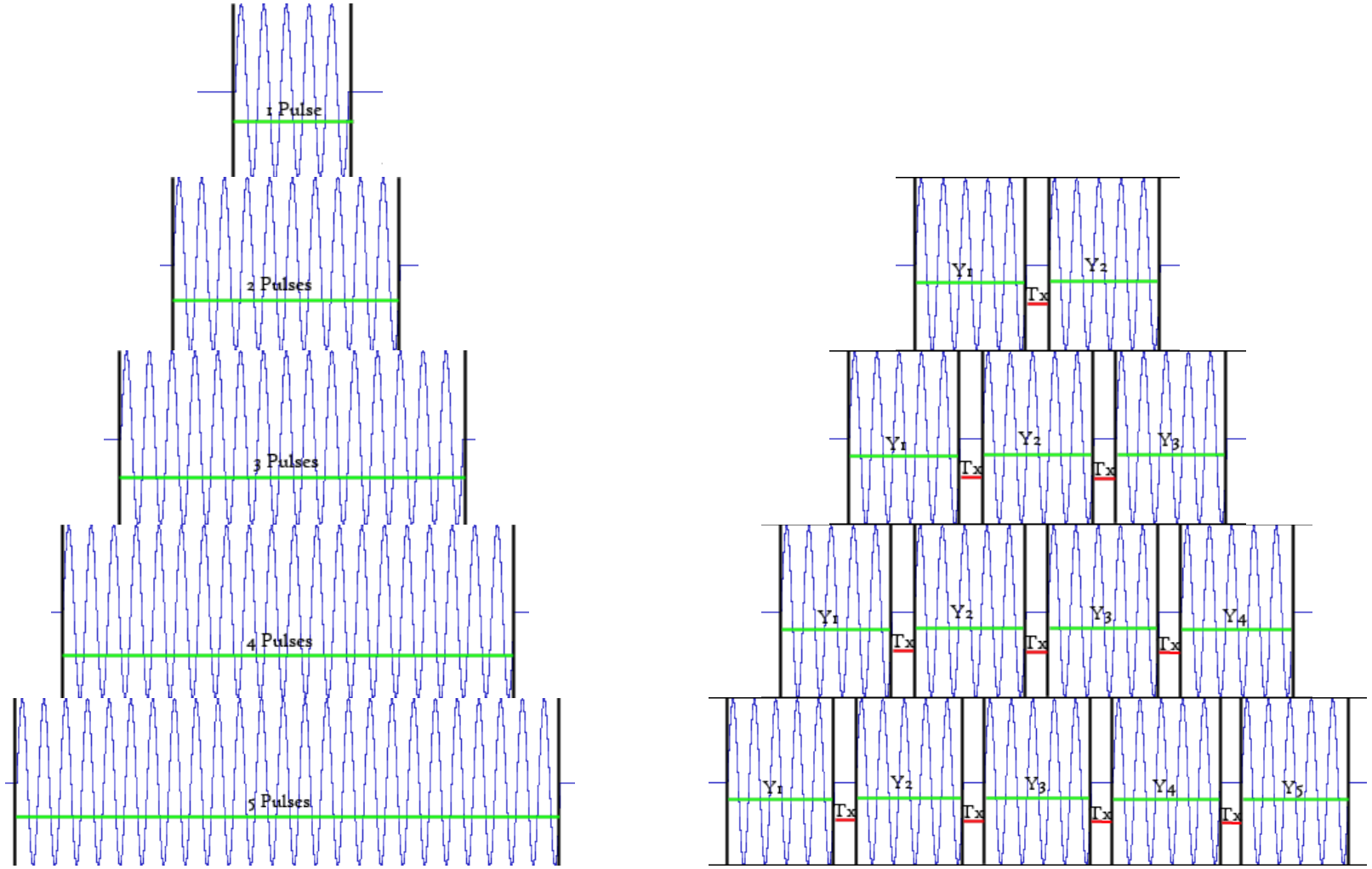


Figure 7-15: Example signals for the TGD experiment. Left shows the '1 Pulse' substitutions, which were randomly selected as 1, 2, 3, 4 or 5 pulse lengths with no gap, meaning in the context of the experiment should have been reported as 1 pulse. Right shows the 4 thresholds each test aimed to determine, i.e. the TGD (Tx time value) for 2, 3, 4 and 5 pulses (Y values).

Similarly to the rationale for this experiment within the initial investigation, frequency was altered to compare the perceptual effects of the two vibratory mechanoreceptors (i.e. the Meissner and Pacinian corpuscles, discussed in section 4.2.1) with regards to the perception of time.

Furthermore the reason for choosing the particular pulse lengths for the two frequencies was to compare whether the pulse length and or the number of cycles per pulse affected the perception of time. Table 7-9 displays the comparisons explored between each of the three tests (Table 7-8).

Comparison	Tests	Like Terms	Independent Variable of Interest
1	1 & 3	Pulse Length	Frequency
2	2 & 3	Number of Cycles	Frequency
3	1 & 2	Frequency	Number of cycles

Table 7-9: Summary of the comparisons explored in the Participant TGD Experiment

The initial methodology for this experiment was a masked 2AFC, in that during each test the participants were either only presented with 2, 3, 4 or 5 pulses. The question per trial was 'how many pulses did you feel? For example, one test always had 5 pulses, each with a length of 250 ms and frequency of 20 Hz. During each trial the only variable that altered per trial was the gap time between the pulses. If the participant answered 5 the trial correctly QUEST reduced the gap in between the pulses. Answering anything other than 5, the trial is wrong and the gap between the pulses would increase.

The major problem with the initial design was the effect of habituation, i.e. the participants soon became aware that the pulse number did not vary. Furthermore after completing one of the tests there was a bias towards the other tests, which amplified the effect of habituation. Hence the randomisation element was introduced in the new method to nullify any bias and removed the effect of habituation.

The new method is more fitting for simulating real-world application scenarios, whereby the number of pulses would relay information to an individual. Hypothetically, if this method where to be used to alert a user of an incoming message (similar to that seen commonly in mobile phones); each pulse number (1-5) would relate to a different message type (e.g. text message, email, social media, etc.). Assuming the probability of receiving each message type is equal, the number of pulses transmitted would randomly

be 1 in 5. Hence the randomisation within this design is better suited for determining threshold values that could be used for this application.

Due to the large number of trials (220) per test, there are two minute forced breaks at particular trial numbers: 55, 110 and 165. This tries to ensure that participants were not affected by long-term potentiation and fatigue.

7.5.7.2 *Methodology*

As before firstly experimental setup for each participant is completed, outlined in section 7.3.5. A similar GUI used in the previous experimentation (explained in section 7.5.6) has been used here. Other than the layout, the only difference between the two GUIs is the table for the results. The table presents the three tests and the output from the four QUEST functions run per test. The columns represent the test status (complete or not), followed by the four QUEST outputs (mean and STD) for the 2, 3, 4 and 5-pulse thresholds obtained per test.

Figure 7-16: The Custom made GUI for the 5AFC QUEST based tests

The three tests conducted in this experiment are summarised in Table 7-8. As before the 4 QUEST functions used within each test requires multiple variables to be initialised for operation:

- $\boldsymbol{\beta}$ – 3.5
- $\boldsymbol{\lambda}$ – 0.01
- $\boldsymbol{\gamma}$ – 0.2
- **Estimated mean** – The threshold estimation (Table 7-8)
- **Estimated STD** – The threshold estimation (Table 7-8)
- **Range** – Two times the threshold estimation (Table 7-8)
- **Correct-response rate** – 0.95

The program then creates a similar trial matrix to the previous ones, i.e. it outlines the parameters for each trial of each test. Within these tests the only parameter changed per trial (other than the threshold value) is the number of pulses. This is created by replicating a matrix containing [1 2 3 4 5] 44 times and then randomly ordering it.

After the completion of the initial setup each test followed an iterative process which is similar to the previous method (section 7.5.6):

1. Determine the number of pulses to be played using the trial matrix.
   a. If the number of pulses is '1', randomly select a number of pulses (1, 2, 3, 4 or 5).
   b. Else the number of pulses is defined by the trial matrix and the appropriate QUEST function is selected.
2. Determine the gap time required.
   a. If statement 1-a is true and the number of pulses is greater than 1, the time gap between the pulses is set to zero.
   b. Else determine the target value (i.e. gap time) for the trial by using the QuestQuantile function (explained in section 4.3.2) on the selected QUEST function.
3. 'Create and Play' stimulation signal by using the variables found in 1 and 2.
4. Ask the participant 'How many pulses did you feel (1, 2, 3, 4 or 5)?'.
5. Check answer to trial against the actual answer i.e. number of pulses determined in statement 1 (for examples of input see Figure 7-13).
6. Post-trial update.
   a. If number of pulses is '1' skip this step.
   b. Else if the trial number is > 4 (N.B. the first 4 trials were training sets), update the appropriate QUEST function (determined by statement 1) with a correct or incorrect response (found in statement 5) using the UpdateQuest function.
   c. Else skip this step.
7. Record the data in the Data Matrix (values saved are shown in Appendix J).
8. Repeat steps 1 through 7 until all 220 trials are completed. If the trial number is 55, 110 or 165, force a 2 minute break time.

In order to 'Create and Play' the stimulation signal (statement 3) within these tests, 4 variables were required. These are the pulse(s) length (ms), the pulse(s) frequency (Hz), the number of pulses and the time gap between them. The first two variables are

predefined by the test number, the values for which are shown in Table 7-8. The number of pulses and time gap between them (as stated in statement 3) are determined at each trial. Using these variables the program thus generates the stimulation signal and 'plays' it using the sound function within Matlab.

Upon completing the test, the Data Matrix is outputted (shown in Appendix J) which contains the four QUEST estimates (mean and STD). Trial outputs for each of the four thresholds are outputted as graphs similar to that shown Figure 7-14.

7.5.8 Data Analysis & Null Hypothesis Statements for the QUEST Based Experimentation

In order to identify any outliers within the data firstly exploratory analysis will be completed. Statistical analysis will only be conducted on the main study and the SSUS studies (described in section 7.2.2), as the three-month study only has two participants. The SSUS data analysis, as previously explained have been conducted using Z-score testing to compare the results to the results obtained from the main study (see section 7.2.2.3). Statistical models were fitted to the main study results using SPSS; the null hypotheses for each of the experiments are presented in this section.

7.5.8.1 Frequency Discrimination

The Weber fractions (discussed in section 4.3.1.1) will be used for the statistical modelling. As discussed in section 4.4.5, the Weber fractions for frequency discrimination vary as frequency increases. Hence tests, 1-3, 4-6, 7-9 and 10-12 (Table 7-7) will be analysed in separate models. The null hypothesis statements for each model are presented below:

1. Hypothesis – Implant Type
   - H_0 Implanted = Superficial
   - H_1 Implanted ≠ Superficial
2. Hypothesis – Participants (included in the model as a random effect)
   - H_0 All Participants will equal each other
   - H_1 All Participants will not equal each other
3. Hypothesis – Waveform
   - H_0 Sine = Square = Sawtooth
   - H_1 All waveforms will not be equal to each other

7.5.8.2 *Amplitude Detection, Amplitude Discrimination and Temporal Discrimination*

Although the temporal discrimination, amplitude discrimination and amplitude detection tasks will be statistically analysed separately, the null hypothesis statements for each model is identical:

1. Hypothesis – Implant Type
   - H_0 Implanted = Superficial
   - H_1 Implanted ≠ Superficial
2. Hypothesis – Participants (included in the model as a random effect)
   - H_0 All Participants will equal each other
   - H_1 All Participants will not equal each other
3. Hypothesis – Frequency
   - H_0 20 Hz = 200 Hz
   - H_1 20 Hz ≠ 200 Hz

The Weber fractions obtained for the amplitude and temporal discrimination experiments will be used for their statistical analysis. A TTi 1705 True RMS Programmable Multimeter [218] is used to measure the RMS current across the stimulation coil. These current readings have been used for the data analysis of the amplitude detection and discrimination experiments.

7.5.8.3 *Temporal Numerosity Discrimination With Respect to Temporal Gap Detection*

Comparisons 1* and 2*	Comparison 3*
1. Hypothesis – Implant Type • H_0 Implanted = Superficial • H_1 Implanted ≠ Superficial 2. Hypothesis – Participants (included as random effect, not individually examined) • H_0 All Participants will equal each other • H_1 All Participants will not equal each other 3. Hypothesis – Pulse Number • H_0 2 pulse = 3 pulse = 4 pulse = 5 Pulse • H_1 All Pulse numbers will not equal each other 4. Hypothesis – Frequency • H_0 20 Hz = 200 Hz • H_1 20 Hz ≠ 200 Hz	1. Hypothesis – Implant Type • H_0 Implanted = Superficial • H_1 Implanted ≠ Superficial 2. Hypothesis – Participants (included as random effect, not individually examined) • H_0 All Participants will equal each other • H_1 All Participants will not equal each other 3. Hypothesis – Pulse Number • H_0 2 pulse = 3 pulse = 4 pulse = 5 Pulse • H_1 All Pulse numbers will not equal each other 4. Hypothesis – Number of Cycles • H_0 50 = 5 • H_1 50 ≠ 5

Table 7-10: Null hypothesis statements for the TND with respect to TGD participant experiment.

*The comparisons are in reference to those presented in Table 7-9.

Three statistical models will be created to analyse the comparisons stated in Table 7-9. The final mean threshold estimates obtained for the tests, i.e. the separation time between

pulses in milliseconds, will be used for these analyses. The null hypotheses for each model are stated in Table 7-10.

7.6 Summary

This chapter introduces the participant experimentation conducted in order to ascertain whether there are any perceptual benefits of SMIs in comparison to superficially attached magnets. Each section is summarised below:

- **Participant Testing** –This section introduces the participant selection process, the participants chosen and the three studies conducted, which are the main study, the three-month study and the SSUS.
- **MIVS Participant Experimentation Experimental Setup** – This section describes the experimental setup used for the experimentation. This covers: the method for attaching the magnets to the superficial candidates; the finger/hand placements for MIVS; subjectively setting up the power amplifier used as well as fatigue considerations.
- **Reaction time, RT** – This section presents the custom made hardware used for the simple RT experiment, as well as the experimental methodology and data analysis techniques which will be used. The simple RTs examined per participant are: audio, MIVS, light in the focal and light in the peripheral area.
- **QUEST Based Perceptual Experimentation –** The introductions, rationales, methodologies and data analysis techniques for each of five the QUEST based perceptual experiments, are presented within this section. The five experiments described are: amplitude detection, amplitude discrimination, frequency discrimination, temporal discrimination and TND with respect to TGD.

The following chapter presents the results and discussion for all of the participant experimentation conducted.

Chapter 8 – Results & Discussion

8.1 Introduction

This chapter presents the results from the participant experimentation. Each of the three studies conducted (see section 7.2.2) are individually examined. The main study results for each of the six experiments are individually discussed both qualitatively and quantitatively. The chapter then presents a qualitative analysis of the three-month study results. Finally the results from the SSUS are discussed in comparison to those obtained from the main study.

8.2 Main Study

This section explores the data collected from all of the experiments conducted upon the main study participants (see section 7.2.2.1). Each of the results from experiments is individually presented and discussed, along with a cross comparison to the literature for each experiment as presented in section 4.4. The data analysis techniques used for each of the experiments, along with the null hypothesis statement are presented in sections 7.4.5 and 7.5.8 for the RT and QUEST based experimentation respectively.

8.2.1 Reaction Time

Results for the RT experiment that was conducted on all of the participants within the main study are presented in this section.

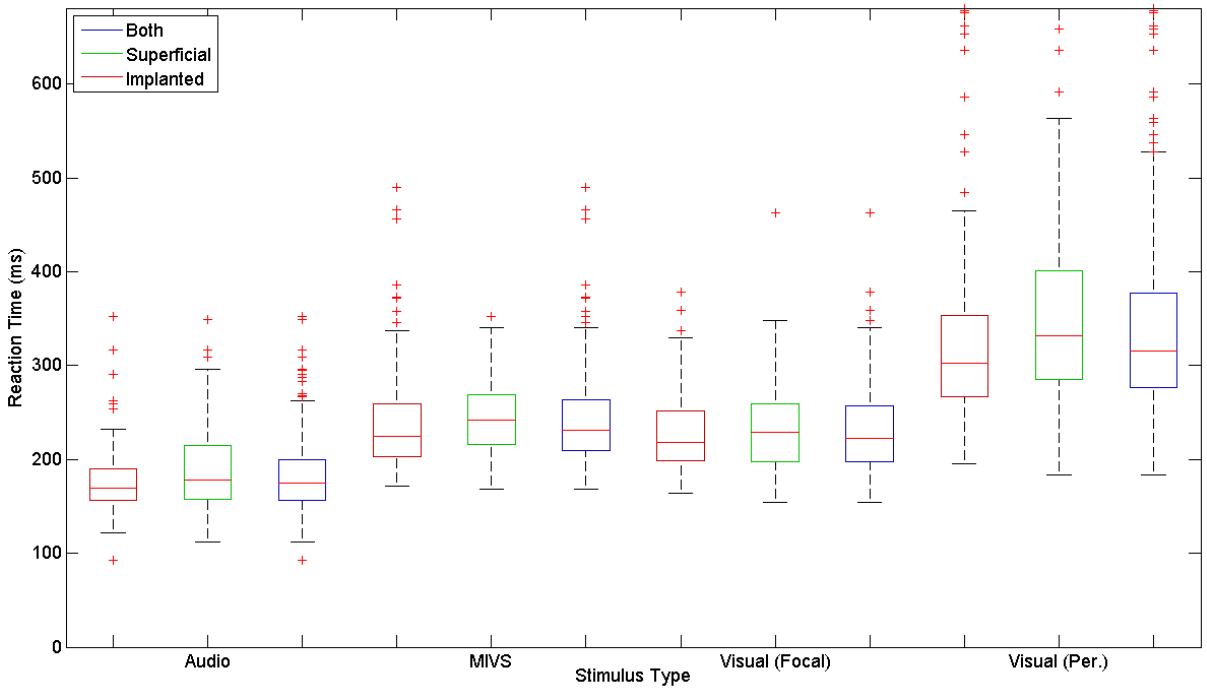


Figure 8-1: Box plot to summarise all RT Data from participants within the main study (categorised by group)

Figure 8-1 displays the results of all of the participants within the main study and categorised by group (i.e. implanted and superficial). The data used within these box plots are the 20 trials recorded per participant as described in section 7.4.5. The results for both groups (blue boxes with Figure 8-1) displays the anticipated increase in reaction time as the modality alters from auditory to peripheral vision as well as the large variance typical of RT data.

The largest variance comes from the peripheral vision RT data. This is quite concerning as during high stress scenarios, delays in RT to a stimulus such as vehicle brake lights could cause a road traffic accident. For ease of discussion corresponding vales are given in Table 8-1. As can be seen in the table the standard deviation values for the peripheral vision data is almost double any of the other standard deviation values for the other modalities.

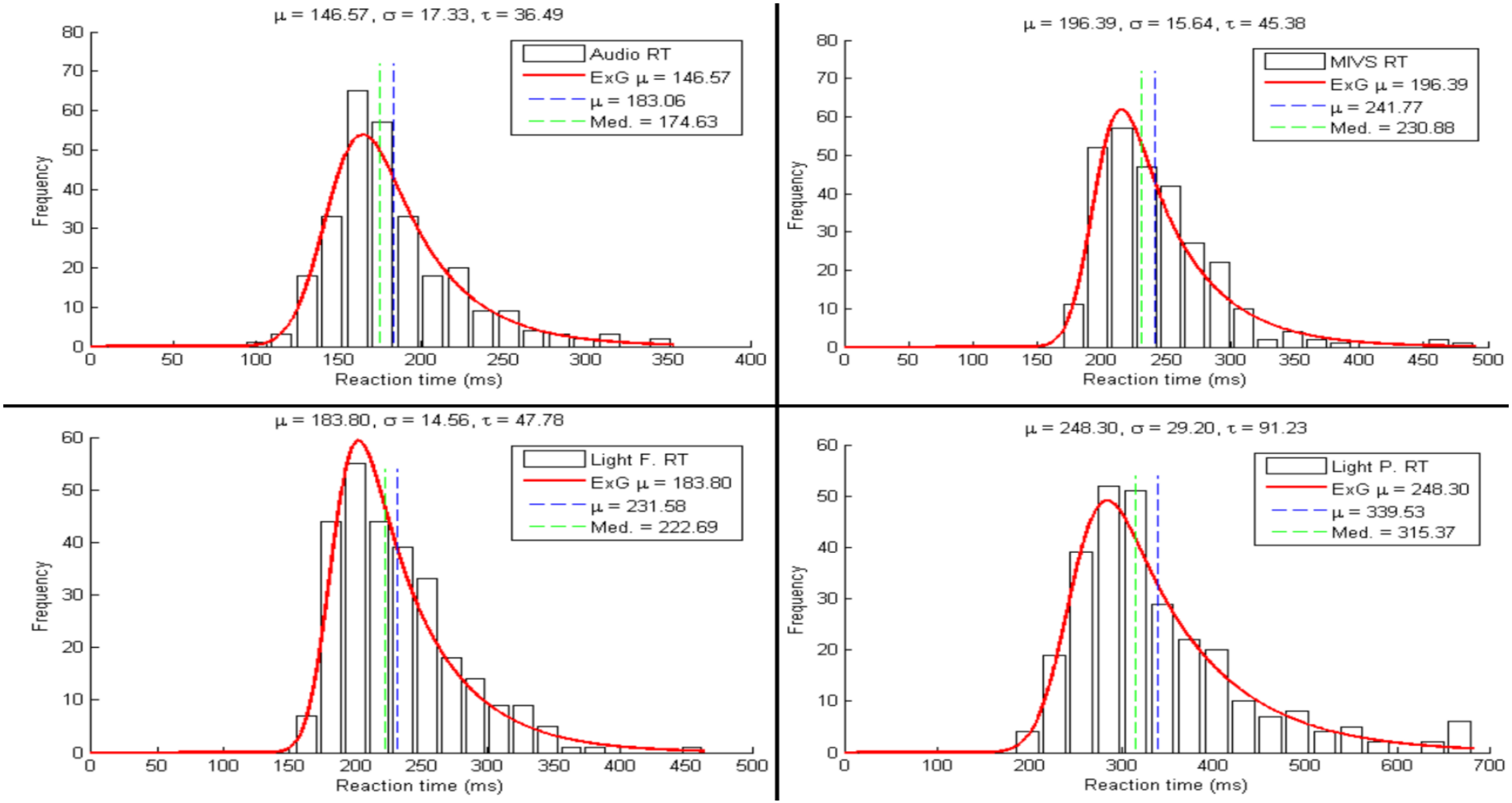


Figure 8-2: Histograms of all of the participants RT data within the main study. The fitted ex-Gaussian distribution, mean (μ) and median (Med.) of the data are presented for comparison of the measures of central tendency. The parameters used for the ex-Gaussian distribution function (defined in equation 7.1) are given as titles to each graph. The y-axis labelled frequency is frequency of occurrence. (Top Left) – Audio RT Data, (Top Right) – MIVS RT Data, (Bottom Left) – Visual Focal area RT Data (Bottom Right) – Peripheral Vision RT Data.

Modality	Group	Mean (ms)	STD (ms)	Median (ms)	Ex-Gaussian Parameters		
					Mean (ms)	STD (ms)	Skewness (ms)
Audio	Implanted	176.7	36.1	169.5	147.1	17.4	29.6
	Superficial	189.5	43.7	178.4	147.4	17.7	42.1
	Both	183.1	40.5	174.6	146.6	17.3	36.5
Vibrotactile	Implanted	239.1	54.6	225.1	188.2	10.6	50.92
	Superficial	244.4	37.5	241.7	218.9	28.3	25.6
	Both	241.8	46.8	230.9	196.4	15.6	45.4
Visual (Focal)	Implanted	228.5	42	218	184.9	13.53	43.7
	Superficial	234.7	49.4	229.2	183	15.8	51.7
	Both	231.6	45.9	222.7	183.8	14.6	47.8
Visual (Per.)	Implanted	339.5	95.6	315.4	240.5	26.5	84.1
	Superficial	354.5	91.2	331.4	262.8	34.5	91.7
	Both	339.5	95.6	315.4	248.3	29.2	91.2

Table 8-1: Mean, Standard Deviation, Median and Ex-Gaussian Parameters for all of the participant's RT data in main study (categorised by group)

Figure 8-2 displays the results from all of the main study participant RT data as histograms for each of the modalities examined. Each chart is also fitted with an ex-Gaussian distribution function (previously described in section 7.4.5). These results are presented as separate groups (i.e. implanted and superficial participants) in Appendix K. These results are in agreement with the concept discussed by Whelan in 2008 [231], in that RT data does resemble the shape an ex-Gaussian distribution. Observations of the STD and skewness values the fitted ex-Gaussian distribution functions further illustrates the large amount of variation within the peripheral vision RT data.

It is clear from the graphs presented in Figure 8-2 and values presented in Table 8-1 that the mean and median overestimate the underlying central tendency value, i.e. the fitted ex-Gaussian distribution mean. For example the mean and median values for the MIVS modality are 241.8 ms and 213.9 ms, which overestimates the central tendency value (196.4 ms) by more than 30 ms. Hence the measure of central tendency used for the statistical analysis (i.e. the dependant variable) is the fitted ex-Gaussian distribution mean.

The statistical model used to analyse this data is a mixed model, which accounts for the following factors:

- **Participant ID** – used a random factor to account for the variability of subjects.
- **Implant Type** –Implanted or superficially attached.
- **Stimulus Modality** – audio, MIVS, visual focal and peripheral vision.

- **Stimulus Modality * Implant Type** – in order to determine if any interaction effects were present.

Furthermore in order to explore any statistic difference found by the model post hoc analysis is performed in the form of pairwise comparison using the Šidák correction. This post hoc analysis is performed on the stimulus modality and the interaction of stimulus modality * implant type. The output of the mixed model is presented in Appendix K.

Given that a plethora of factors affect reaction time as it is a highly subject dependant measurement (previously discussed in section 4.4.2); it is rather unsurprising to see that the variance explained by the participant's data is ~19%. The results from the fixed factors of the model displayed a significant difference for sensory modality of the RT data [$F(3,36) = 32.525$, $P < 0.001$]. Post hoc analysis of which found that each modality was significantly different from each other ($P < 0.01$) with the exception of MIVS and vision in the focal area ($P = 0.861$). The significant increase in RT measured in the peripheral area in comparison with the visual focal area, is in agreement with previous findings in the literature [7, 8, 121].

The simple RT test aimed at empirically determining the effectiveness of MIVS within high stress scenarios. While the test only examined simple RT with no stress stimulus presented to the participants; MIVS has shown significant reduction in reaction time to that of the vision system in the peripheral area. This reduction is important with regards to the application of this research, as warming visual stimuli such as car break lights or speed awareness can often be within a driver's peripheral vision, especially if the driver is distracted. Although the results do show that the audio RT was less than that of the MIVS RT, this experiment was conducted in a quiet room. Within high stress scenarios such as driving or piloting the environment, be it a car or a cockpit is not often quiet. This increase in environmental noise plus auditory distractions such as conversing with passengers or colleagues increases the audio RT of drivers; investigated by Mohebbi *et al.* in 2009 [10] (see section 4.4.2).

Implant type has shown to be not statistically significant. This result is unsurprising seeing that the only factor that differed between the two groups is the position of the magnet. Given that the distance between the superficial and implanted magnets is less than 1 cm, the time taken to invoke a neuronal response is negligible in the context of RT.

The interaction of implant type and sensory modality is significant [F(3,36) = 3.270, P = 0.032]. Post hoc analysis of this interaction revelled that the significance lies between the implant types for the peripheral vision data. This is based on examination of the 95% confidence intervals for the interaction, presented in the mixed model output in Appendix K). This result is understandable given that the peripheral vision stimulus was not clearly defined and variation of angle could have occurred between each participant.

The ex-Gaussian mean RTs of the MIVS stimuli is slightly higher than the range of touch given by Robinson [8] (126-182 ms measured from the hand). However as discussed by Robinson and other previous authors [118, 8] methodology has also been found to have an effect on RT data. For instance the equipment itself may have had an effect on the participants RTs due to factors such as stimulation amplitude and the mechanical resistance of the stop switch. Stimulus amplitude is known to have an effect on RT data, as discussed by Woodworth and Schlosberg [105] e.g. a bright light is more rapidly perceived in comparison to a dim one. As stimulus amplitude of the auditory and MIVS was subjectively set, it could have affected the overall participant mean obtained compared with that of the previous data.

In order to further analyse the effects of high stress scenarios on simple RT would require the participants to be in a simulated or actual high stress scenario. Initial development of a simulated driving scenario for this purpose is presented in Chapter 9.

8.2.2 Amplitude Detection

The section explores the results of the amplitude detection experiment conducted. As stated previously, the values used for this analysis are the recorded RMS current readings across the stimulation coil measured at the absolute thresholds for each participant.

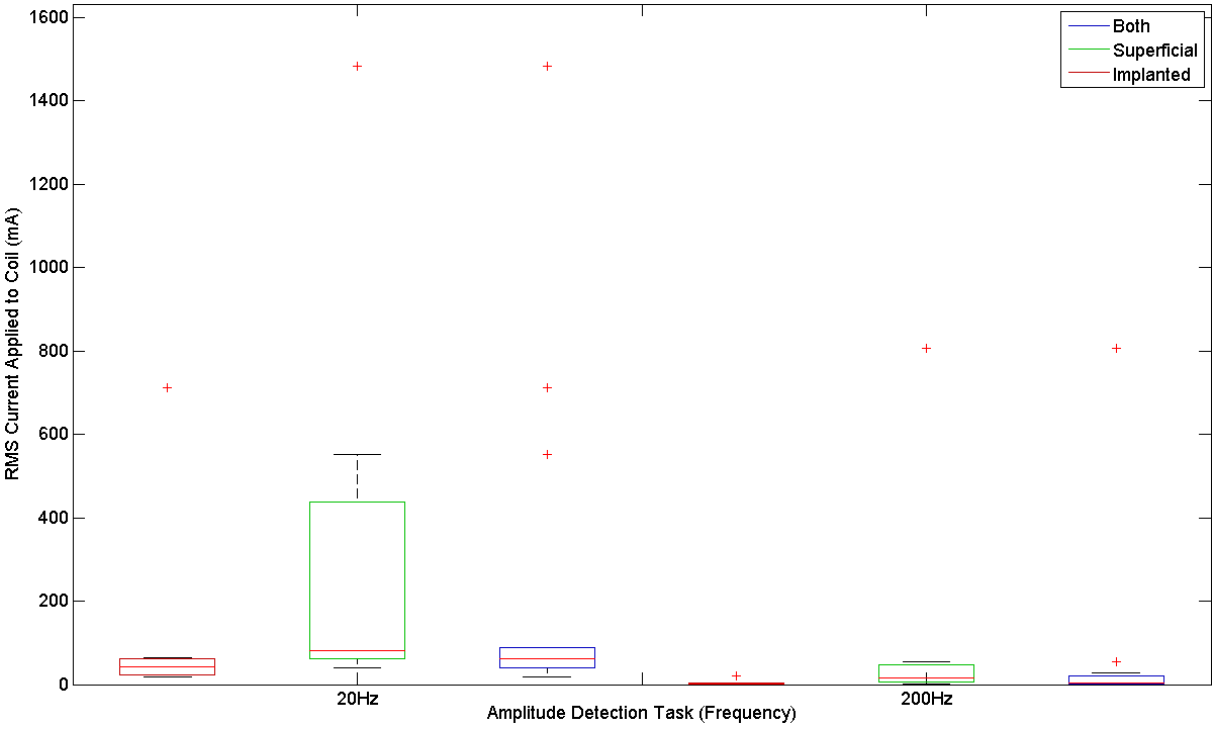


Figure 8-3: Box plot to summarise the amplitude detection threshold (presented as the RMS current supplied to coil (mA)) for all participants within the main study (categorised by group)

Figure 8-3 displays the current measured at the amplitude detection threshold for the participants in the main study. The data presented suggests that a small amount of current was required in order to stimulate both groups. However the results indicate that the implanted group requires a smaller current that the superficial group. Furthermore the results indicate that as frequency changes from 20 Hz to 200 Hz the current required for stimulation reduces in both groups. For discussion purposes the threshold values for each of the participants are presented in Table 8-2.

The results considered to be outliers (Table 8-2 marked in red) are the 20 Hz results for I7LR and S2LP, and both results for S7LR. The rationale for removal of the I7LR (20 Hz) and S7LR (20 & 200 Hz) was based on observation of the amplitudes that each of the participants were tested at the other QUEST based experiments. I.e. the recorded absolute thresholds were larger than that used in the other threshold in experiments (presented in Table 7-2). The removal of the S2LP (200 Hz) is based on the location of stimulation (i.e. the lateral area of the palm) in comparison to the other participants (i.e. their finger pads). Although I2LP's results seem valid for this experiment, the stimulation for I2LP was also presented in the same area as S2LP and hence has been removed in order to keep consistency. These results have been marked in green in Table 8-2.

Amplitude Detection RMS Current (mA)					
UID	20 Hz	200 Hz	UID	20 Hz	200 Hz
I1LI	22.58	21.33	S1LI	40.14	14.172
I2LP	63.34	3.665	S2LP	553	28.82
I3LI	18.432	0.884	S3LI	59.88	1.58
I4RM	43.26	1.695	S4RM	81.69	15.858
I5RM	25.62	1.832	S5RM	70.51	4.533
I6LR	59.97	1.466	S6LR	88.78	54.45
I7LR	711	1.842	S7LR	1484	806

Table 8-2: Current supplied (mA) to coil at the amplitude detection threshold for all participants within the main study. Unique ID, UID, is in reference to the codes used per participant as identifiers as described in Table 7-1.

The mean, standard deviation and median values for the data are presented in Table 8-3. These values further highlight the reduction in absolute amplitude thresholds when varying both frequency (i.e. from 20 to 200 Hz) and group (i.e. from the superficial to the implanted). Outliers-1 further refers to the outliers marked in red in Table 8-2. Outliers-2 further refers to the outliers and S2LP and I2LP, i.e. both the red and green marked results in Table 8-2.

		All Results			Results with Outliers-1 removed			Results with Outliers-2 removed		
Freq.	Group	Mean	STD	Median	Mean	STD	Median	Mean	STD	Median
20 Hz	Implanted	134.9	19.6	34.4	38.9	19.6	34.4	34.0	17.3	25.6
	Superficial	339.7	19.2	70.5	68.2	19.2	70.5	68.2	19.2	70.5
	Both	237.3	23.9	59.9	52.2	23.9	59.9	51.1	24.9	51.6
200 Hz	Implanted	4.7	7.4	1.8	4.7	7.4	1.8	4.8	8.1	1.8
	Superficial	132.2	19.5	15.0	19.9	19.5	15.0	18.1	21.2	14.2
	Both	68.4	15.7	3.7	11.7	15.7	3.7	10.9	16.1	1.8

Table 8-3: Mean, Standard Deviation and Median from all participants in main study categorised by group

The results with outliers-1 removed and the results with outliers-2 removed have both been fitted to mixed models in SPSS, accounting for the following factors:

- **Participant ID** – used a random factor to account for the variability of subjects.
- **Implant Type** –implanted or superficially attached.
- **Frequency** –20 or 200 Hz.

- **Frequency * Implant Type** – in order to determine if any interaction effects are present.

The full model outputs as well as additional box plots of the results with outliers-1 and outliers-2 removed are presented in Appendix L. The variance explained by the participant's data within this model was ~22%. This is unsurprising given the vast number of personal factors that have been shown to effect amplitude detection thresholds (described in section 4.4.3). The implanted group required a significantly lower current supply to the coil for amplitude RL than the superficial group [$F(1,11.379) = 8.938$, $P = 0.012$]. The assumed reason for this reduction is 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 [$F(1,10.860) = 46.0129$, $P < 0.001$]. This result is in agreement with the result U-shape response of amplitude RL described by Verrillo [139] (see section 4.4.3). Within the context of this research the result suggests that for stimulation in high stress scenarios, it is more cost effective (in terms of power) to use a higher frequency for stimulation. There was no significant interaction between frequency and implant type found within this model.

The results from the second model showed that ~28% of variance was explained by the model, this increase in due to the decrease in the participant number in the second model. The implanted group again showed a significant reduction over the superficial group [$F(1,9.205) = 8.321$, $P = 0.018$]. This slight increase in significance is again due to the removal of the implanted candidate (I2LP). Frequency of stimulation was also found to be significant in this model with no change in significance from the previous model [$F(1,8.901) = 40.056$, $P < 0.001$]. Finally there was no significant interaction present between stimulation frequency and implant type.

For the implanted participants with magnet type 1 (see Table 7-1), and their superficial counter parts, an approximate force estimation to perceive MIVS has been calculated in Table 8-4. These estimations have been established by utilising the results of the 'flipping experiment' described in section 5.7. These results are less than that obtained by Israr *et al.* [148], who reported absolute amplitude thresholds of ~3.3E-2 N and ~2.7E-4 N for 20 Hz

and 200 Hz respectively. However as explained in section 5.7, the experiment used to calculate these force values is only an approximation. Further analysis of the forces required for stimulation is thus left for future research presented in section 10.6.5.

Frequency	Group	Mean (mA)	Estimated Force (N)
20 Hz	Implanted	33.97	1.56E-4
	Superficial	68.2	3.14E-4
	Both	51.09	2.35E-4
200 Hz	Implanted	5.44	2.50E-5
	Superficial	18.12	8.34E-5
	Both	11.78	5.42E-5

Table 8-4: Using values from Table 8-3 (excluding I2LP, I7LR, S2LP and S7LP) in order to estimate force applied to the magnet at the amplitude RL for participants of magnet type 1 (Table 7-1) in main study categorised by group.

It is evident that a 200 Hz stimulation signal is more favourable over 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 author describes as a buzz.

8.2.3 Amplitude Discrimination

Results of the amplitude discrimination experiment for all participants within the main study are presented in this section. As stated previously, the Weber fractions used within this analysis are based on the RMS current recordings measured across the coil.

Figure 8-4 presents the participant's Weber fractions (see section 4.3.1.1) for the amplitude discrimination experiment. The results indicate that a lower Weber fraction has been empirically determined for the 20 Hz stimulation frequency over the 200 Hz. Furthermore the range of Weber fractions suggests that there is no difference between the implanted and superficial participants. Within the data there is one clear outlier found within the superficial group at stimulation frequency 200 Hz. The results of the Weber fractions attained per candidate are given in Table 8-5.

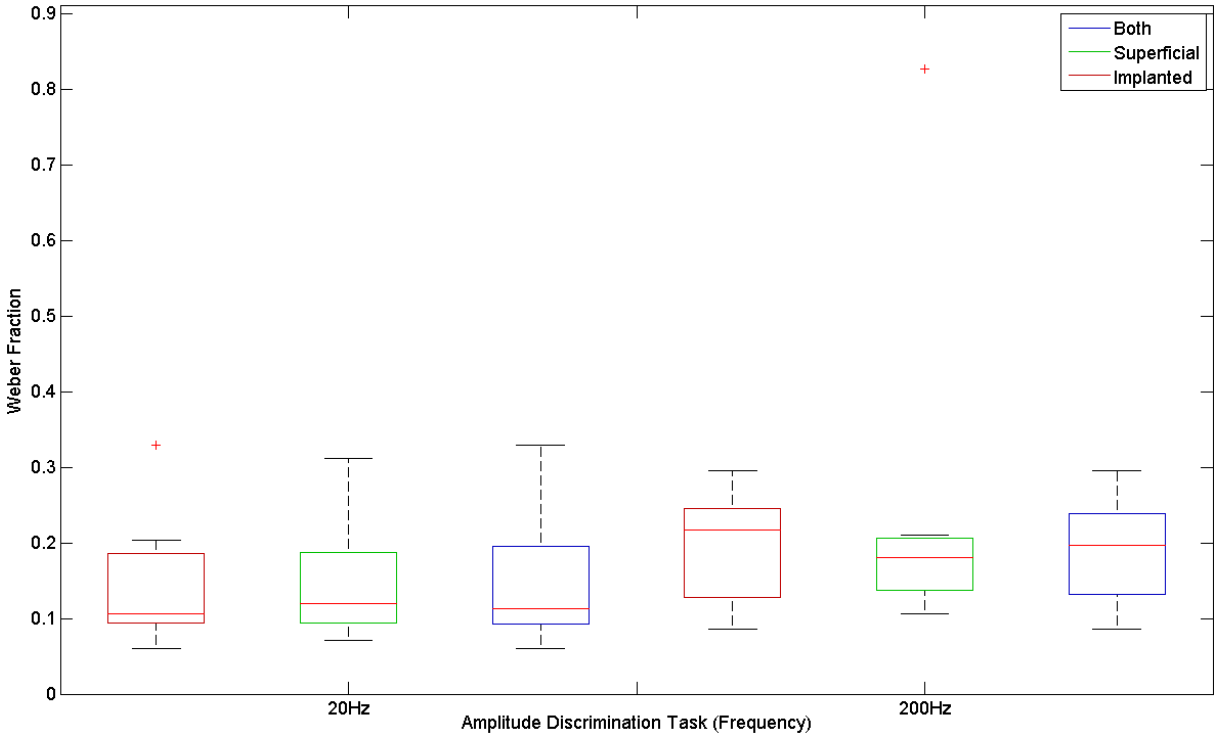


Figure 8-4: Box plot to summarise the results of the amplitude discrimination experiment (presented as Weber fractions) for all participants within the main study (categorised by group)

Amplitude Discrimination Weber Fractions					
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 8-5: Weber fractions for amplitude discrimination experiment for all participants within the main study

The result suspect to be an outlier is S7LR 200 Hz, marked in red in Table 8-5. The results is assumed to be higher than that this particular participant's actual threshold. This assumption is based on observation of the QUEST output from S7LR for this test shown in Appendix M.

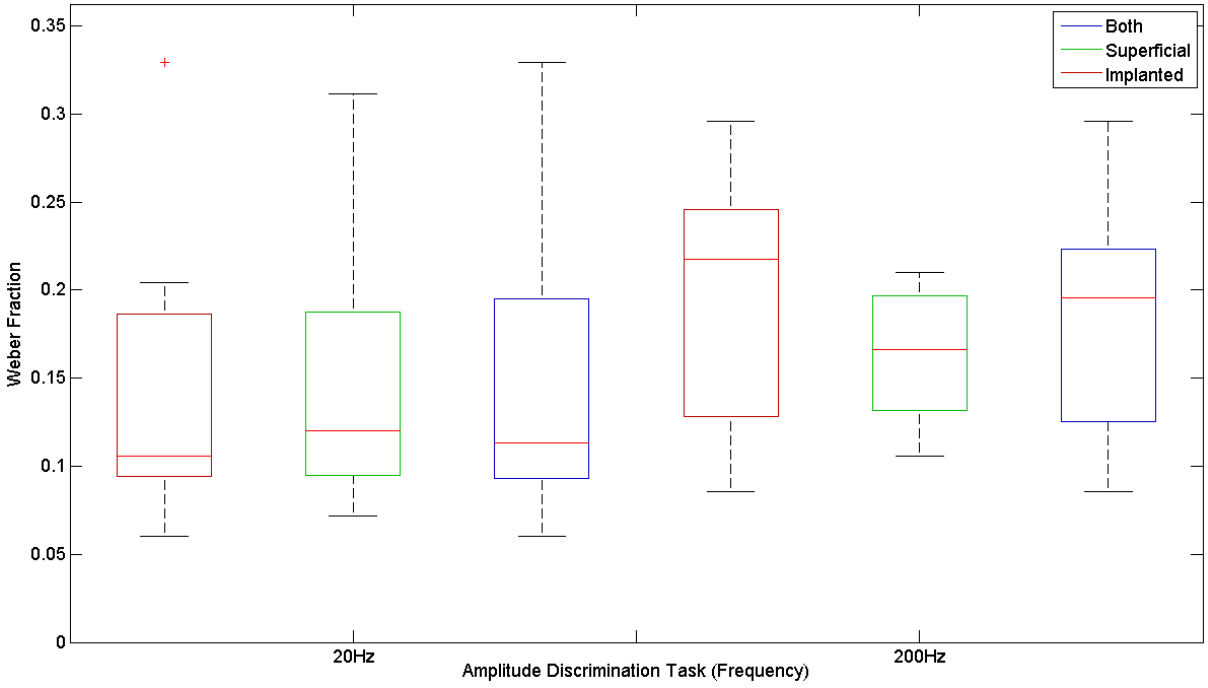


Figure 8-5: Box plots as presented in Figure 8-4 excluding outlying data

Figure 8-5 displays the participant Weber fractions without the outlying data. This plot suggests that the 20 Hz stimulation frequency gave reduced Weber fractions in comparison to the 200 Hz. The summary of the statistics obtained from each group is presented in Table 8-6. The table shows that removal of the outlier clearly affects the mean value attained for the superficial group at 200 Hz, reducing it from 0.26 to 0.16.

		All Results			Results with the outlier removed		
Frequency	**Group**	**Mean**	**STD**	**Median**	**Mean**	**STD**	**Median**
20 Hz	**Implanted**	0.15	0.09	0.11	0.15	0.09	0.11
	Superficial	0.15	0.08	0.12	0.15	0.08	0.12
	Both	0.15	0.08	0.11	0.15	0.08	0.11
200 Hz	**Implanted**	0.20	0.08	0.22	0.20	0.08	0.22
	Superficial	0.26	0.04	0.17	0.16	0.04	0.17
	Both	0.23	0.06	0.20	0.18	0.06	0.20

Table 8-6: Statistics summary of Weber fraction for all of the main study participant's amplitude discrimination thresholds. The outlier is marked in red in Table 8-5.

The range of Weber fractions values, 0.15 - 0.26, is in agreement with the literature. As discussed in section 4.4.4, Craig in 1972 [154] stated the Weber fractions of vibrations determined by Sherrick (1950), Schiller (1953), Knudsen (1928) [95], as 0.3, 0.11 and 0.05 respectively.

Much like with the amplitude detection results, a mixed model accounting for the same factors as before has been fitted to these results. The difference being that for this experiment the dependant variable used is the participants' weber fractions. The full model output is presented in Appendix M.

Similarly to the amplitude detection experiment a large number of personal factors can attribute to variations in the amplitude discrimination experiment as described in section 4.4.4. 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 effect. The model does provide evidence that the frequency of stimulation signal significantly increased the Weber fractions of the participants when changing from 20 Hz to 200 Hz [$F(1, 10.09) = 5.102$, $P = 0.047$].

Whilst this result is in contrast to that presented by Forta *et al.* [158] these authors did conduct their experimentation at different frequencies (10 and 125 Hz), different contactor sizes (1 mm diameter and 10 mm diameter). Furthermore their reference (baseline) amplitude for their experiment was based off of decibel difference from their subjects' absolute threshold. Such differences can dramatically affect Weber fractions of this nature as discussed in section 4.4.4.

Bossomaier [57] discusses 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 more optimum solution would be to perhaps use a continuous pedestal method. This has also been shown to reduce amplitude DL [149, 150, 151]. However the reason for using this methodology 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. Whilst the 20 Hz stimulation frequency has shown empirically to be a better

frequency for amplitude DL, the author personally would still opt for the 200 Hz signal for reasons discussed in the closing remarks of section 8.2.2.

8.2.4 Frequency Discrimination

Results from the frequency discrimination experiment conducted on the main study are presented in this section. Figure 8-6 presents the web fractions for the 20 and 50 baseline frequency discrimination tasks for all the participant's thresholds normalised using Weber fractions. From the data presented for the 20 Hz baseline it is clear that the use of complex waveforms (square and sawtooth) 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 baseline suggests that the sawtooth waveform is the optimum choice for increasing frequency discrimination capabilities of the participants tested. Here the square waveform seemed to dramatically increase participant variation.

Figure 8-6 suggests there are differences between the implanted and superficial groups in particular results. For example, the 50 Hz sinewave results for the implanted group are overall reduced compared to the superficial group. However observing the 20 Hz sawtooth waveform the superficial group seemed to outperform the implanted group. This coupled with the large subject variation indicates the implant type does not have an effect upon these two frequency baselines with regards to frequency discrimination.

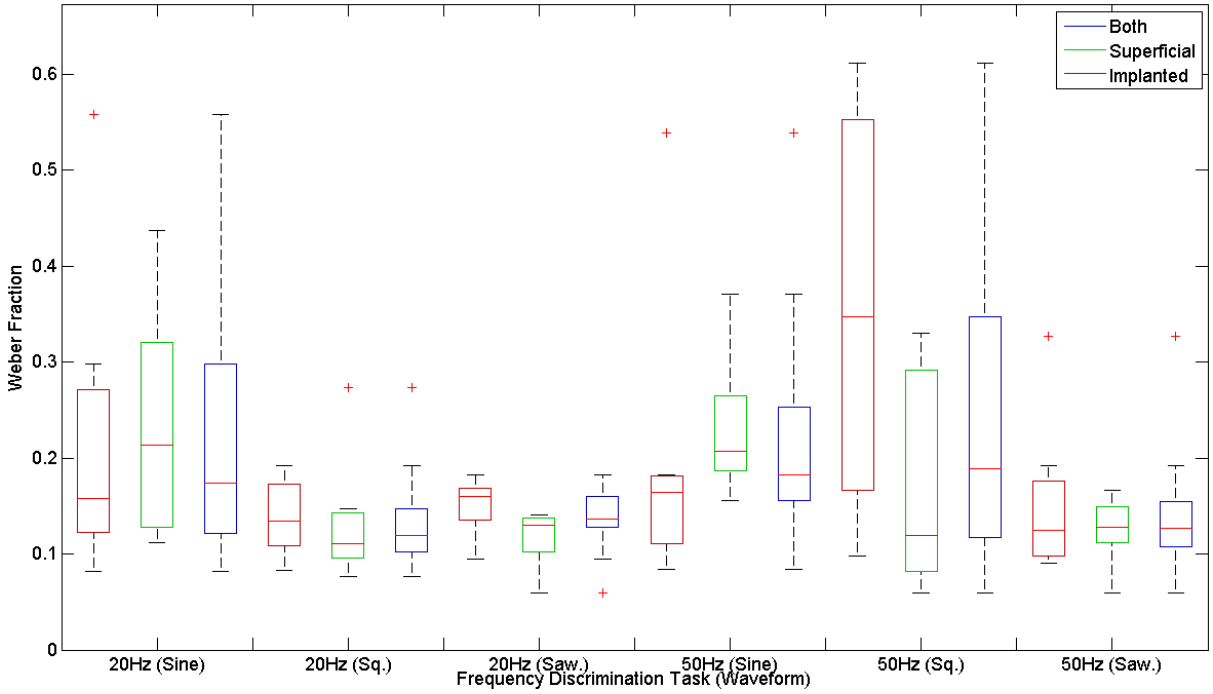


Figure 8-6: Box plot to summarise all Weber fractions for the 20 and 50 Hz baseline frequency discrimination task for all participants within the main study (categorised by group). Sq. – Square. Saw. – Sawtooth.

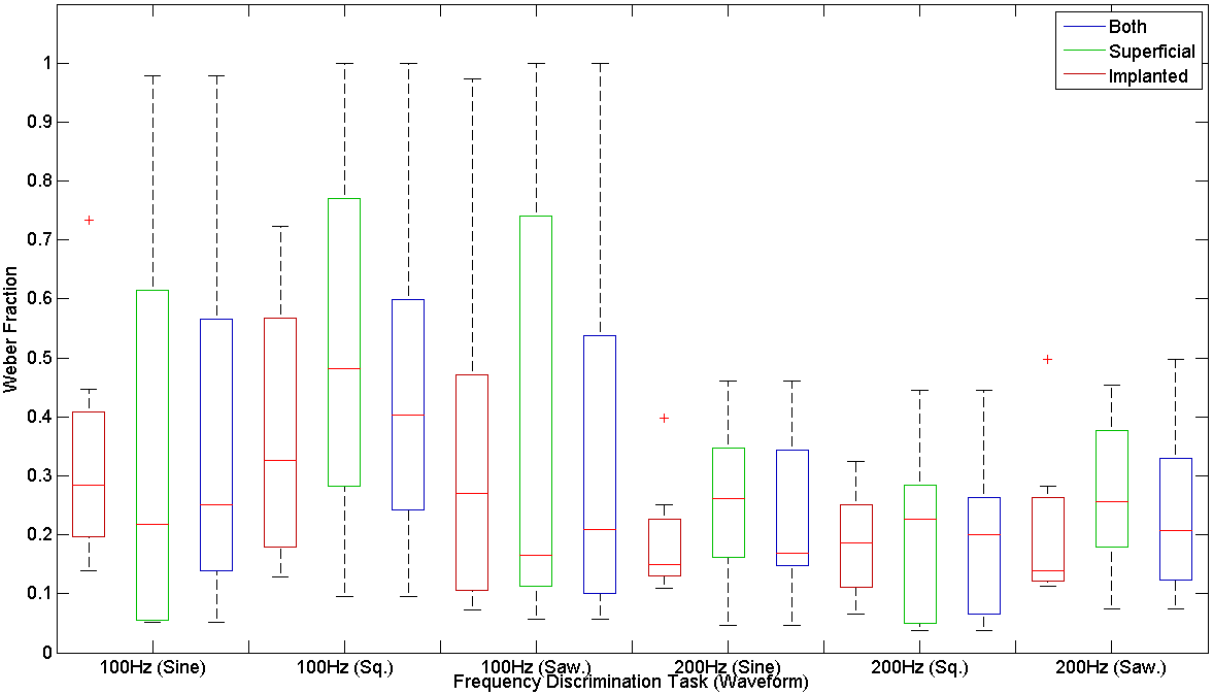


Figure 8-7: Box plot to summarise all Weber fractions for the 100 and 200 Hz baseline frequency discrimination task for all participants within the main study (categorised by group)

Figure 8-7 presents the Weber fractions of all participants within the main study for the 100 and 200 Hz baseline frequency discrimination tasks. The results from the 100 Hz

show a remarkably high range of values. The standard deviation values for the 100 Hz tests, presented in Table 8-7, 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 by Sherrick stating that frequency discrimination 'is poor above 100 Hz' (see section 4.4.5). As previously discussed in section 6.3.1 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.

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

Table 8-7: Statistical summary of all of the participant's Weber fractions from the main study for the frequency discrimination task, displaying the mean, standard deviation and median (categorised by group). Sq. – Square. Saw. – Sawtooth.

The results of the participant's data for the 200 Hz baseline frequency DL experiment seem consistent regardless of the stimuli's waveform. Overall the results seem to indicate that (as hypothesised in section 6.3.1) 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 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, but stimulate the Pacinian corpuscles also (see section 6.3.1).

From Table 8-7, the results for sinewave stimuli are: 0.22, 0.22, 0.35 and 0.22, for the 20, 50, 100 and 200 Hz baseline frequencies respectively. Asides from the 100 Hz results, on average the participant's performance in this experiment, does conform to Weber's law (as discussed in section 4.3.1.1). These results are somewhat in agreement with the results attained by Goff [161], i.e. ~0.18, ~0.19, ~0.3, ~0.28 and ~0.37 for 25, 50, 100, 150 and 200 Hz. The difference in these results to Goff's could be due to differences 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. Here the amplitude is subjectively set to a comfortable level for each participant.

Whilst the data Figure 8-6 and Figure 8-7 contained outliers, they will not be removed from this data analysis as there was no clear reason for their removal. Individual results for this experiment are presented in Appendix N.

The five statistical models have been fitted to this data. The first four are aimed at individually examining the baseline frequencies in order to determine the effects of waveform (see section 7.5.8.1). The final model will be fitted to the entire dataset in order to determine if the 100 Hz results are statically different to the other three.

The model type used was mixed models for all of the models except for the 20 Hz baseline. The reason for this was that when the 20 Hz baseline frequency data was fitted to a mixed model an error occurred due to the lack of variation of the participant's data; this caused SPSS to display a warning informing that this model was not fit for purpose. Hence for the 20 Hz baseline a univariate model was used. The dependent variable used for each of the models was the Weber fraction. The factors (i.e. independent variables) that were accounted for within each of the statistical models were as follows (models are presented in Appendix N):

- **Participant ID** – used a random factor to account for the variability of subjects (in models 2-5).
- **Implant Type** – implanted or superficially attached.
- **Frequency** –20 or 200 Hz (model 5 only).
- **Waveform** – Used predominantly in models 1-4 in order to determine if waveform has an effect on each of the four baseline frequencies. However was also included in model 5.

- **Interaction** – The models used a full factorial approach i.e. all factors were cross examined for interaction effects.

	Model Number			
Factors and Effects	**1 (20 Hz)**	**2 (50 Hz)**	**3 (100 Hz)**	**4 (200 Hz)**
Participant's Data 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

Table 8-8: Summary of models 1 – 4 fitted to the frequency discrimination Weber fractions from each participant within the main study, i.e. individually examining each baseline frequency for waveform effects. *[F(2,36) = 4.540, P = 0.017], **[F(2,24) = 4.222, P = 0.027]

A summary of the results of models 1 – 4 is presented in Table 8-8. The largest variance explained by the participant's data was the 200 Hz, the 4th model. This is interesting in that while the range of values attained within the 100 Hz task was a lot larger than that of the 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 Hz and 50 Hz baseline frequencies. Post-hoc analysis with the Šidák correction was conducted upon the waveform factor in order to ascertain which variables caused these significant values. A summary of which is presented in Table 8-9.

Model 1 (20 Hz)	**Square**	**Sawtooth**	**Model 2 (50 Hz)**	**Square**	**Sawtooth**
Sine	P = 0.04*	P = 0.038*	**Sine**	P = 0.657	P = 0.227
Square		P > .999	**Square**		P = 0.025*

Table 8-9: 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). * The mean difference is significant at the 0.05 level.

The results in Table 8-9 combined with Table 8-7 show that the complex waveforms for the 20 Hz baseline both significant improved the participants ability to perform the frequency discrimination experiment. The pairwise comparison of the 50 Hz baseline revealed that the only significant difference that is present is between the square and sawtooth waveforms. Exploring the mean results presented in Table 8-7 gives reason to this, however still indicates that on average the sawtooth wave increases the participants ability to discriminate frequencies.

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 [165] (as described in section 4.4.5) have shown that as SOI increases the ability to accurately discriminate frequency significantly decreases. From undocumented self-conducted testing by the author, the continuous pedestal method does indeed make the discrimination task easier to comprehend, which is essential for a high stress scenario.

From the author's personal experience of the sensations perceived with the complex waveforms, he makes the following recommendations. For lower frequencies (20-70 Hz) the author recommends using the sawtooth waveform for two reasons. Firstly, it has been shown here to increases one's ability to discriminate frequencies. Secondly, to the author at least, the sawtooth waveform feels more intrusive than the sine and square waveforms, which is essential for warning alerts in high stress scenarios. For higher frequencies (200-300 Hz) the author recommends using the square waveform, again due to its intrusive nature.

A final point of interest for the frequency discrimination experiment came from remarks of participants post completion of a number of these tests. 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 whilst 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.

Whilst further discussion of these comments is omitted from this thesis as it does not fall within the context of the research, its inclusion in this section is merely as an interesting side note.

8.2.5 Temporal Discrimination

The following section provides the results from the temporal discrimination experiment. Figure 8-8 presents the participant's Weber fractions for the 20 and 200 Hz temporal discrimination experiments. Through observation of the results it appears that

the 200 Hz stimulation frequency slightly increased the participant's temporal discrimination threshold. This observation is emphasised through examination of the mean results for both groups presented in Table 8-10; 0.24 and 0.31 for the 20 and 200 Hz stimulation frequencies respectively. Whilst there is an outlier within the data presented in the 20 Hz stimulation frequency (Figure 8-8), there exists no valid real world reason for its removal from statistical analysis. The individual results for participants can be found in Appendix O.

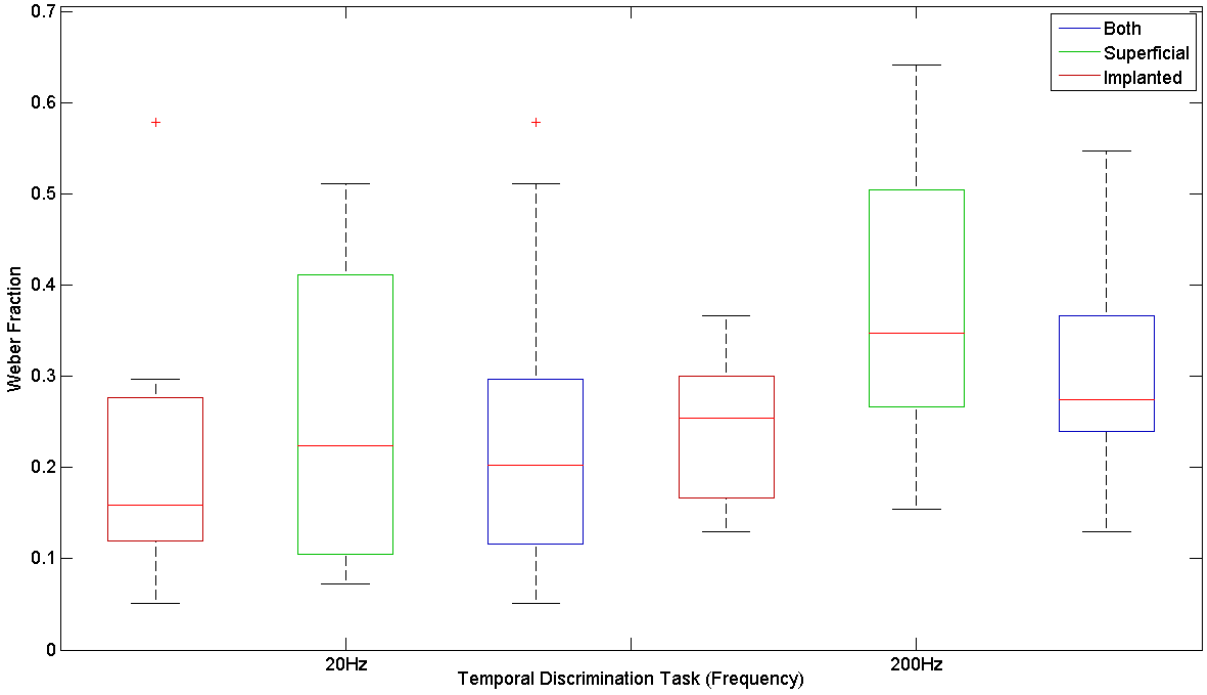


Figure 8-8: Summary of the participant's Weber fractions for the 20 and 200 Hz temporal discrimination task (categorised by group)

Test	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

Table 8-10: Statistical summary of the participant's Weber fractions for the temporal discrimination experimentation

The closest comparable result (due to variables used) is that presented by Güçlü *et al.* [176], whom examined temporal DL with a 500 ms baseline (250 Hz sinewave) signal, and reported a Weber fraction of 0.4. Whilst the result obtained by the experiment conducted in this research is smaller than this, i.e. 0.31 (Table 8-10, mean 200 Hz, from both groups),

the difference can be attributed to 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 factors used with the same as that used in the amplitude detection experiment model and the dependent variable used are the participant's Weber fractions. The full model output is presented in Appendix O. The variance explained by the participant's data is ~26%, however none of the factors examined have shown to be significant. This is unsurprising given the results presented in Figure 8-8 and Table 8-10.

The aim of this experiment was to empirically determine whether a change in frequency affects an individual's ability to perform a temporal discrimination task. Through qualitative and quantitative analysis this is found not to be the case for this set of participants. If changes in signal length were used to relay information, in order 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 sawtooth signal concatenated (with no SOI) with a 200 ms, 200 Hz squarewave 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 particular piece of information.

8.2.6 Temporal Numerosity Discrimination With Respect to Temporal Gap Detection

The following section presents the main study participant's results of the temporal gap detection experiment that was conducted in the form of a temporal numerosity discrimination task. The results for all participants in the main study are presented in Figure 8-9. The results for each of the three pulse types show a similar somewhat linear increase in separation time is required for the participants to correctly identify the number of pulses. However there are a few differences. 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 Figure 8-10. 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 the 20 Hz, 250 ms. The gradient is similar between the two, however the intercept is much greater in the 20 Hz, 250 ms pulse type (see Figure 8-10).

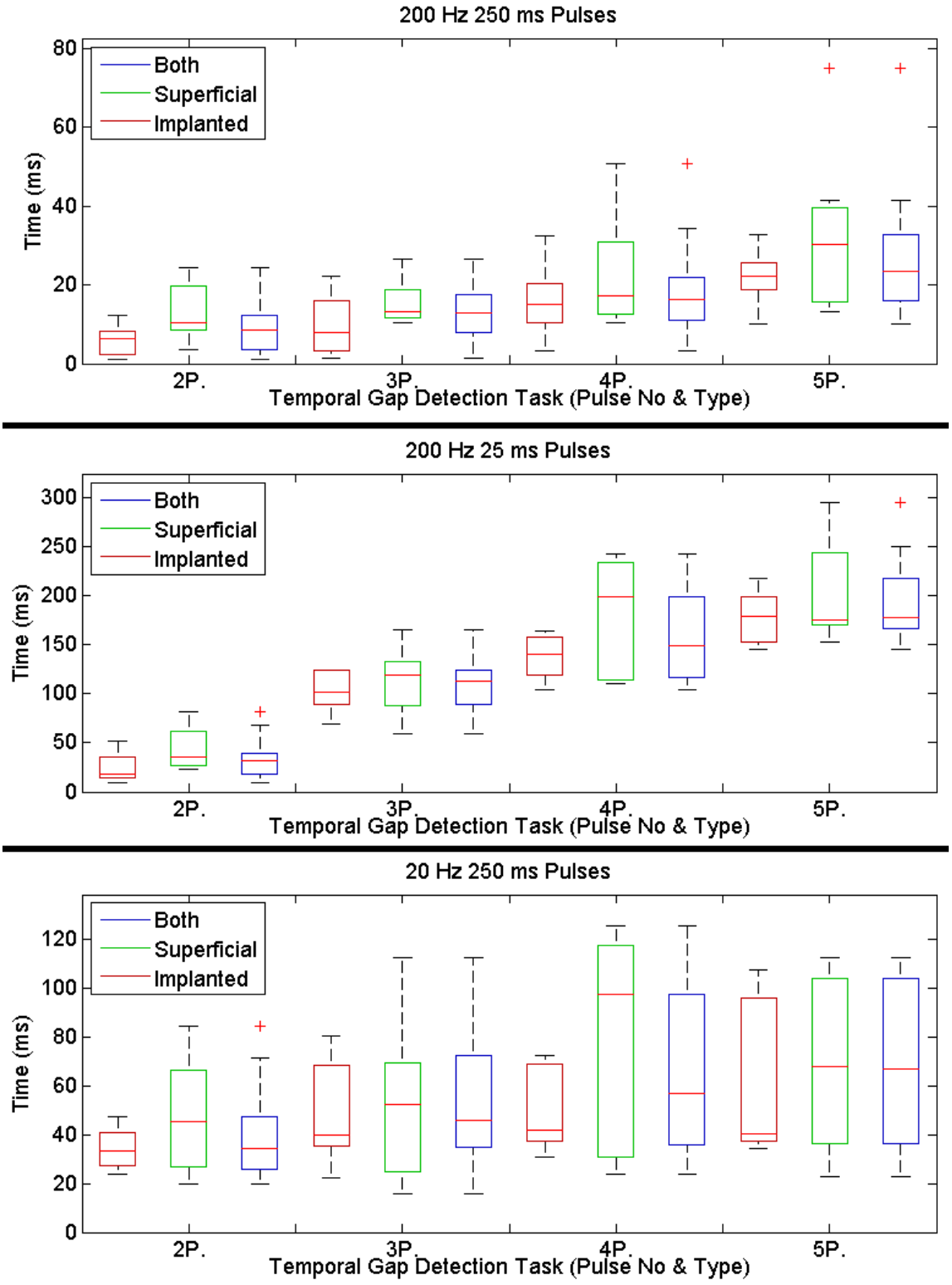


Figure 8-9: Summary of the main studies participant's data collected in the temporal gap detection experiment, stimulation pulse type is defined in each title. (N.B. the time label on the y-axis refers to the separation time between pulses)

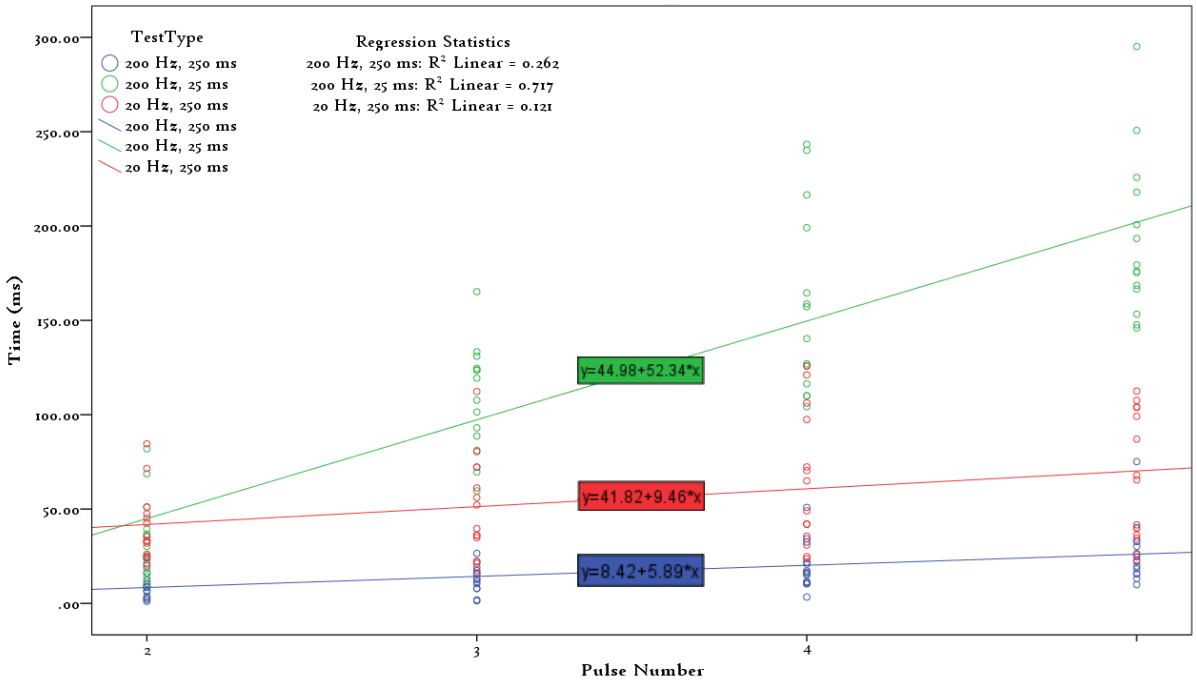


Figure 8-10: Scatter plot with fitted regression lines of participant's data for the temporal gap discrimination experiment. (N.B. the time label on the y-axis refers to the separation time between pulses)

		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	Imp.	5.70	4.02	6.26	25.24	14.81	18.56	34.42	8.40	33.25
	Sup.	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	Imp.	10.41	7.82	7.95	103.51	21.34	101.44	48.80	21.41	39.67
	Sup.	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	Imp.	15.81	9.34	15.09	138.19	23.31	140.29	51.17	17.44	42.07
	Sup.	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	Imp.	21.94	7.11	22.16	178.80	27.15	179.37	63.48	32.82	40.11
	Sup.	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

Table 8-11: Statistical summary of the participant's data collected as part of the temporal gap detection experiment, the values presents are all measured in ms. (Imp. – Implanted, Sup. – Superficial)

Whilst there is some variation shown between the implanted and superficial groups, it is most likely due to participant variation rather than the implant type factor itself. As can be seen a few outliers are present within this data however much like the frequency discrimination experimental results, there is no valid reason to remove these data points from statistical analysis.

The regression statistics shown in Figure 8-10, describes a strong linear correlation between pulse number and separation time for the 200 Hz, 25 ms pulse type (R2 = 0.717). This can be observed numerically from the mean and standard deviation results presented in Table 8-11. 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.

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, see section 7.5.7. 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 8-11), 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 attained in this experiment to those presented in the literature section 4.4.7, the closest comparable results are those presented by Philippi *et al.* [180]. 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, 3, 4 and 5 pulses SOI was ~20 ms, 80-160 ms, and 160-320 ms. 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 the Bresciani and Ernst [186] who presented that separation time decreased as pulse frequency increased; i.e. 65 ms to 50 ms as frequency changed from 35 Hz 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 ms to 9.48 ms for the both group's 2-pulse TGD as shown in Table 8-11.

As discussed in section 7.5.7.1, in order to examine comparisons is outlined in Table 7-9 three models have been created. To clarify, each model number comparison is given below:

- **Model 1** – compares the 200 Hz, 250 ms pulse type and the 20 Hz, 250 ms pulse type

- **Model 2** – compares the 200 Hz, 25 ms pulse type and the 20 Hz, 250 ms pulse type
- **Model 3** – compares the 200 Hz, 250 ms pulse type and the 200 Hz, 25 ms pulse type

The model type used is once again mixed models and the dependent variable for each of the models is the separation time estimated (by QUEST) per pulse number per participant. The factors, effects and controlled factors examined within the each of the models are presented below:

- **Participant ID** – used a random factor to account for the variability of subjects.
- **Implant Type** – implanted or superficially attached.
- **Frequency** – 20 or 200 Hz (examined in models 1 & 2, controlled in model 3).
- **Pulse Number** – 2, 3, 4 or 5.
- **Number of Cycles** – 5 or 50 (examined in model 3, controlled in model 2).
- **Pulse Length** – 25 or 250 ms (controlled in model 1).

	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 8-12: 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

The results of each model are presented in Appendix P, a summary of which is given in Table 8-12. As stated in Table 7-9, the factors of interest for each model are the following: frequency for models 1 and 2 and the number of cycles for model 3. Each of the factors of interest significantly affects the separation time required for these participants to correctly determine the number of pulses.

The model 1 results presented in Table 8-11 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).

The model 2 results presented in Table 8-11 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).

The model 3 results presented in Table 8-11 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 is to minimise the total signal length required to convey information to an individual via this method in a high stress scenario. A summary of the total signal lengths dependent upon the gap time required per pulse number is presented in Table 8-13. These are based on the estimated mean separation times for both groups given in Table 8-11, as there was no significant difference found in implant type (Table 8-12).

	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

Table 8-13: Summary of total signal lengths (ms) for the given pulse type and the TGD threshold determined per pulse number for all participants within the main study

As the 200 Hz, 25 ms pulse type has the shortest total signal lengths (Table 8-13), from those tested, it would be the most optimum for use in high stress scenario applications. However in order to empirically determine if this is 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 sinewave, a square waveform would be better suited for application as it is perceptually more intrusive than

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

8.3 Three-Month Study

The following section provides a qualitative analysis of the results obtained from the two participants within the three-month study (described in section 7.2.2.2). The section explores the results of the RT experiments and further examines the results of the QUEST based experiments.

8.3.1 Reaction Time

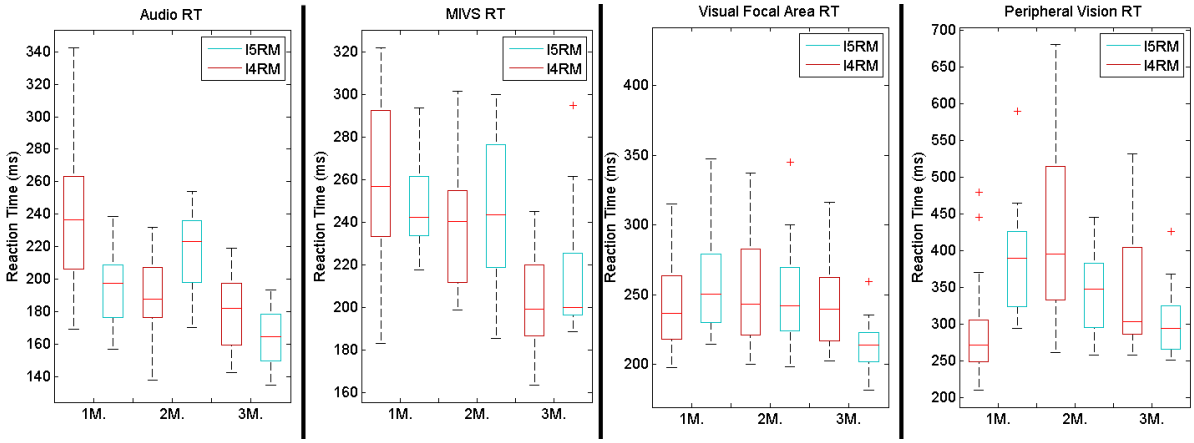


Figure 8-11: Summary of the RT data collected from the two participants within the three-month study (xM. – Month Number)

Figure 8-11 presents the results of the two participant's RT data over the three months. There are a number of ways in which this data could be interpreted. Two of which are described below:

- **Effects of Training** – A possible observation that can be made from this data is that the two participants may have improved over time due to training effects. For example the results of I4RM's MIVS RT data suggests that the participants RT has reduced over the three months, this is similar to the results of I5RM's peripheral vision RT which also shows a reduction over the three month period.
- **Participant variation** –A more plausible explanation as to the variation in the data obtained over the three months is simply that external factors affected their results, such as fatigue (although none was commented see section 7.3.4), stimulant intake (e.g. caffeine) and/or distractors (e.g. personal circumstances). This interpretation

is based knowledge of the number of subject dependant factors that affect RT data (section 4.4.2), as well as the number of examples where training seems to have not occurred. For example, the audio RT data from I5RM and the peripheral vision RT data from I4RM.

8.3.2 QUEST Experiments

As stated previously, there are four QUEST based experiments conducted as part of the three month study. These are frequency discrimination, temporal discrimination, amplitude discrimination, and amplitude detection. Similarly to the three-month RT data, high participant variation is present in the results for the QUEST based experimentation. This again could be attributed to external factors such as those described in the participant variation discussion in the previous section. In order to remain concise and the graphs displaying the QUEST based experiments are presented in Appendix Q.

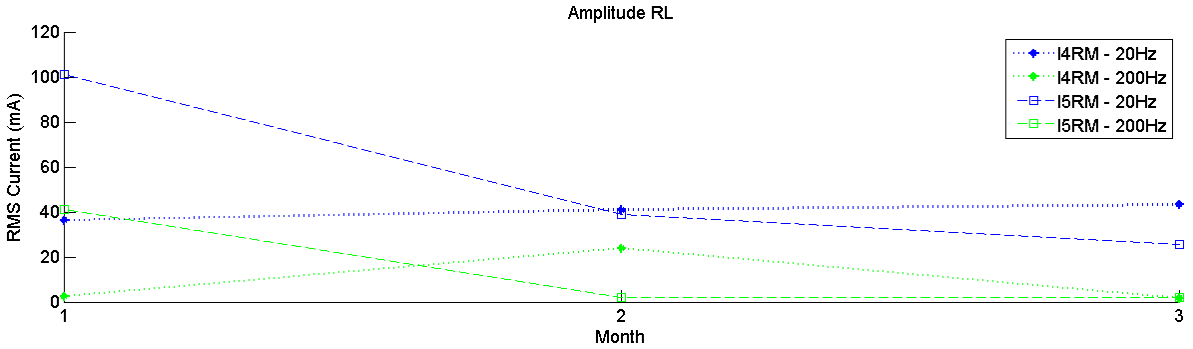


Figure 8-12: Participant's data for the amplitude detection experiment as part of the 3-month study

Of the data collect there is only one case that presented a high indication that training effects and/or healing effects are potentially present. Figure 8-12 presents the participant's data for the amplitude detection experiment for the three-month study. I5RM results show a threshold reduction in both tested frequencies over the three months. However as this is not present in I4RM's results, this more likely a coincidence, as large number of personal factors contribute to amplitude detection thresholds (see section 4.4.3).

The purpose of the three month study is to ascertain if there are any perceptual changes over the three months post implantation which may be attributed to healing effects. From the results obtained this appears not to be the case. These results further highlight how subjectively dependent psychophysical experimentation is.

8.4 SSUS

The following section briefly discusses the SSUS participant's results in comparison to the main study results. As stated in sections 7.4.5 and 7.5.8 the comparison of the SSUS participant data was conducted using (two tailed) Z scoring analysis against the main study. The outcome of the Z score testing has shown that the SSUS participant's results are not significantly different to any of the results from main study. The detailed Z score results are presented in Appendix R.

Wan *et al.* [168] presented results showing that individuals with congenital blindness had significantly improved frequency discrimination capabilities when compared with that of normally sighted participants (discussed in section 4.4.5). The study presented by Wan *et al.* contained 30 participants whereas here only one participant has been tested. Whilst the frequency discrimination results presented for the SSUS participant are not statistically different to that of the main studies', in 11 out of the 12 tests the Z scores comparing the two studies are negative in the range of -0.09, to -1.34. This suggests that the SSUS participant does possess a somewhat consistent average increase in his ability to discriminate frequencies. The effects of tactile training through conditions such as congenital blindness should have an effect on tasks such as frequency discrimination, much like musical training has shown to have an effect on temporal discrimination in the auditory sense [176].

8.5 Summary

Within this chapter the results from the participant experimentation experiments (as introduced in Chapter 7) have been presented and discussed. A summary of the findings for each of the experiments is presented below:

- **Main Study**
  - **Reaction Time** – The RT data collected and examined has been shown to best fit an ex-Gaussian distribution. Using the values from the ex-Gaussian distribution means, a mixed model has been fitted to the data. The results from the model showed that of the data collected the stimulus modality factor had a significant effect ($P < 0.001$). The analysis revealed that the auditory modality significantly reduced ($P < 0.001$) RT compared with the MIVS modality; the MIVS modality is not statistically significant to the visual focal ($P = 0.861$); yet these modalities have

significantly reduced ($P < 0.001$) RTs compared with the peripheral vision stimulus. Finally there is no statistical evidence to suggest that the implanted group differed from the superficial group.

- **Amplitude detection** – The results from the amplitude detection experiment are presented as the RMS current provided to the coil at the absolute vibrotactile threshold. The mixed model fitted to the data collected has shown that the 200 Hz stimulus frequency significantly reduced ($P < 0.001$) the participant's amplitude detection threshold. Furthermore statistical evidence suggests that the implanted group required significantly less ($P = 0.012$) current in order to perceive MIVS compared to the superficial group.
- **Amplitude discrimination** – The results from the amplitude discrimination experiment are presented as Weber fractions calculated against the subjective amplitudes of each of the participants. Of the results collected the 20 Hz stimulation frequency showed significantly improved ($P < 0.047$) participant's ability to discriminate vibrotactile amplitudes when compared with the 200 Hz stimulation signal. However there is no statistical evidence to suggest any difference between the performance of the implanted and superficial groups.
- **Frequency discrimination** – The results of the frequency discrimination experiment are presented as the Weber fractions calculated against baseline frequencies used per test. Statistical analysis of the results of each individual baseline showed that waveform significantly affected the participant's ability to discriminate frequencies at the 20 Hz and 50 Hz baseline ($P = 0.017$, $P = 0.027$). Post hoc analysis revealed that the square and sawtooth waveforms significantly increased the participant's ability to correctly discriminate between waveforms at the 20 Hz baseline. Post hoc analysis of the waveform for the 50 Hz baseline frequency revealed that the square waveform significantly reduced ($P = 0.025$) an individual's ability to discriminate frequencies when compared with the sawtooth waveform. Overall the Weber fractions collected at each baseline frequency for the sine waveform were consistently 0.22, for the 20, 50 and 200 Hz baseline frequencies and was increased at the 100 Hz baseline to 0.35. There is no statistical evidence to suggest any difference in the implanted group when compared with the superficial group.
- **Temporal discrimination** – The results from the temporal discrimination experiment are presented as Weber fractions compared against the baseline signal

length of 250 ms. Statistical modelling presents no evidence that neither frequency nor implant type has an effect upon the participant's ability to discriminate temporal lengths.

- **TND with respect to TGD** – The results of the TGD experiment are presented as the separation time (ms) between concatenated signals required for the participants to perform a TND experiment. Statistical analysis revealed that for a given pulse length and pulse cycle number frequency significantly affected ($P < 0.001$) the separation time required for that participants to correctly perform the TND experiment. Furthermore for a given pulse frequency, the pulse cycle number was found to significantly affected ($P < 0.001$) the separation time required for that participants to correctly perform the TND experiment. The pulse type determined most optimum for information transfer for use within high stress scenarios was the 200 Hz, 25 ms. Finally there is no statistical evidence to suggest there is a difference between the implanted and superficial participants within this experiment.

- **Three month study** – The results obtained from the three month study participants is qualitatively analysed with the overall goal observing effects of healing post implantation of SMIs. Given the large variation of the results collected from the two participants, the results do not suggest that any negative healing effects or effects of training across the recording sessions. However do highlight how subjectively dependent psychophysical experimentation is.
- **SSUS** – The results obtained from the SSUS participant are analysed by use of Z scoring to the results of the main study. Of the 30 experiments cross examined, there is no statistical evidence to suggest that the SSUS participant's results are different to the main study results.
- **Implant type** – To clarify the results of the two implant groups tested (implanted and superficial) the only result which showed enough statistical evidence to reject the null hypothesis (that the two groups are equal), is the amplitude detection experiment.

Chapter 9 – Application – VDrift

9.1 Introduction

As previously mentioned, this research has the potential to be used within the automotive industry as a form of human machine interface for a driver. As discussed in section 4.4.1 tactile warning systems have been shown experimentally to reduce a driver's reaction time in braking tasks. This chapter describes how modifications to an open source driving simulator called VDrift have been used in order to explore the application of this research within the automotive industry.

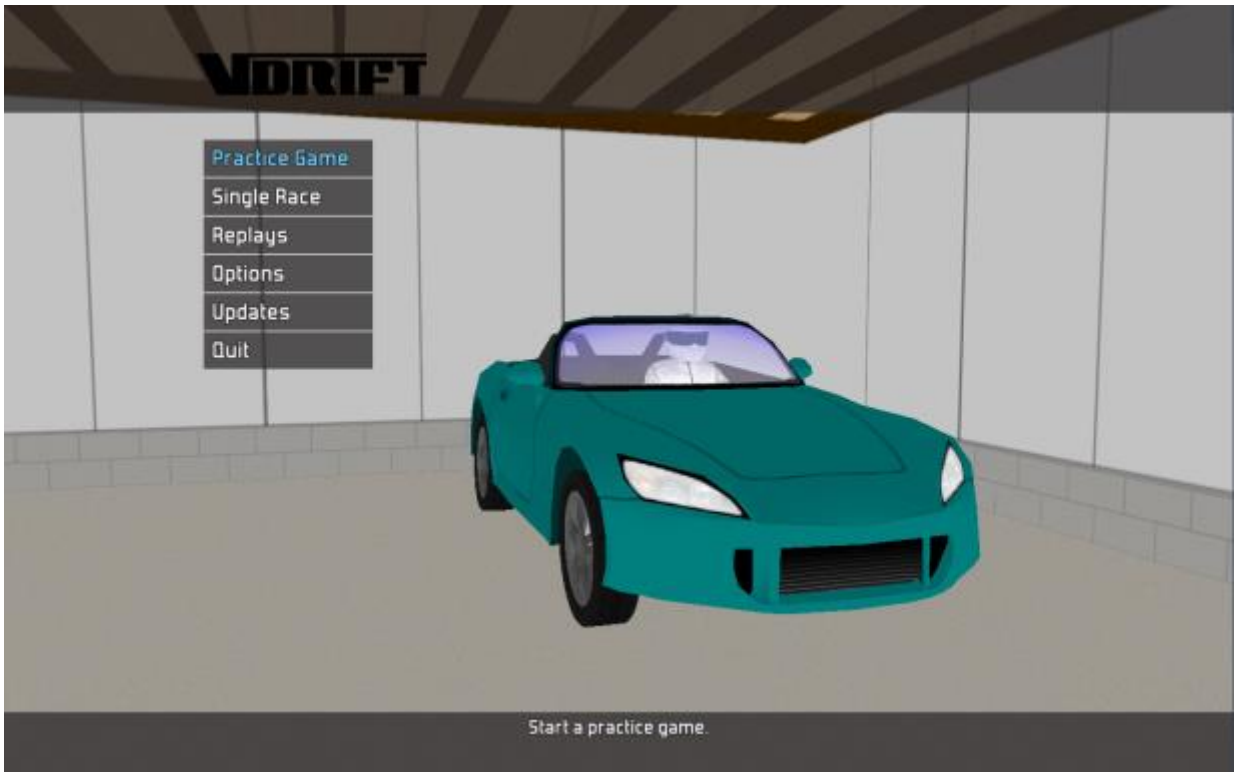


Figure 9-1: VDrift title screen

VDrift is a cross-platform, open source driving simulation made with drift racing in mind [233]. VDrift was initially created by J. Venzon in early 2005 in an attempt to create a more realistic game that better simulated a car's dynamics during the loss of traction in

comparison with racing games that were available at the time. Since then many developers have worked on this project's development. Now not only is it a game, but is also used within the automotive industry to simulate particular driving scenarios.

The development/modification of Vdrift for this particular application was conducted as a collaborative task between the author and his industrial funding body. The particular aspect of driving in which the modifications to the game were tailored towards were to simulate rear to end collision situations in city like environments.

Figure 9-2: Logitech G27 racing wheel

In an attempt to recreate a more realistic driving situation the Logitech G 27 racing wheel was used (Figure 9-2). The specification for the racing wheel is presented on Logitech's website [234]. This system provides not only a steering wheel, pedals, and gearstick, but also in this particular model, force feedback in the steering wheel. This force feedback features works in collaboration with VDrift, which ultimately increased the immersive feel of the simulation.

The aim of the developed algorithm was to simulate automotive rear-to-end collisions and observe how MIVS warning alerts affect the RT of the driver compares with that of visual (i.e. the simulation) and auditory feedback. This required a number of specific changes needed to be made to the game, which are outlined in this chapter.

9.2 The distance to the car ahead

As the game is typically used for simple racing there is no requirement for the driver within the virtual realm to have any knowledge other than visual feedback of the distance to objects within its path. Within this simulation the distance of the object in front of the driver was crucial in providing tactile feedback. This was attempted using two methods: CastRay and Geometric Location.

9.2.1 CastRay

The CastRay function was built into the game at the time of this development. This function creates a virtual beam/ray to be cast from the central point of the driver's vehicle in a predefined direction which is used programmatically to determine the distance to the closest object. Through empirical testing of this method many problems arose which are illustrated in Figure 9-3. As can be seen in screenshots along the top row of Figure 9-3, there are points in the driving simulation at which the CastRay simply does not function as required. This is due to the projection vector of the ray.

For instance during acceleration (Figure 9-3 (1,1)) the car is angled upwards slightly, such that the front of the car is higher that the rear. This causes the ray to be angled into the 'sky' and hence the maximum range of the ray (1000) is given by the function. During breaking (Figure 9-3 (1,2)) the car is angled downward slightly, such that the front of the car is lower than the rear. This causes the CastRay function to output a much lower value, as the closest object is the road itself. The output of the CastRay function before the AI car before turns the corner (Figure 9-3 (2, 1)) is 6.6. However as the AI car turns the corner (Figure 9-3 (2, 2)) the ray is no longer colliding with it, and so the CastRay function outputs 132.9. As these output values are somewhat volatile, an alternative measurement of distance between the two cars was required.

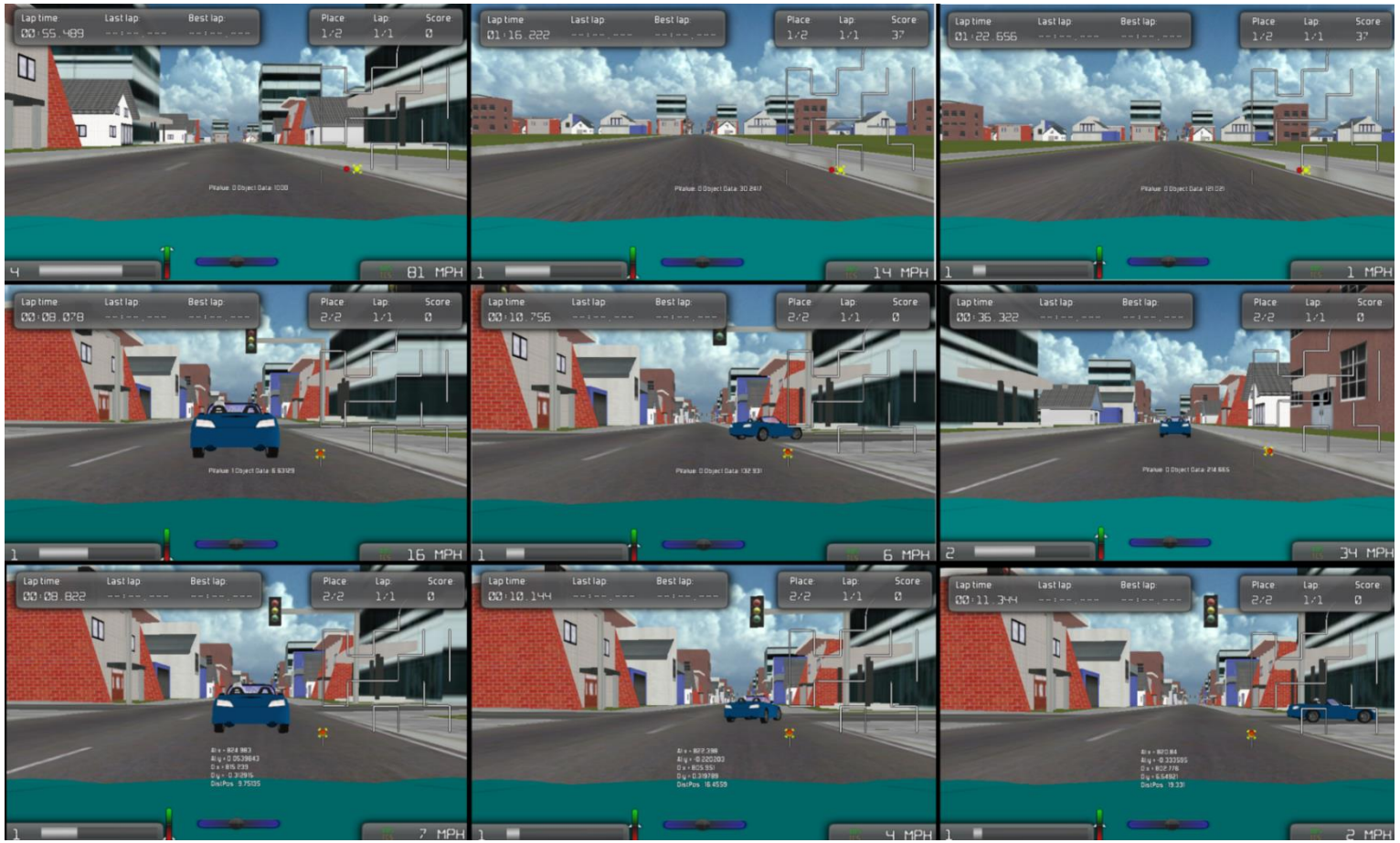


Figure 9-3: Screenshots taken from VDrift with debugging information displayed. (1, 1) CastRay = 1000 during acceleration. (1, 2) CastRay = 30.1 during breaking. (1, 3) CastRay measurement 121 constant velocity. (2, 1) CastRay = 6.6 prior to AI car turn. (2, 2) CastRay = 132.9 post AI car turn. (2, 3) CastRay = 214.6 inaccurately locating AI car. (3, 1) Geometric Location = 9.7 prior to AI car turn. (3, 2) Geometric Location = 16.4 during AI car turn (drivers car almost stationary). (3, 3) Geometric Location = 19.3 post AI car turn (again drivers car almost stationary).

9.2.2 Geometric location

Although CastRay is a better simulation of an automotive sensor, its unreliable position data meant that the geometric location was the most logical method of determining distance. This was completed simply by using the Pythagorean distance from the simulated driver's car to the simulated AI car. Although this approach has the apparent downside of not providing feedback to the driver of in game objects other than the simulated AI car; this was deemed sufficient by the author's industrial funding body for this particular application. The output of this method as the AI car turns around a 90° corner is present in the bottom row of screenshots in Figure 9-3.

9.3 Providing tactile feedback

Figure 9-4: (Left) Photograph of the 'stimulation glove'. (Right) Photograph of the author using the simulator.

A varied number of pulses per second are used to provide tactile feedback of varied intensity level from the simulation to the driver, in this case the author. These pulses are provided to the author from the simulation via MIVS from the 'stimulation glove' (see Figure 9-4). The pulses are amplified by the STA 235 IMG power amplifier; the same used in experiments presented in Chapter 6 and Chapter 7. The stimulation glove is simply a cycling glove with coil windings around the authors implant areas, i.e. his left index and middle finger pads. The proposed method for providing this feedback in a

vehicle would be to emit electromagnetic fields for the MIVS from the steering wheel, the dashboard and the gear lever using hidden coil like devices.

In order to achieve this, the strength of the field required to stimulate the driver would have to be taken into account in the design of the coil/electromagnet, which further gives reason as to why the amplitude detection experiment (described in Chapter 7) has been conducted.

The tactile warning alerts signals have three levels when presented, which vary with the number of pulses. These alerts consisted of 1, 2 or 3, 25 ms, 200 Hz sinewave pulses with a 100 ms separation time between them every 500 ms. One pulse per 500 ms represented the lowest intensity which represents that light breaking is required by the driver, and three pulses represented the highest intensity which informed the driver that heavy breaking is required.

The tactile warning pulses were created and embedded into the game's program as sound files. These are outputted from the pc via the power amplifier to the electromagnetic glove creating MIVS, based on two factors: the drivers speed and the distance between the driver's car and the AI car. The safe stopping distance D (m) at any speed u (mph) is given by the following equation (when x = 1) which has been adapted [235] from the UK Highway code [236].

$$D \cong x * ((u + 0.05 * u^2) * 0.3048) \tag{9.1}$$

Where 0.3048 is the constant for converting between feet (for mph) and meters (as VDrift uses SI units as measurement) and x is the pre-multiplier used to continuously provide tactile feedback as shown in Figure 9-5.

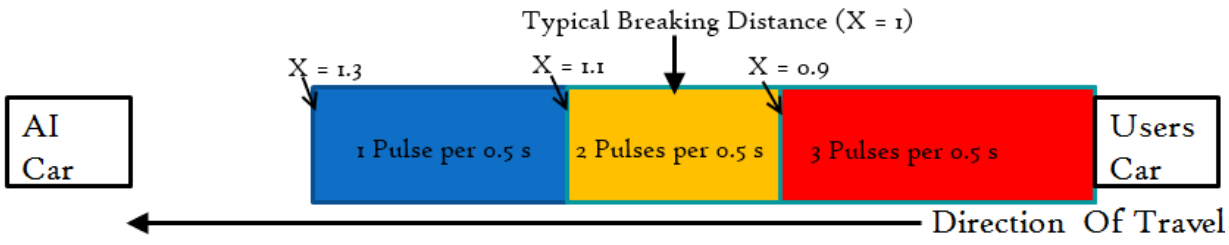


Figure 9-5: Illustration of tactile warning tones dependent upon the distance between the users/drives car and the AI car.

For example if the driver's car is traveling at 40 mph and it's distance to the AI car is in the ranges of, 83.7 m to 70.8 m, 70.8 m to 57.9 m or 57.9 m to 0 m, the driver would receive a level 1, 2 or 3 tactile warning alerts respectively. If the distance was greater than 83.7 m no tactile alerts would be presented.

9.4 Modification to typical AI car

The typical operation of the AI car within VDrift is such that it maximises its speed around the course dependent upon the predefined game difficulty setting, whilst following a predefined 'raceline'. Within this application however the AI car is required to travel at city driving speeds (~30 mph); furthermore in order simulate rear to end collision the AI car needs to accelerate and decelerate randomly. In this simulation however, the AI did not perform this process randomly, instead it was instructed to follow a set path and increase and decrease its speed at set locations. The reason for this is that during corning the AI car could have undesirably randomly increased it speed. In future development of this modification the random increase and decrease in acceleration of the AI car will be computer randomised whilst the AI car is driving in a straight line, and then set to reduce its speed around corners as standard.

9.5 The speed of data collection

In order to modify VDrift such that data regarding the measurements of the hardware (e.g. pedal positions and steering wheel position) and the game state (e.g. the car's speed, the in game time and the distance to the AI car) could be recorded and also provide the tactile feedback to the driver, the created function has been added to the 'Game Loop'. The 'Game Loop' refers to the indefinite for loop used to update the games visual display. This was chosen as the place to add the created function due to the complexity of the game program itself and the limited time available for the creation of a separate thread to perform these tasks.

Whilst this prototype does function i.e. it provides tactile feedback when required; the recording of data is limited to the games frames per second, FPS. After attempting to increase this rate by the use of increased graphical processing power, the game still only operates at approximately 65 FPS. Furthermore the FPS could not be stabilised even after removing of all graphic intensive processes such as antialiasing and shadowing effects.

This unfortunately means that data recording is not only restricted to a resolution of ~15.3 ms, but also this value is not constant from one measurement to the next. Hence no accurate RT measurements can be recorded.

9.6 Further development

Future development of VDrift would be aimed predominantly at increasing the accuracy of the RT measurements. This could potentially be achieved with implementation of a combination of the following solutions:

9.6.1 Hardware

Further increasing the graphics processing capabilities of the computer would potentially increase the FPS of the game such that the rate of data recordings is sufficient enough to increase the resolution of the RT measurements. However solely increasing the graphics may not solve this issue. The current function saves data upon every update, which could be causing a potential 'bottleneck' with data read/write speeds from the hard disk. A solution to which would be to change the traditional hard disk for a solid state drive. Solid state drives due to the non-reliance upon moving parts (i.e. disks and headers) attain faster read/write speeds which should speed up the data saving process. This would ultimately increase FPS and thus the resolution of the RT data.

Another approach would see a more suited simulator hardware (i.e. steering wheel and pedals) being implemented, such that it bypasses the need for the game itself to save any of the data. This method would require the game to output the game time, the speed of the driver's car, the distance between the driver and the AI car and notification as to which tactile stimulus was being presented (i.e. none, level 1, level 2 or level 3). This data would then be received by an external data logger; which would be used to collect both the game values and the hardware positional data.

9.6.2 Software

In order to increase efficiency the function used to collect the game data and hardware positional data could be improved. This could be implemented by firstly increasing code efficiency through optimisation techniques; which would ultimately have the function repositioned into a separate thread operating at a faster rate than that of the game loop. This would remove the need to increase and stabilise in game FPS and is seen essential for the progression of this project.

9.7 Summary

This chapter briefly introduced an adaptation to an open source driving simulator called VDrift. The modification implemented attempted to apply this research to an automotive application in the form of using MIVS to provide feedback to a driver in rear to end collision scenarios. The modification ultimately aimed to record the RT of the driver using a tactile warning alert tone system and with visual and auditory feedback. Unfortunately due to time constraints and resolution times of the RT data, this could not be completed. Subsequently this is open for future work of which some is discussed within this chapter.

This platform has the potential to not only simulate rear to end collision scenarios, but a variety of other automotive scenarios as well. For example, this simulation could be used to investigate methods of modifying behavioural patterns of driver's speed awareness through non-invasive tactile feedback. This has been left open for future work and is further discussed in section 10.6.6.

Chapter 10 – Conclusions & Future Work

10.1 Introduction

This chapter concludes this thesis and is separated into the following sections:

- **Thesis Summary** – This section presents an overall breakdown of this thesis.
- **Contributions** – This section cross examines the contributions outlined in the introduction chapter, and subsequently provides a review of the results obtained in this thesis.
- **Limitations** – This section discusses the limitations of the methodology and practices used within this thesis.
- **Broader Utility** – This section discusses the broader utilises for this research.
- **Legal and Ethic Aspects** – This section discusses the legal and ethical issues of SMIs with regards to body modification and non-medical implants.
- **Future Work** – This section provides a summary of this research's direction.

10.2 Thesis Summary

The research presented in this thesis initially was aimed at creating a multitude of signals that could be used in order to relay information to an individual in situations such as high stress scenarios. The method presented in order to relay this information was that of utilising MIVS. In order to create signals of varied 'intensity' to relay different 'levels' of alerts one must first determine the perceivable changes, i.e. perceptual thresholds (described in section 4.3.1.1), in variables affecting that particular signal. This thesis thus attempted to determine perceptual thresholds of three main variables: amplitude, frequency and time. To the author's knowledge this method of vibrotactile stimulation

has not been previously examined, hence determining these perceptual thresholds was the main focus of this research.

An initial investigation (Chapter 6) was self-conducted upon the author's in order to refine the method and variables that were to be used within in the main participant experimentation (Chapter 7). The participant experiments not only investigated the perceptual thresholds of individuals who possess an SMI, but also individuals who had the magnets superficially attached. This enabled quantification as to any perceptual benefits to an implant of this nature. These two groups are referred to as the implanted and superficial groups within this thesis. The overarching methodology used within these thresholding experiments based around the adaptive psychometric procedure known as QUEST (described in section 4.3.2).

In order to provide stimulation to an individual in the implanted group, firstly the individual required an SMI to be implanted. The properties of the author's SMI, and method for implantation used is presented in section 5.3. In order to provide stimulation to an individual in the superficial group, the individual simply required a similar magnet to be attached using an adhesive to the surface of the skin. In order then to cause movement upon the magnet a custom made electromagnetic 'stimulation coil' was created (section 5.5). This method of vibrotactile stimulation has been throughout this thesis referred to as MIVS (magnetically induced vibrotactile stimulation). It is this stimulation coil along with signals provided from developed software which allowed for all of the thresholding experiments to occur (section 7.5).

Considerations were taken as to the personal views of the public regarding the concept of human enhancement with the use of the survey (section 2.2). Arguably SMIs fall into the field of human enhancement as a form of sensory enhancement; from the point of view that humans cannot innately, via the tactile sense, detect magnetic or electromagnetic fields. This survey was mainly conducted in an attempt to determine how likely an individual would be to undergo a sensory enhancement if it were to become available and what factors may affect their decision upon actually getting an implant. A further survey was conducted on individuals who possess (or have possessed) an SMI(s). This was conducted in order to ascertain their personal perceptual views of the implant with a focus on determining their reasons for undergoing the implant procedure, and any negative experiences they have had (section 2.3). The results of which indicated that a few

individuals also had to have their implants explanted. These along with other cases known to the author (including the author himself) are presented and discussed on a case by case basis in section 5.4.

An attempt was made at applying MIVS to a high stress scenario application. This involved modification of an automotive driving simulator in order to provide rear to end collision information (via warning tones) to a driver and quantify the effects it had on an individual's RT (Chapter 9). Whilst this could not be achieved for as explained within the chapter the initial work seems promising and hence will remain open for future work.

10.3 Contributions

10.3.1 Perceptual testing analysis

Within this thesis a quantitative perceptual analysis has been conducted in order to cross compare, participants who possess an SMI and participants who had magnets superficially attached to their dermis via an adhesive. This saw each of the participants undergo a series of psychometric testing. The results of these experiments are each summarised below:

- **Simple RT** – Statistical analysis of the simple RT data obtained from all participants determined to that from fastest to slowest the examined stimulus modalities were ordered: auditory, visual (focal area), MIVS and visual (peripheral area); each with a mean and STD of 146.6 (±17.3), 183.3 (±15.8), 196.4 (±15.6) and 248.3 (±9.2) respectively. Statistically there was evidence to suggest that the auditory RT was significantly ($P < 0.001$) reduced in comparison with the visual (focal area) and MIVS stimuli; the two of which were not statistically different ($P = 0.861$); finally the visual (peripheral area) caused significantly larger RTs than each of the other stimulus types ($P < 0.001$). There was also no statistically significant difference found between the implanted and superficial group.
- **Amplitude Detection** – Statistical analysis showed that both frequency and implant type significantly ($P < 0.001$) affected the data recorded. That is the 200 Hz stimulus frequency showed a significant reduction in minimum RMS current that was required to cause stimulation to the participants when compared with the 20 Hz stimulus frequency. Furthermore the implanted group when compared with the

superficial group required a significantly reduced amount of current required to cause stimulation also.

- **Amplitude Discrimination** – Statistical analysis of the results obtained showed that frequency significantly affected the results obtained, whereas the implant type did not. The 20 Hz stimulation frequency significantly ($P < 0.047$) improved the participant's ability to discriminate vibrotactile amplitudes when compared with the 200 Hz stimulation frequency.
- **Frequency Discrimination** – Statistical analysis of the results collected showed that as anticipated waveform significantly affected the participant's ability to discriminate frequencies at 20 and 50 Hz ($P = 0.017$, $P = 0.027$); however implant type showed no statistical difference. Post hoc analysis of the 20 Hz results with respect to waveform showed that the square and sawtooth waveforms significantly improved the participants' ability to discriminate frequencies when compared with the sine waveform. Interestingly the 50 Hz waveform post hoc analysis revealed that the square waveform significantly reduced an individual's ability to discriminate frequencies when compared with both the sine and sawtooth waveforms. Further analysis of the baseline frequencies showed that the 100 Hz stimulus frequency significantly reduced the participant's ability to discriminate frequency when compared with the other baseline frequencies tested (i.e. 20 Hz, 50 Hz, and 200 Hz).
- **Temporal Discrimination** – Following statistical modelling there was no evidence to suggest that neither the stimulus frequencies tested (20 Hz and 200 Hz) nor implant type (implanted and superficial) affected the participant's ability to discriminate differences in temporal lengths.
- **TND with respect to TGD** – Statistical analysis revealed that for a given pulse length (250 ms) and pulse cycle number (5) the 200 Hz stimulus frequency significantly reduced ($P < 0.001$) the separation time required for that participants to correctly perform the TND experiment, when compared with the 20 Hz stimulus frequency. For a given pulse frequency of 200 Hz, the pulse cycle number was found to significantly affected ($P < 0.001$) the separation time required for that participants to correctly perform the TND experiment. Of the pulse types tested the 200 Hz, 25 ms has been determined most optimum for information transfer for high stress

scenarios. Finally there was no statistical evidence to suggest that implant type affected the participant's ability in this experiment.

Out of the experiments conducted, SMIs have statistically shown to improve an individual's amplitude detection threshold. Based on personal experience of SMIs the author personally makes the following recommendation, anyone wishing to experience MIVS should undergo the implantation procedure.

10.3.2 Human Enhancement Survey

This survey was aimed at determining the views of individuals regarding human enhancement. The survey respondents were split into two groups. The first was a general group who consisted of 407 respondents from across the globe, named the sample group. 394 responses analysed as there was missing data in 15 of the respondents. The second group was a focus group for comparison consisting of 44 responses. Whilst several questions were asked regarding this topic, the seen key for the progression of this research was: "how likely an individual would be to undergo a procedure to improve their senses if it were to become available?" To which ~39% of the sample group and ~52% of the focus groups responded positively, a further ~25% and ~20% respectively gave an indecisive response (i.e. maybe/not sure). If the dissemination of this, and similar, research is carefully and considerately thought out, these respondents may tend towards a more positive acceptance of sensory enhancement, which is quintessential for the uptake of this research. When asked "how much would the risk of the implantation/procedure effect affect your decision upon getting an enhancement?" The majority of both groups, i.e. ~74% and ~55%, of the sample and focus group respectively responded positively (i.e. a little or a lot). Thus the risk of the SMIs would also require careful publicity in order for uptake of this research.

10.3.3 SMI Survey & Explantation

10.3.3.1 Survey Responses

This survey received a total of 56 responses and queried respondents who have (or had) an SMI about their personal experiences of them. From the responses there were some rather interesting results within the context of this research. For instance when asked "why did you get this implant?" the majority of the respondents (60%) replied for magnetic vision purposes (i.e. the perception of magnetic fields). Furthermore the vast

majority of respondents ~80% responded that they had not had any bad experiences, recurrent pain or been hindered in day-to-day activities due to their implant. There was only one case of an individual who responded to the survey with a personal account of undergoing an MRI procedure with an SMI. This case has been explored in the explantation section of this thesis (section 5.4). However personal experiences of individuals whom have undergone MRI procedures with an SMI have been included for discussion, which have been sourced from online blogs.

10.3.3.2 Explantation

In summary of the reported cause of individuals whom have undergone the explantation procedure, the author would like to state that; "anyone wishing to undergo this implantation procedure should firstly be aware of the object to which they are going to be implanted with." The first reported case of explantation, explores the views of an individual whereby the coating of the magnet critically failed; this was due to a poor choice coating, the manufactures of it stated on their website the following. "Sugru isn't food or medical grade; therefore we can't recommend it for internal use" [212].

The second case of note reported "I felt a pinching and burning sensation" during an MRI procedure and subsequently had the magnet removed. The author would like to reiterate that he does not advise undergoing MRI procedures if one does have a SMI; due to potential tissue damage and severe pain that could incur. In the final case of note the individual, stated the following. "I had one of the two implants removed due to pain and discomfort that started after having the finger and implant area crushed under a very heavy object" – Hameed [personal correspondence]. To which the author would like to reiterate that, caution must be taken in day-to-day activities in order to preserve the implanted magnet and its coating. The final two cases reported were from the author and Davey who both underwent the explantation procedure as a precautionary measure. To which the author would like to stress that if one does not feel comfortable with one's implant, he would always recommend seeking medical advice and if still unsure removal.

10.4 Broader Utility

The main application proposed from this reason as previously mentioned is for providing feedback in high stress scenarios, such as driving or piloting; preliminary work in this area is presented in Chapter 9. Whilst this area is still in its developmental stages,

there are a number of different application areas that could be explored for this implant. The concept of sensory substitution has been explored in section 3.2, which possible area of application for this research is utilising this method of input to the body (MIVS). As briefly discussed in [4], MIVS has been examined to convey distance information to the body using a device with ultrasonic sensors.

In unreported works this devices has been extended to convey not only distance but object information. A secondary passive infra-red sensor, similar to those used in intruder alarm systems, was added to the device which now not only conveyed distance but whether the object detected was a body or not. Furthering this, the device could include a number of sensors such as accelerometers to provide vestibular feedback to the body via the tactile sense.

A further application for this research is its use a human machine interface, in order to provide feedback from a system in a novel method. The main proposes idea for this is a 'virtual surface', which creates a varied electromagnetic field platform (further detailed in section 10.6.7). This device could not only provide a sensory substitution for the blind, but also a new form on 'visualisation' of models, as well as simply creating 'magnetic art.

A body modification enthusiast, Rich Lee, [237] has undergone the SMI implantation procedure to the tragus part of his outer ear. This has enables him to make use of "bone vibration" [237] to be able to perceive audio via a magnetic coil and amplification. A furthering potential idea from this would be to surgically implant a suitable magnet onto either the ear drum or up through the Eustachian tube and affix it to the outside of the cochlear. This could then be agitated through magnetic induction to cause movement of the ear drum or cochlear to act as an early stage hearing aid device.

Medical engineering research has always been a keen interest of the author's. In the following statement he expresses his views on the possibilities for this research; "the prospect of progressing and ultimately utilising this research for the benefit of the medical community, is a very exciting concept indeed. Creating a human machine interface device that could aid medical staff in any way would be a truly rewarding feat for this research".

10.5 Legal and Ethical Aspects

SMIs are a form of sensory extension, which can be considered as an enhancement, which originated in the body modification community. In terms of the regulations that govern body modification with regards to non-medical implants, the literature is rather limited. However, there are regulations on piercing and tattoos. For example, the regulations of tattooing and body piercing businesses [238] from the House of Commons library. This document outlines the legislation, heath guidance, training and consumer law for businesses practicing this art form.

The General Dental Council's website [239] summarises the legal position with regards to anaesthesia.

> *"An injection of local anaesthetic involves the use of a prescription-only medicine (POM) which means that, under the Medicines Act 1968 it can only be prescribed by a suitably qualified prescriber - traditionally a doctor or a dentist."*

Topical anaesthetic creams, such as EMLAs, which are available over the counter are exempt [240].

In terms of enhancement the regulations and ethical considerations are starting to be discussed. Projects such as the EU project named NERRI have been put together to discuss the ethical and political aspects of neural-enhancement [241]. However as the project has yet to be completed, publications from the group have not been released. The ethics of enhancement has previously discussed with regards to cyborgs by Warwick in 2003 [242] who discusses cyborg morals, values and ethics; and Frank in [243] who discusses a case for cyborg ethics and morals based on surgical body modification and altruistic individualism.

There are numerous examples of individuals self-experimenting for personal and or scientific gain. For example; Newton, pressing on his eyeball with a stick to experiment visual distortion [244]; Volta, who used a battery to invoke hearing sensation [72] (see Figure 3-1); Davy, who experimented with a new gases called nitrous oxide, commonly referred to as laughing gas, a now well known, powerful anaesthetic [245]. Yet more and more people are continuing to undergo the SMI procedure for self-experimentation, and or artistic purposes. This opens a number of legal questions;

- Should the implantation procedure be governed, much like that of augmentations such as, tattoos, subdermal anchors or breast implants?
- Should the coating used be standardised or approved for safety reasons?
- What should the policy be for the work environment, with regards to health and safety?

Ethically, the choice to undergo a procedure for self-experimentation is valid. However this does come with grey areas, for instance, it should not be advantageous to undergo this procedure for academic or industrial advancement; as this would put pressure on individuals. The social aspects also must be considered, for instance if SMIs became popular;

- Would there be a social pressure to undergo the procedure?
- Moreover would the cost of the implantation cause a separation of class?

The answers to both questions in the authors opinion should most certainly be no. Although this view is very idealistic as today restorative technologies and certain incur a financial class separation; the author believes this should be a human right, and that healthcare and indivual wellbeing should be paramount on governmental agenda.

10.6 Future Work

10.6.1 Prospective Study

The psychophysical results from the main experimentation given in Chapter 8, do not give strong indication for the benefit of an intervention study. However a follow up prospective study should be conducted in order to gather further qualitative data. The proposal for this study would involve finding a cohort of at least 10 participants who possess SMI(s) or are about to undergo the implantation, and track their progress with them over 6 months to a year. The study would aim to firstly gather data much like that collected in the reported questionnaire (see section 2.3.3), magnet specifics, who implanted them etc. Secondly, continual data collection would occur, gathering information such as, day to day experiences and bad experiences from the individuals, in both group based and standalone meetings. The data collected would ultimately aid in the assessment of risks involved in possessing a SMIs, the general experiences of them and more sensory

experiences of the implant. This study would aid in portraying valuable information to those individuals who have or are thinking of having an SMI.

10.6.2 Medical MRI Experiment

Medical MRI procedures have been undertaken by individuals with SMIs, see sections 2.2.3 and 5.4.1 for examples. The case reported by the individual mentioned in section 5.4.1 experienced a "burning sensation". Multiple authors have previously reported on implantable medical devices within MRI machines. For example: Risi *et al.* in 2004 [246] empirically examined the Nucleus® 24 Cochlear Implant; Biakousiss *et al.* in 2011 [247] reviewed the safety of implanted cardiac prostheses and metallic cardiovascular electronic devices; and Nyenhuis *et al.* in 2005 [248] explored medical device interactions with MRIs, with an emphasised on heating.

A further review on the health and safety of medical devices has been widely explored by Shellock [249] who continues to catalogue the MRI safety of implantable device in his 'List' [250]. Exploration of this list suggests that the majority of device containing magnetic materials are unsafe due to "movement or displacement of the object".

Further work in this research aims to determine empirically the effects of MRI procedures on MRI, focusing on heating. The proposed experiment would involve the use of:

- **A dermal manikin** – resembling a fingerpad with similar thermal and mechanical properties to that of a human fingerpad.
- **Multiple magnets** – varying in dimensions that have been used for SMIs (see Table 2-21).
- **Temperature sensing system** – a suitable MRI safe temperature probing system; such as the EASY4MRI system manufactured by speag [251].
- **Optical fibre based vibration sensor** – a bespoke or specific system made for detecting vibration in the MHz range.
- **Flat solid surface suitable for MRI** – this will be used in the second part of the experiment.

The test could be conducted by firstly taking a control temperature measurement of the dermal manikin within the MRI by running a standard diagnostic examination. The

temperature sensors would be placed such that they measure temperature in a linear distance starting from the position of where the magnets are to be placed. This part of the experiment would aim to determine whether the experienced temperature increase by the respondent in section 5.4.1, was due to the vibration of the magnet and its interaction with the skin; hence the optical fibre vibration sensor would be positioned as close to the position of where the magnets are to be placed. Then in turn each of the magnets would be positioned within the dermal manikin and the same diagnostic examination would be run.

The second part of this experiment would aim to determine whether the reported temperature increase is due to Eddie currents from the alternating RF field within the MRI, also known as RF heating [246]. Here the experiment would be run similar to the previous test with two changes. Firstly the magnets would be attached to the flat hard surface (in order to preventing movement) and covered in the dermal manikin material. Secondly, since there would be no movement the optical fibre vibration sensor is no longer required.

The outcome of both of these experiments would be able to determine firstly whether a temperature increase is present and also what is causing this increase, mechanical vibration or Eddie currents? Examination of the tested magnets' field strength would be conducted before and after each test in order to determine demagnetisation.

10.6.3 Optimising Temporal Numerosity Discrimination through adaptive Temporal Gap Time

Within this thesis a TND with respect to TGD experiment was conducted. This experiment determined the separation time, T_x that was required between different pulse numbers such that the individual could still correctly identify the number of pulses. For each of the four different pulse numbers examined (2, 3, 4 and 5) there was a corresponding T_x value determined. Each of the four T_x values were different however they were identical for each gap within their respective pulse number. I.e. the T_x value determined for both of the gaps for three pulses were identical, however a different T_x value was determined for each of the three gaps for four pulses etc.

The new experiment will examine whether changing T_x values will allow for a further reduction in the total signal length. For instance, suppose a signal constructed of three

pulses as such it has two gaps in between them, T_{x1} and T_{x2}. Where before these T_x values were identical, the experiment will examine whether T_{x1} has to be equal to T_{x2} such that an individual is still perceive the correct number of pulses (three in this case). If they do not need to be the same length the main question is, is the sum new values for new values less than that of the previous method? If this is the case this would result in shorter overall signal lengths. This experiment would involve devising a new protocol that is somewhat similar to the TND with respect to TGD methodology presented in this thesis.

10.6.4 Investigate Cytotoxicity effects of SMIs

After consultation within in vitro scientist, L. Wheeler, a proposed method for analysing the cytotoxic effects of SMIs could be conducted through two methods. The first would be to measure the short term effects using cell culturing techniques. This would involve the growth of two skin cell cultures from the same source one to act as the control and the other to act as the experimental. Within the experimental culture a similar magnet to that of the authors SMI would be positioned central and then examined by professional in vitro scientists in order to ascertain cytotoxicity effects. This method would also allow for observation of cell proliferation as well as their viability. The second method would measure long-term effects, which could be conducted through biopsy of the author's left middle fingertip, as the SMI within this finger pad was implanted in August 2010, and cross compare it to a biopsy of the author's right middle fingertip.

10.6.5 In depth analysis of Force applied to magnet

10.6.5.1 Biosynthetic testing

A proposed method for analysing the force applied to SMIs during stimulation would be to use a biosynthetic material of similar mechanical properties to that of skin, which is translucent (or preferably transparent). Firstly a similar magnet to that implanted in the author would be inserted inside of it. Secondly this material and the magnet would be placed within the created electromagnetic coil such that the magnet is positioned horizontally (i.e. the flat face of the magnet is in line with the central axis of the coil). Thirdly would be to use a high resolution fast frame rate camera, a suitable scaling measurement and suitable lighting such that the movement of the magnet can be observed and measured whilst it is under direct influence from the coil.

10.6.5.2 *Linear Actuator and Fine Current Supply*

As posed previously a more accurate method of determining force applied to the magnet would be to use a fine linear actuator attached to a long cylindrical Perspex Rod to which would be attached a similar magnet to that implanted in the author. Multiple Perspex Rod's would be used such that the orientation of the attached magnet could be varied; i.e. the angle between the flat face of the Perspex Rod and the flat face of the magnet varied in steps of 5° in the range of 0 and 90°. A similar to the setup to the B field verification experiment presented in section 5.5.3.3 could be used, however here the Hall Effect probe would be replaced by the linear actuator (with the Perspex Rod and magnet). The Rod would be positioned such that the magnet was central to the coil and various signals would be passed to the coil; e.g. a 200 Hz sine wave. Thus the recordings obtained from the linear actuator would show the force against time.

10.6.6 Modification of behavioural patterns of drivers, with regards to speed awareness through non-invasive tactile feedback

Speed awareness could perhaps be modified by use of tactile feedback. Current speed awareness in vehicles involves the driver re-orientate in their visual focus from the road to their speedometer; however as previously posed a driver could be informed when they are breaking the speed limit via vibrotactile feedback in this case MIVS. It would be interesting to see whether over a long-term study feedback of this nature would actually alter the behaviour of the driver with regards to speed awareness; such that visual (movement observed whilst driving) and auditory (the sound of the engine) cues alone would now suffice and that visual focus remained solely on the road.

10.6.7 Virtual Surfaces

An interesting device that could be developed would be a virtual surface device for use with SMIs. The proposed method would be to use an array of (initially) 16 coils each with varied signals being passed to them, e.g. variations in amplitude, waveform and frequency. The ultimate goal of which would be to allow an individual with an SMI to perhaps distinguish things such as shape; i.e. utilising this MIVS as a man machine interface (in this case a display like tool) and sensory substitution device.

10.7 Final Statement

From discussions throughout this thesis it is clear that implants are becoming more and more common for multiple applications; such as medical applications, to more benign applications like sensory substitution and sensory augmentation. This thesis intended to provide the grounding experimentation for subdermal magnetic implants, and further provide evidence of the evolution of implants. The particular implant discussed throughout this thesis was established in the world of body modification and has now been brought into the realm of scientific study. The ethics and broader utility of this implant have been discussed but are both in early developmental stages.

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Appendix A – Project 10 Ethical Submission form

Consent Form

1. I have read and had explained to me by Prof. Kevin Warwick the accompanying Information Sheet relating to the project on: Project 10

2. I have had explained to me the purposes of the project and what will be required of me, and any questions I have had have been answered to my satisfaction. I agree to the arrangements described in the Information Sheet in so far as they relate to my participation.

3. I understand that participation is entirely voluntary and that I have the right to withdraw from the project any time, and that this will be without detriment.

4. I authorize the Investigator to consult my General Practitioner.

5. This application has been reviewed by the University Research Ethics Committee and has been given a favourable ethical opinion for conduct.

6. I have received a copy of this Consent Form and of the accompanying Information Sheet

7. I have already had the subdermal magnetic implants; I fully accepted responsibility and liability for these risks at the time of the implantation procedure and continue to do so now.

Name:

Date of birth:

Signed:

Date:

Contact Number:

Contact Email:

GP Name:

GP Address:

Emergency Contact
Name/Number:
ADMIN ONLY – ID:

Project 10 – Information Sheet

Principle Investigator: Prof Kevin Warwick

Student Investigator: Ian Harrison

Candidate Selection

The candidates wishing to apply must be aware, that subdermal magnetic implants are a requirement, for application consideration to join Project 10. The proposed method to obtain candidates is as follows:

1. Through consultation with Mr McCarthy, and various other online communities we intend to identify 10 individuals whom already have subdermal magnetic implants and invite them to take part in our study. Mr McCarthy is a Master Body Modification artist whom consults the UK Health and Safety commission in body modification; McCarthy performed Ian Harrisons' implantation procedure in August 2009.
2. When the willing candidates are determined they will be given both an information sheet describing the procedures and what will be expected of them & a copy of previous reported research work.
3. The candidates will then undergo an interview process to determine that the information regarding the experimentation is fully understood by the prospective candidates – Professor Kevin Warwick will be involved at all stages of this process.
4. Candidates wishing to apply must be informed that; any magnetically effected medical implanted devices (e.g. Cardiac Pacemakers, defibrillators, etc.) are not permitted in this research; the proposed candidate should never have had the magnet implants if they have had such a device implanted prior. Candidates wishing to join this project must NOT possess such a device.

Risks associated with having the Implants

There are risks associated with having subdermal magnetic implants. Candidates must confirm, through initial and signature on the consent form for this project, that they fully accepted responsibility and liability for these risks at the time of having the implantation procedure carried out and that they continue to do so now.

This information sheet will set out the (very small) risks associated with the experiments we propose to conduct; the consent form will ask the candidate to confirm that they accept responsibility and liability associated with these risks.

Experiments to be conducted

A series of experiments will be conducted involving all of the candidates. The experiments to be performed on each candidate are as follows:

The magnetic field strength around implanted area

The aim of this experiment is to determine the magnetic field strength measured from the surface of skin and the surface of the implanted magnet (measured in SI units Tesla). This test is performed using standard magnetic sensing equipment, by where a magnetic field sensing probe will positioned around the candidates implanted finger to determine the surrounding magnetism.

Perception Testing

The aim of this group of experiment is to determine the perceptual capabilities of the candidate using standard Psychological testing, for example; 2/3 alternative forced choice testing and a Just Noticeable Difference (JND) test, to test perceptual response to frequency change. This involves the candidate positioning their implanted finger within an electromagnetic coil, whilst the amplitude and frequency of the inputted signal (i.e. the signal from the PC to the electromagnetic coil, via amplification) alters. This group of tests will determine the candidates' maximum frequency response, and the minimum amplitude (i.e. input signal amplitude, which will have direct influence upon the magnetic field strength produced by the electromagnetic coil) required for stimulation to occur.

Subjective Frequency Response

The aim of the experiment is to obtain the subjective response from the user dependant on the electromagnetic frequency acting upon the implanted magnet, by varying the frequency and wave form, from sine to squarewave. This test is rather similar to the previous test, in this test however the candidates will be present (via and electromagnet) a frequency varied EMF (Electromagnetic Field), and presented this frequency in two forms, sinewave and squareware. The candidate will be asked (after being subjected to the

full frequency range) to determine their perceptual response out of 10. For instance, ~ 200 – 250Hz is the determined as the optimum range for Pacinian Corpuscles (hence around this frequency the expected result is ~10).

Application Test:

The following application tests are performed by the candidate to determine the plausibility of using the implanted magnets, as a form of information channel to the body. The candidate will be subjected (via EMF from an electromagnetic coil) to various frequencies that they are to relate to real world environments; for instance, in prior testing a 250Hz signal represented an object within close proximity (i.e. boundary 1, which is between 0 – 50cm from the sensor). The second application test see's two channels of information being used; (i.e. 1 information channel/EMF/input signal per implanted finger, hence requires candidates with 2 implants) in this case, the first information channel will provide the distance from the sensor to the object, the second will be used to determine whether the object is a body (measured using a passive infrared, the same technology used in movement detectors for house alarm systems).

Ultrasonic & IR distance testing

The aim of this experiment to determine whether the candidate, can accurately say which is the correct bounded distance (0 – 50cm, 50 – 100cm, 100 – 150cm or >150cm) to an object using only the magnet implant and technology to accompany it (i.e. various distance detectors, microcontroller, transistor power amplifier and the electromagnetic coil).

2 Channel Input (Distance and PIR Detection)

Furthering the prior experiment the aim of this experiment is to enable the user to accurately determine bounded distance (0 – 50cm, 50 – 100cm, 100 – 150cm or >150cm) and determine whether the object (detected by the ultrasonic sensor) is a human body or just an inanimate object based purely on the input (to the body) given from the equipment alone.

Response Time

The aim of this experiment is to determine the reaction time (RT) of the candidate using the movement of the magnet stimulus, compared to reaction from a light turning

on, when the light is both in the focal area and when it is in the periphery. This experiment will see the candidate subjected to said stimuli (i.e. the movement of magnet stimulus, achieved by having the candidate place their implanted finger into an electromagnetic coil and be subjected to EMF. The light stimulus, this will be present using an LED, the candidate will be required to test the RT not only when staring at the LED, but also test the RT when the LED is in the peripheral vision of the candidate) with a random start time in the range of 1-3 seconds. The candidate simply must push a 'stop' button once they have perceived the stimulus, the RT is taken from stimulus start, to 'stop' button being pressed.

Encoding signal input

The aim of this experiment is to find the shortest 'random frequency time' that causes the limit of percentage error, by varying the time per random frequency {1; 2; 3} from 1 second to 0. This will give the shortest time for a signal to be input and correctly understood by the candidate. The candidate will be presented, again via an electromagnet, a series of 3 frequencies in quick succession with pauses (no stimulation) in between and at the start; this will now be referred to as a random signal. An example of a random signal might be: between, 0-1s - no stimulus, 1-2s - 250Hz (stimulus 1), 2-2.25s - no stimulus, 2.25-3.25s - 600Hz (stimulus 2), 3.25-3.5s - no stimulus, 3.5-4.5s – 250Hz (stimulus 3). Notice that the time of no stimulus between the frequencies is ¼ of time that the frequency is on (i.e. stimulus 1/2/3). As the time per stimulus is reduced from 1 -> 0, the time of no stimulation will continue to reduce by remaining a ¼ of the stimulus time of the random signal. The period of no stimulation for 1 second at the start is kept constant throughout. The candidate will simply have to recall the frequency sequence of random signal. Using the prior example, the correct response would be, 250, 600, 250 or high, low, high.

Concept of Auditory Perception via the Vibrotactile Sense

The aim of this experiment is to test the response of the candidate whilst presented with audio signals. These audio signals will not be inputted to the body via the conventional transverse wave forms of air particles to the auditory system; instead they will be input via EMF signals to the implanted magnets for the tactile system to response to. These complicated audio signals, in theory, will be mostly out of the perceptual range

of the candidates' vibrotactile receptors. However, the lower octaves (>=6) of music, have the collective frequency range of 16 – 1024 Hz, typically bass where lower and upper bass frequencies lie. This range is almost fully perceivable via vibrotactile receptors, the candidates will be subjected to audio signals, once again via EMF from an electromagnet, only this time this signal will be an audio signal that has been filtered to accommodate the perceptual response of the vibrotactile sensors (i.e. a low pass filter with a cut off frequency of 1KHz, will be applied to the signal before it is inputted to the candidate).

Guidance & Notes

All experiments will be conducted under the full supervision of Professor Kevin Warwick in order to ensure both the safety of the candidates involved and the scientific accuracy of the results. Professor Warwick is one of the world's leading authorities on scientific investigations involving implantations – having safely conducted prior experiments at UoR (with UoR Ethics & Research Committee approval).

It is expected that for each candidate this will involve an absolute maximum of 8 hours of experimentation over a one month period. The candidates will however also be expected to attend two general meetings, lasting approximately 30 minutes each; the purpose of which will be to discuss any discoveries/issues the candidates have encountered.

It is not expected that the candidates will be paid for their time and/or involvement.

Risks of Experimentation

All experiments will see the candidates being subjected to varied EMFs, the frequencies of which will not exceed 1000 Hz. A Pacinian corpuscle is a vibrotactile receptor, (i.e. it enables the body to perceive vibration) it is grouped with a few other receptors and these are collectively known as mechanoreceptors; which are responsible for mechanical stress and strain detection in the body. The max frequency response of the Pacinian corpuscle is ~800Hz (In accordance with Bach-y-Rita and colleagues, see Table 1 [21]). This frequency covers the entire range of these receptors enabling full frequency response/perceptual response from each candidate.

The maximum magnetic field strength applied to the candidates implant will be 30mT. These fields should not cause any reaction (other than desired sensation) in your implants

that would have negative physical consequences. Should you (the candidate) suffer any discomfort or pain during any of the experiments you should inform the experimenter immediately and the experiment will be stopped.

Dr. George Boulos is acting as a consultant during the experimentation. Dr. Boulos is a GP at Pottery Rd. Surgery, Tilehurst, Reading and an FRCGP, GMC number 2350817. It was he who performed the first RFID implantation on Professor Kevin Warwick in 1998, and subsequently was involved with the microneurography for Mrs Irena Warwick in 2002, for which the UoR Ethics and Research committee gave its full approval.

Dr Boulos has already acted consultant with regard to this project and will act accordingly throughout its duration. His views to date have focused on the implantation/surgical procedure only and hence fall out of the scope of the project.

Contacting Health Centre and Candidates GP

Although it is not expected that any medical intervention will be required, the UoR Health Centre will be informed prior to the commencement of the experiments. In the interests of health and safety, proposed **candidates' GP contact details have been asked for**; this is purely as a precautionary measure for the research.

Confidentially and Security of Disposal after Trial

Each candidate will knowingly be given an unknown an identification number for record purposes. This number will be written on the signed copy of the consent form. The paper copies with all contact details will be kept separate with all personal information from electronic storage. All electronic records will refer to the candidate by the identification number. Upon Removal from Trial, or Trial termination the personal information stored on paper will the shredded; however, will be retained within the School for a minimum of five years after the date that the project is completed.

Publishing and releasing results to candidates

Candidates will be given full acknowledgement for their participation in the project; unless otherwise specified. The candidates will be given access to their results, when required, subject to review constraints.

Removal from Trial

Every candidate involved is welcome to pull out of the research, at any time for whatever reason.

Acknowledgement

The Ph.D. of Ian Harrison is being supported by Nissan Motor Co. We acknowledge here our gratitude for their support.

Closing Statement

This project has been subject to ethical review, according to the procedures specified by the University Research Ethics Committee, and has been given a favourable ethical opinion for conduct.

Works Cited

[1] Lu Xia Dong Xia, "Three Permanent Magnet Driving Device for Artificial Heart," in International Conference on Electrical and Control Engineering (ICECE), 2010, pp. 5765 - 5768.

[2] Poleni P-E, Guimard D, Arakawa Y, Sakai Y, *et al.* Pereira-Rodrigues N, "Modulation of Hepatocarcinoma Cell Morphology and Activity by Parylene-C Coating on PDMS," PLoS ONE, vol. 5, no. 3, 2010 [Online]. http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0009667

[3] Nathan Roseborrough. Feeling Waves. [Online]. http://feelingwaves.blogspot.com/

[4] M. Gasson, I. Harrison, J. Hameed K. Warwick, "A Novel Man-Machine Interface using Subdermal Magnetic Implants," in IEEE International Conference on Cybernetic Intelligent Systems (CIS 2010), vol. 9, Reading, 2010.

Project Submission Form

School: School Of Systems Engineering

Principal Investigator: Prof. Kevin Warwick

Email: k.warwick@reading.ac.uk

Student Investigator: Ian Harrison

Student Email: ck001619@reading.ac.uk

Title of Project: Project 10

Proposed starting date: Pending Candidates ~ 1 month post submission

Brief description of Project:

The aim of Project 10 is to gain data from 10+ volunteering candidates (individuals, wishing to be part of the research) whom have already undergone the implantation procedure. The basis being that with this data, research can be performed which will enable a much more detailed scientific study to be carried out. Without this data the issue arises that 'almost all' data currently collected in this research is subjective (largely from only 1 candidate) (see Information sheet).

I confirm that to the best of my knowledge I have made known all information relevant to the Research Ethics Committee and I undertake to inform the Committee of any such information which subsequently becomes available whether before or after the research has begun.

I confirm that if this project is an interventional study, a list of names and contact details of the subjects in this project will be compiled and that this, together with a copy of the Consent Form, will be retained within the School for a minimum of five years after the date that the project is completed.

Signed:

..... Date: .....

Prof. Kevin Warwick (*Investigator*)

..... Date: .....

Dr. Ben Cosh (*Head of School*)

..... Date: .....

Ian Harrison (*Student Investigator*)

Checklist

1.	This form is signed by my Head of School, Dr. Ben Cosh.	☐
2.	The Consent form includes a statement to the effect that the application has been reviewed by the University Research Ethics Committee and has been given a favourable ethical opinion for conduct.	☐
3.	I have made, and explained within this application; arrangements for any confidential material generated by the research to be stored securely within the University and, where appropriate, subsequently disposed of securely.	☐
4.	I have made arrangements for expenses to be paid to participants in the research, if any, OR, if not, I have explained why not.	☐
5.	The proposed research does not involve the taking of blood samples.	☐
6.	The proposed research does not involve the storage of human tissue, as defined by the Human Tissue Act 2004.	☐
7.	In the circumstance that any test reveals an abnormal result, I will inform the participant and, with the Participant's consent, also inform their GP, providing a copy of those results to each and identifying by name and date of birth.	☐
8.	The proposed research does not involve children under the age of 5.	☐

RISK ASSESSMENT FORM (RA2)

Ref. No.

School / Dept / Unit	School of Systems Engineering
1. Brief summary of work activity or project assessed	The aim of Project 10 is to gain data from 10+ volunteering candidates (individuals, wishing to be part of the research) whom have already undergone the magnet implantation procedure. The candidates will undergo a series of experiments that will see them subjected to EMF (Electromagnetic Fields), the frequencies of which will not exceed 2KHz. The candidates will be exposed to these fields for no longer than 1 minute of continuous stimulation and a settle time will be minimum of 10 seconds.
2. List significant hazards	Electromagnetic Fields
3. Relevant University or local guidelines or standards	Safety Note 23 – HAV Interim guidelines on limits of exposure to 50/60Hz electric and magnetic fields (1989) – National Health and Medical Research Council
4. List who might be exposed to the hazards	Staff/Student Investigator Candidates (Third Party Visitors)
5. How might they be harmed?	Fingertip soreness Loss of sensation Blood circulatory system, vibration white finger (VWF)
6. List control measures in place to reduce risks	Following the set range of frequencies and duration to be applied, i.e. max 2 KHz for 1 minute. Most tests require only 7-10 seconds of stimulation, also the allocation of minimum 10 seconds settling time. Breaks will be allocated with a minimum of 10 minutes per hour. Interim guidelines on limits of exposure to 50/60Hz electric and magnetic fields (1989) – National Health and Medical Research Council, states that during occupational use for short periods a maximum of 25mT (magnetic flux) can be applied to limbs. – The maximum theoretical stimulation required is 5mT. This is the approximate magnetic strength of a typical fridge magnet. Through a standardized script for the experimentation, the candidates will be informed that, if they fell any discomfort, they are to immediately remove their fingertip/s from the stimulation coil/s and inform the investigator. Following this, the first experiment involving stimulation, is to determine the minimum level of stimulation (i.e. magnetic field) required for the candidate. This will be used to determine a comfortable level of stimulation so as not to cause discomfort. In the unlikely event of candidates having Pacemakers implanted in them, they will NOT be permitted to join this research. This due to possibility of EMFs' causing Pacemakers to go unstable and ultimately not function correctly.
B: Assessing the level of risk and further action needed	

7.1 How severe is any injury or health effect likely to be?	Tick one box (S =score given in brackets)	Minor ☑ (1)	Serious ☐ (2)	Major ☐ (3)	Fatal ☐ (4)
7.2. How likely is exposure to the hazard?	Tick one box (P =score given in brackets)	Very unlikely ☐ (1)	Unlikely ☐ (2)	Possible ☐ (3)	Likely ☑ (4)
7.3. Calculate the risk score by multiplying the 2 scores in Q7.1 & 7.2	Risk Score (S x P) =	Low ☐ (1–3)	Medium ☑ (4–6)	High ☐(8–9)	Very High ☐ (12–16)

8. Immediate further action to be taken to make the situation safe / reduce risk to health	Action to be taken by whom?	Implementation Date
Ensure the set range of frequencies and duration to be applied is max 2KHz for 1 minute.	Student Investigator	

9. Further action or additional controls needed to reduce risk as low as reasonably practicable	Action to be taken by whom?	Implementation Date
There is simply no avoiding the Electromagnetic Fields as they are the vital part of the research, however any signs of numbness or pain from the candidates will immediately terminate the testing procedure.		

Name of Assessor (please print)	Ian Harrison	
Signature of Assessor		Date: 12/03/2015
Signature of Head of Dept/School/Unit		Date:12/03/2015
Date for Review (maximum 12 months from date of assessment)		10/2013

ANNEX B

Research Ethics Committee

University of Reading

Project Submission Form

Principal Investigator: Prof. Kevin Warwick

Student Investigator: Ian Harrison

School: Systems Engineering

Principal Investigator Email: k.warwick@reading.ac.uk

Student Investigator Email: ck001619@reading.ac.uk

Title of Project: Project 10 (Supplement)

Proposed starting date: 4/7/2013

Brief description of Project:

Questionnaires (×2) (See Attached)

I confirm that to the best of my knowledge I have made known all information relevant to the Research Ethics Committee and I undertake to inform the Committee of any such information which subsequently becomes available whether before or after the research has begun.

I confirm that I have given due consideration to equality and diversity in the management, design and conduct of the research project.

I confirm that if this project is an interventional study, a list of names and contact details of the subjects in this project will be compiled and that this, together with a copy of the Consent Form, will be retained within the School for a minimum of five years after the date that the project is completed.

Signed:

……..... Date: ……..……

(Investigator)

……..... Date: ……..……

(Head of School)

……..... Date: ……..……

(Student -where applicable)

Checklist

1. This form is signed by my Head of School (or authorised Head of Department) ☐

2. The Consent form includes a statement to the effect that the project has been reviewed by the University Research Ethics Committee and has been given a favourable ethical opinion for conduct ☐

3. I have made, and explained within this application; arrangements for any confidential material generated by the research to be stored securely within the University and, where appropriate, subsequently disposed of securely. ☐

4. I have made arrangements for expenses to be paid to participants in the research, if any, OR, if not, I have explained why not. ☐

5. EITHER
   (a) The proposed research does not involve the taking of blood samples; ☐

   OR

   (b) For anyone whose proximity to the blood samples brings a risk of Hepatitis B, documentary evidence of immunity prior to the risk of exposure will be retained by the Head of School or authorized Head of Department. ☐

   Signed:

   …….... Date……

   (Head of School or

   authorised Head of Department)

6. EITHER
   (a) The proposed research does not involve the storage of human tissue, as defined by the Human Tissue Act 2004; ☐

   OR

   (b) I have explained within the application how the requirements of the Human Tissue Act 2004 will be met. ☐

7. EITHER
   (a) The proposed research will not generate any information about the health of participants; ☐

OR

(b) If the research could reveal adverse information regarding the health of participants, their consent to pass information on to their GP will be included in the consent form and in this circumstance I will inform the participant and their GP, providing a copy of the relevant details to each and identifying by date of birth ☐

OR

(c) I have explained within the application why (b) above is not appropriate. ☐

8. EITHER

(a) the proposed research does not involve children under the age of 5; ☐

OR

(b) My Head of School (or authorised Head of Department) has given details of the proposed research to the University's insurance officer, and the research will not proceed until I have confirmation that insurance cover is in place. ☐

Signed:

…….... Date……...…

(Head of School or

authorised Head of Department)

This form and further relevant information (see Sections 5 (b)-(e) of the Notes for Guidance) should be returned to:

Dr Mike Proven
Coordinator for Quality Assurance in Research
Whiteknights House
Email: mailto: m.j.proven@reading.ac.uk

- both electronically and in hard copy

You will be notified of the Committee's decision as quickly as possible, and you should not proceed with the project until then.

Appendix B – Global View on Human Enhancement

Survey

Global View on Human Enhancement

This survey is attempting to determine the global view on Human Enhancement. Human Enhancement is the idea of giving humans enhanced senses, e.g. hearing ultrasonic's, similar to bats, or seeing ultraviolet light. Even perhaps increased physical capabilities e.g. increased strength or manoeuvrability. This survey is for everyone! Please share it.

Basic Information

These questions are simply to find out the types of people answering the survey.

1. What is your gender?

   ○ Female

   ○ Male

2. Where do you currently live?

   N.B. For residents of the USA, states are listed below the countries.

   ---

3. How old are you?

   ---

4. What is your Ethnicity?

Human Enhancement

Questions regarding human enhancement.

5. Are you aware of research being carried out in Human Enhancement?

- ○ Yes
- ○ A little
- ◉ No

6. How does the general idea of Human Enhancement make you feel?

Scared Negatively Okay/Not Sure Positively Excited

7. How likely would you undergo an implant/procedure to improve your senses, if it were to become available?

e.g. seeing ultraviolet/infra-red, or hearing ultrasonics similar to bats

Definitely Not Unlikely Maybe/Not Sure Likely Definitely

8. How likely would you undergo an implant/procedure to improve your physical capabilities, if it were to become available?

e.g. increased strength, improved manoeuvrability.

Definitely Not Unlikely Maybe/Not Sure Likely Definitely

9. How likely would you undergo an implant/procedure to enable your location to be seen by friends and family, and alert the social services in emergency situations, if it were to become available?

Assuming it remained private. i.e. only people you want to see your position can.

Definitely Not Unlikely Maybe/Not Sure Likely Definitely

10. Regardless of your previous responses. How much would the risk of the implantation/procedure affect your decision upon getting an enhancement?

Not at all Very little Not sure A little A lot

11. Again regardless of your previous responses. How much would social factors affect your decision upon getting an enhancement?

I.e. friends/family/partners opinions.

Not at all Very little Not sure A little A lot

12. How does the general idea of thought communication make you feel?

Thought communication, i.e. being able to pass thoughts, feelings and memories, to one another. Assuming it stayed private, i.e. only people you wanted to communicate with could send/receive them.

Scared Negatively Okay/Not Sure Positively Excited

13. Would you undergo the implant/procedure to give yourself thought communication?

Again assuming it stayed private, i.e. only people you wanted to communicate with could send/receive them.

Definitely Not Unlikely Maybe/Not Sure Likely Definitely

14. How does the general idea of nanotechnology for medical purposes make you feel?

E.g. tiny machines being implanted into patients to destroy diseases, tumours and perhaps correct genetic defects. Assuming it was an approved medical method.

Scared Negatively Okay/Not Sure Positively Excited

15. Would you undergo a medical procedure involving nanotechnology?

Again assuming it was an approved medical method.

Definitely Not Unlikely Maybe/Not Sure Likely Definitely

16. Do you have any Implants/Enhancements already? If so please brief specify.

- ○ Sensory Enhancement
- ○ Physical Enhancement
- ○ Medical Implantation
- ○ Body Modification (Art Work)
- ○ Other, please specify...

17. Finally, would you consider having an artificial organ or limb, if you hypothetically ever needed a transplant?

- ○ Yes
- ○ No

Thank you for answering this survey.

Data

Where do you currently live?	Group		Total
	Population	Control	
United Kingdom	248	44	292
Australia	2	0	2
Bahamas	1	0	1
Belgium	4	0	4
Brazil	2	0	2
Bulgaria	1	0	1
Canada	3	0	3
Colombia	2	0	2
Cyprus	2	0	2
Czech Republic	2	0	2
Estonia	1	0	1
Finland	14	0	14
France	2	0	2
Germany	3	0	3
India	4	0	4
Ireland	1	0	1
Italy	2	0	2
Japan	2	0	2
Malaysia	2	0	2
Maldives	1	0	1
Netherlands	3	0	3
New Zealand	1	0	1
Philippines	1	0	1
Poland	39	0	39
Portugal	1	0	1
Romania	2	0	2
Russia	1	0	1
South Africa	1	0	1
Spain	1	0	1
Sweden	3	0	3
Tanzania	1	0	1
Venezuela	1	0	1
USA	40	0	40
Total	394	44	438

Table B-1: Number of respondent separated by country of residence

Group		Frequency	Percent	Cumulative Percent
Population	White / Caucasian	334	84.8	84.8
	Spanish / Hispanic / Latino	16	4.1	88.8
	Black / African American	3	.8	89.6
	Asian	17	4.3	93.9
	Native American	1	.3	94.2
	Other	11	2.8	97.0
	Prefer Not to Answer	12	3.0	100.0

	Total	394	100.0	
Control	**White / Caucasian**	30	68.2	68.2
	Asian	13	29.5	97.7
	Other	1	2.3	100.0
	Total	44	100.0	

Table B-2: Frequency table of Ethnicity within the Human Enhancement Survey

Appendix C – The Global View on Magnetic Implants

Survey

The Global View on Subdermal Magnetic Implants

My name is Ian Harrison; I am a current PhD student of Reading University. My thesis is in investigating the perceptual capabilities of the Human tactile/touch sense. This survey is aimed at anyone with a subdermal magnetic implant, thanks to everyone who spends the time to complete it! :)

Background Information

These 4 questions are too simply to gauge the range of people adopting body modification.

1. How old are you?

---

2. Where do you currently live?

N.B. For residents of the USA, states are listed below the countries.

3. What is your gender?

Male Female

4. What is your Ethnicity?

Magnet Questions

These few questions are to gain information about the implant procedure, the magnets, and your views.

5. When did you get the magnet/s implanted?

Text Response Box

6. Where are your magnets located?

- ☐ Left Thumb
- ☐ Left Index
- ☐ Left Middle
- ☐ Left Ring Finger
- ☐ Left Pinky/Little Finger
- ☐ Right Thumb
- ☐ Right Index
- ☐ Right Middle
- ☐ Right Ring Finger
- ☐ Right Pinky/Little Finger
- ☐ Other areas of body (please specify)

7. Who implanted them?

- ○ Self-Implantation
- ○ Local Doctor/Surgery

- ○ Brian Decker
- ○ Steve Haworth
- ○ Mac 'Doctor-Evil' McCarthy
- ○ Divine Canvas
- ○ Body Modification Artist (please specify) _____
- ○ Other (please specify) _____

8. Where did you hear/read about the implant?

- ○ Body Modification Circles (Artists, Websites, etc.)
- ○ Word of mouth (Friends, Family)
- ○ Youtube
- ○ Other Website (please specify) _____
- ○ Other (please specify) _____

9. Please specify your views to the following statement: Before having the magnet/s implanted, I fully understood the risks involved. E.g. risk of: having an MRI, neodymium poisoning, implant rejection, tissue damage, etc.

Strongly Disagree	Mostly Disagree	Partly Agree	Mostly Agree	Strongly Agree

10. What is the size of your magnet/s? (If you have multiple sizes please enter the largest.)

- ○ 6mm Diameter, 0.7mm Thick
- ○ 3mm Diameter, 0.7mm Thick

- ○ 2mm Diameter, 1mm Thick
- ○ Other (please specify) _____
- ○ Unsure/don't know

11. What type of coating is on your magnet/s?

- ○ Parylene
- ○ Silicon
- ○ Sugru
- ○ Other (please specify) _____
- ○ Unsure/don't know

12. What is the material of the magnet/s?

- ○ Neodymium N52
- ○ Neodymium N48
- ○ Neodymium N42
- ○ Samarium–Cobalt
- ○ Other (please specify) _____
- ○ Unsure/don't know

13. Why did you get this implant/body modification and do you have any others?
    Text Response Box
14. Since having the magnet/s implanted have you had any bad experiences, recurrent pain or been hindered in day-to-day activities due to them? (If no please leave blank.)
    Text Response Box

15. Have you been able to 'feel' things like microwave ovens, computer fans or laptop power packs? If so, which is your favourite and why? What does it feel like? (If no please leave blank.)

    Text Response Box

16. How long did your implant take to heal (approximately)?

    ○ 1 - 3 Days ○ 1 Week ○ 2 Weeks ○ 3 Weeks ○ 1 Month +

17. How many times have you been stopped at security scanners (e.g. Airport Security) due to your implanted magnet/s? I.e. has anyone ever ran a security wand over your hands (or other area) and questioned you about it, if so how many times.

    ○ 0 ○ 1 ○ 2 ◉ 3 ○ 4 ○ 5+

18. Have your magnet/s or implants ever prevented you from receiving medical treatment, for example an MRI? If so, what was the outcome? (If no please leave blank.)

    Text response Box

Data

Data	What is your Ethnicity?	Frequency	Percent	Valid Percent	Cumulative Percent
Valid	White / Caucasian	47	83.9	90.4	90.4
	Spanish / Hispanic / Latino	4	7.1	7.7	98.1
	Asian	1	1.8	1.9	100.0
	Total	52	92.9	100.0	
Missing	Prefer Not to Answer	4	7.1		
	Total	56	100.0		

Table C-1: Frequencies of the ethnicities of the respondents

Data	When did you get the magnet implanted?	Frequency	Percent	Valid Percent	Cumulative Percent
Valid	JAN 2001	2	3.6	3.8	3.8
	JAN 2002	1	1.8	1.9	5.8
	MAR 2009	1	1.8	1.9	7.7
	MAY 2009	1	1.8	1.9	9.6
	JUN 2009	1	1.8	1.9	11.5
	NOV 2010	1	1.8	1.9	13.5
	JAN 2011	2	3.6	3.8	17.3
	MAR 2011	1	1.8	1.9	19.2
	JUN 2011	1	1.8	1.9	21.2
	AUG 2011	1	1.8	1.9	23.1
	NOV 2011	1	1.8	1.9	25.0
	DEC 2011	1	1.8	1.9	26.9
	JAN 2012	2	3.6	3.8	30.8
	FEB 2012	1	1.8	1.9	32.7
	MAR 2012	2	3.6	3.8	36.5
	APR 2012	1	1.8	1.9	38.5
	MAY 2012	3	5.4	5.8	44.2
	JUN 2012	2	3.6	3.8	48.1
	JUL 2012	4	7.1	7.7	55.8
	AUG 2012	3	5.4	5.8	61.5
	SEP 2012	1	1.8	1.9	63.5
	OCT 2012	3	5.4	5.8	69.2
	NOV 2012	2	3.6	3.8	73.1
	DEC 2012	3	5.4	5.8	78.8
	JAN 2013	2	3.6	3.8	82.7
	MAR 2013	1	1.8	1.9	84.6
	APR 2013	5	8.9	9.6	94.2
	MAY 2013	2	3.6	3.8	98.1
	AUG 2013	1	1.8	1.9	100.0
	Total	52	92.9	100.0	
Missing	NA	4	7.1		
	Total	56	100.0		

Table C-2: Date of magnetic implant from respondent (MMM YYYY)

Where do you currently live?	Year Of Implant							Total
	2001	2002	2009	2010	2011	2012	2013	
UK	2.0%				6.0%	10.0%	8.0%	26.0%

Australia		2.0%				4.0%		6.0%
Canada			2.0%			2.0%		4.0%
Denmark	2.0%							2.0%
Finland							2.0%	2.0%
Germany					2.0%	4.0%	2.0%	8.0%
Maldives						2.0%		2.0%
NZ						2.0%		2.0%
USA			4.0%	2.0%	6.0%	26.0%	10.0 %	48.0%
Total	4.0%	2.0%	6.0%	2.0%	14.0 %	50.0%	22.0 %	100.0 %

Table C-3: Comparison between year of implant and the country of residents of the respondents

Where did you hear/read about the implant? [other]	Frequency	%	Valid %	Cumulative %
No Answer	44	78.6	78.6	78.6
CCC (talk by Lepht Anonymous)	1	1.8	1.8	80.4
Cyberpunk/Transhumanism	1	1.8	1.8	82.1
gizmodo, then various online	1	1.8	1.8	83.9
grindhouse.wetware.com	1	1.8	1.8	85.7
H+ Magazine	1	1.8	1.8	87.5
Hacker News	1	1.8	1.8	89.3
http://events.ccc.de/congress/2006/Fahrplan/events/1629.en.html	1	1.8	1.8	91.1
magnetimplantat.de	1	1.8	1.8	92.9
sapiensanonym.blogspot.com	1	1.8	1.8	94.6
scarp paper	1	1.8	1.8	96.4
TED talk	1	1.8	1.8	98.2
Unknown - on the internet many years ago	1	1.8	1.8	100.0
Total	56	100.0	100.0	

Table C-4: 'Other' (i.e. text) responses to "Where did you hear/read about the implant?"

What is the size of your magnet/s? [other]	Frequency	%	Valid %	Cumulative %
No Answer	49	87.5	87.5	87.5
.75mm diameter, 1.0mm thick	1	1.8	1.8	89.3
1 x 3mm disk (silicone coating), 1 cylinder (hard coating)	1	1.8	1.8	91.1
2*3 mm without the coat, 3*4 with it	1	1.8	1.8	92.9
6mm, 2mm Thick	1	1.8	1.8	94.6
6mmx3mm (cylinder shaped)	1	1.8	1.8	96.4
I was told "1/8th"x1/16th", 45 gauss	1	1.8	1.8	98.2
not certain anymore but I reckon (inside of silicone) about 3m diameter and 1mm thick	1	1.8	1.8	100.0
Total	56	100.0	100.0	

Table C-5: 'Other' (i.e. text) responses to "What is the size of your magnet/s?"

Direct Quote From Respondents	Cat.
Uni project, sounds cool, new experiences, interesting project.	E
As a favour to a mate to help him with his PhD research, and no, this is the only type of body mod I have	E
Experimental; no other implants	E

Research, exploration	E
Will try and shorten a long story. I've always been fascinated by the idea of incorporating technology into the body and I am also interested in the world of body modification in general. No other body modifications outside of piercings, but would definitely have more (tech. based ones) if it ever became a possibility.	I/F
I'm a welder and they may help with that but more so because I'm an idiot and love it	I/F
Yes I have others... Transdermal Head Implants, Tongue Split, Brandings, Scarification, Tattoos And Piercings, And Have My Nipples Removed. I Got This Implant Literally "For Shits And Giggles"	I/F
I have several piercings and modifications, had the magnet implant as a whimsical way to entertain friends and as a friend once said that'll, mb. I have several other implants and modifications, the magnet was both, the next unusual one and a way to confuse drunks when you can stick a metallic object to the side of your hand :)	I/F
No other modification/implant. Interest as a physicist.	I/F
Curiosity. I don't have any other body mods or tattoos.	I/F
See article on iamdann.com	I/F
Just thought it seemed interesting. I have gauged lobe piercings, and have previously had trans-dermal anchors near my collarbones, but no other significant mods.	I/F
I implanted the magnet to see what feelings i could get from it, sensations of electricity etc. also to play tricks with ppl. not to mention i wanted to test for "magnetic therapy" reasons , i have various other implants/body mods.	M.V
I was interested in the possibility of sensing magnetic fields, and of integrating such a 'decvice' into my body.	M.V
I was very interested in experiencing the reported effects of being able to "sense" electro-magnetic fields. I'd been active in various "DIY transhuman" groups, because of their concern, that I agree with, that any future optional or potentially necessary beneficial body modifications would be limited to wealthy individuals and organisations. I'd previously had cosmetic body modifications in the form of a septum piercing and a tattoo, although the motivation for these was obviously very different.	M.V
Wanted to experience new sensation	M.V
It's my first implant, but I have two tattoos and 24 piercings. I was interested in the magnetic vision aspect, and wanted to experiment with healing a heavier body modification as preparation to move on to heavier modifications in the future (larger subdermal implants, ear pointing and tongue splitting).	M.V
It was very interesting to me to get a 'sixth sense'. I also have an eyebrow piercing.	M.V
Mainly because I wanted another sensory input; partly because I wanted more body mods, for cosmetic and social reasons; very slightly because at the time I was into self injury. I also have an RFID chip in the back of the same hand. As soon as active electronic implants become a possibility I will probably try to get some for myself. Also, I frequently test prototype sensory extension devices on myself.	M.V
I implanted my magnets for the ability to physically sense magnetic fields, as well as the ability to move/pick up objects via magnetic force. I am a modification artist, and I have many modifications including many piercings & tattoos, split tongue, silicone implanted horns, subdermally implanted genital ribs, chest scarification and have suspended from hooks over 100 times.	M.V
First of all for the experience, I was hoping to get some of the feeling that other people have described.	M.V
Because I love to play with the magnet and because it is great to sense electromagnetic fields. I dont have any other implants or body modifications	M.V
augmenting the human body by adding a new 'sense'	M.V
I wanted to experiment with new senses; still do	M.V
I wanted magnetic vision. No other modifications.	M.V
I was reporting on biohacker/grinder culture and wanted to test out their claims first	M.V

hand.	
This is my first implant and I got it so I could experience more of our world and to interact with machines on a new level.	M.V
Multiple piercings and a single tattoo. I got it to feel em fields.	M.V
I wanted to extend my sensory input and have an "extra sense", so to speak. I have a few normal ear lobe piercings and an Industrial piercing on one ear.	M.V
Our senses are limited, and I wanted to expand mine. I consider this a major step in my pursuit of a more transhumanist future.	M.V
I wanted to show solidarity with others who have gotten the implant and I am curious about the ability to detect magnetic fields.	M.V
I desired this implant solely for the purpose of enhancing my sense of touch. The ability to "feel" waves that are all around us, and that other people cannot feel, is amazing to me. I do not have any other modifications, although I would be open to others that enhance or expand upon my senses. I currently have one tattoo and have had a tongue piercing in the past.	M.V
Wanted to expand senses. RFID chip in right hand under pointer knuckle	M.V
I wanted to gain an additional sense. I've also done circuit design and was hoping I'd be able to detect currents. My only other modifications are tattoos (two).	M.V
It seemed inexpensive for a new sense. And no no other modifications at all. Not so much as a tattoo.	M.V
For cool tricks but to mainly feel the 6th sense of magnetic fields	M.V
Wanted to feel/sense more stuff in the world. I have a few piercing and ~16 hours of tattoo work (less work than it sounds)	M.V
I am tattooed and pierced, I wanted to feel magnetic fields.	M.V
I got it to explore magnetic vision and also to see if it would be useful in my work as an electrical engineer. It's my only implant but I have some body piercings and star shaped holes punched in my upper ears.	M.V
This is my first body mod of any kind; I do not even have a tattoo and I've never had a piercing. I got the implant for mainly the "sixth sense" of EM fields, but also for the party tricks/conversation piece it provides.	M.V
to sense electro-magnetic fields, I have no other body-mods, but am planning on more magnets	M.V
i wanted to feel emf	M.V
I enjoy feeling different	N/A
Nope, this is the only implant I have.	N/A
See article where you took the image from/any other body modifications? yes	N/A
TRUST Studio in Mannheim, Germany. I have one tattoo on my left shoulder.	N/A
First and only modification. It's practical (I need to pick up small metal objects a lot).	P.P
I am a performer (magic, mentalism) and i got it to add an extra secret weapon to my act. Never ended up using for that. I have flesh tunnels, branding, nipple and genital piercing, a silicon sub dermal implant.	P/A
I've wanted one ever since I saw an article about them on BME, it felt like it was "me", just as piercings and suspensions have always felt.	T
I'm into body modification in generel, I always wanted to try implants, and I love the idea of functional body modifications.	T
Because I want to pursue practical transhumanism. I don't have any other modification, but I intend to as they become available.	T
I got it to become modified by a great artist and I have had about 20 something piercings.	T
I had a latent interest in "augmentation"-style body modification, and when I learned of magnetic implants I could think of no reason NOT to get them. I have no others as of yet but am looking into RFID/NFC capsules and implanted magnets for use as earphones.	T
5 years of reading into it and found a biohacking website that supported a specific type. Decides to take the plunge.	T

Table C-6: All text responses as to "Why did you get this implant/body modification and do you have any others?" and their categories (Cat.). I/F – Interest/Fun. M.V – Magnetic Vision. T – Transhumanistic. P.P – Practical Purposes. E - Experimental N/A – Not applicable.

Direct Quote From Respondents	Cat.
Yes. The magnet was very sensitive when it was in there, and compromised my ability to play the guitar. While it did not affect my ability to climb it was frequently quite painful when doing so. After 18 months, the sugru coating failed critically, the magnet rusted and expanded, and stopped working at all. I made an appointment with a local doctor to have it removed. Unfortunately the doctor did not really know what he was looking for (neodymium splinters) and I ended up doing half the operation myself. I still have a lump of scar tissue in my finger, the capsule around the implant folded up and healed into a big clod. It's still fairly sensitive.	C.R.S.R
nope, but I couldn't start bouldering as a hobby. the only day-to-day activity where my magnet sometimes bugs me is when I hover the floor (probably because of the way I grip the handle)	I.N
Pain: only when carelessly playing with neodymium magnets. On occasion my pinky nail will graze the raised skin.	I.N
The magnet flips position fairly often and it's become a bit of a tic to push it back down, but it doesn't really hinder me too much.	I.N
Too soon to tell.	I.N
a little, lifting heavy objects presses on the magnet.	L.O(L.P)
Only thing I have found is when the magnets on my tank bag for my motorbike "take hold" if I'm not paying attention and put my hand in the wrong place when attaching the bag on the motorcycle.	L.O(L.P)
They only (very slight) downside is that the one in my middle finger, which was originally more on the ring-finger side of my middle finger, migrated to the center of the pad on my finger, which makes direct pressure on the pad slightly uncomfortable. However, this has not hindered me at all, as even when doing heavy lifting pressure is typically on my palm and base of my fingers, not on the pad. There has been no pain.	L.O(L.P)
I am an artist and fabricator so I will occasionally feel some soreness in the implants after a day of heavy hand-labor	L.S.W.R
About two weeks after implanting the magnet I found it was probably too close to the surface of my skin for any long-term use, so I removed it before it had fully healed. I have suffered no ill effects from it.	No
I currently feel no pain. The only inconvenience I have had so far is demagnetizing a "player card" at a casino. I had to have it replaced twice in an hour before I realized I was causing the issue and just had to hold it carefully from that point on.	No
I had a decent amount of pain the night I implanted the cylinder (hard coated) magnet in my forehead, but I suspect that it was due to the depth that I implanted it (deeper into muscle tissue). My finger implant (silicone-coated 3mm disk) has given me no problems. I can feel it when pressure is applied, but I make a point of not putting it through undue or excessive pressure. If a slight level of discomfort is experienced, I back off.	No
I have had no bad experiences or pain at all and have never been hindered in my daily life or activities.	No
I use my hands a lot, I build things and use tools often. I have to be aware of my implants so I don't damage them. However its not a major hindrance	No
No	No
no bad experience. I'm not sure if I want to handle the company's tape backups.	No

No recurring pain since it healed. When it gets close to a strong magnet it pulls hard and feels uncomfortable, but not painful. It took getting used to holding my ipad in it's case because they're both loaded with magnets. The magnet is in the pad of my finger and therefore makes gripping things strongly or carrying heavy objects a little awkward because I try to avoid putting much pressure on it. I consider it a minor inconvenience.	No
No.	No
none	No
none	No
the only negative impact of the magnet is that my phone uses a magnetic sensor to identify when it's docked so if I touch a specific area on the back of the phone it will wake up and think it's on a dock. It doesn't happen often tho.	No
It's a lot more difficult and even painful to play bass guitar.	P.S/I (H.P)
Outside of the soreness from healing, I have only one hindrance. Catching a baseball (in a mitt) is excruciatingly painful, as the implant is located facing that side of my finger.	P.S/I (H.P)
No issues for 2 years. One implant was later dislodged and upset by very high pressure. Recurrent subtle pain for the past 8 months.	R.P
a weird pain in my finger sometimes but not unbearable	U/U.S
I have had to adjust my grip on things, so as to not push the magnet out of the "pocket". If this does happen, it can be quite painful. it slides right back in with a bit of manipulation though.	U/U.S
Only very mild problems - it's sometimes uncomfortable when opening jars or anything where I have to put much pressure on it, and can be slightly uncomfortable if something snaps onto the magnet unexpectedly. But no real pain and nothing that is a major problem.	U/U.S

Table C-7: Text Responses from those given by respondents to the question "Since having the magnet/s implanted have you had any bad experiences, recurrent pain or been hindered in day-to-day activities due to them?" and the categories for each response (Cat.). C.R.S.R – Coating Rupture Subsequent Removal. I.N – Inexplicit No. L.O (L.P) – Lifting Objects (Light Pain). L.S.W.R – Light Soreness Work Related. P.S/I (H.P) – Playing Sports/Instruments (High Pain).R.P – Recurrent Pain. U/U.S – Unusual/Uncomfortable Sensation.

Direct Quote From Respondents
Microwave, some plugs, clocking in scanner at work, xray at dentists, cooker, and a few others I can't remember
I can feel the microwave if I have my finger within about 6 inches of it. And of course I can 'feel' other strong magnets. Also, today for the first time I felt something else which were the security barriers exiting a library. I'd never felt something like that before. I am hoping/expecting to feel more as the tissue recovers further.
Seting the welder to pulse in time with my music, it's like having the beat inside your fingers also ac welding is a blast
yeah, i can feel anything that has a strong magnetic field, Microwaves are my favorite as its a vibrating buzzing feeling and actually tickles at the same time.
microwave ovens make the magnet tingle, deskfans also make it twitch and vibrate (i have one of the stronger version capable of being more sensitive)
yes, microwave ovens and power packs are my favourite things to feel, it's like a tickle in my finger.It's a shock when you forget and feel things like old style tvs turning on (the static charge you get)
Yes. Electric motors or transformers(such as listed above), plus other items containing magnets. It feels like a tingle and vibration, which can vary slightly, depending on what it is reacting to.

There is also a tugging or repulsion, which causes a sensation not unlike touching an invisible form if you follow around the magnetic field. I can't say i have a 'favourite', as it is an interesting rather than particularly pleasurable experience.
Laptop power packs. It's a slight tingle.
Yes - and the bass of music tracks routed through an electro-magnetic coil is the most fun, as it enhances the normal ability to 'feel' music to a much greater degree
Yes. Feeling music through electromagnet because it is almost like I can hear it through my finger
Yes, I can. I really like the microwave, it's very strong. Some electrical cords are good too, it's useful to be able to tell whether the iron is switched on or not.
All of those, my favourite would be walking through anti-theft gates at a JB Hi Fi store in Australia. Sadly it's the only store with anti-theft gates that I feel. It feels like a buzzing in the finger.
I have and it was freaking awesome. I like feeling transformers the most, no reason. I'd love to be able to feel a data line instead of just supplies. It feels like tingling buzz, except as your finger moves through space, it is mapped to a three dimensional sense. Sometimes with permanent magnets the orientation of the field is discernable.With a lot of fields going at once the effect can be compared to music
Yes. Monitor degaussing are fun. I feel heat when near microwaves..
I have felt all of the above and much more. The ability to feel the field given off by a microwave when it is turned on inspired me to not ever stand that close to a microwave, assuming that it's unhealthy for multiple reasons.
microwave ovens and computer parts (I asume its the processor) feel pretty crazy. Nothing beats the "stands" at the entrances of libraries that detect if you checked out the books, those feel pretty intense, to the point where other people can place a finger on my hand and feel the "vibrations"
Not yet since it is still healing.
I feel microwave ovens and ventilators, but no luck with laptop power packs so far. after talking to other people with magnetic implants, I think I am a little less sensitive to magnetic fields than most of them, but I'm not sure.
Yes. Favorite: Electronic article surveillance system in my university library. Strong vibrating sensation.
yes. I like transformers, electric motors and hard drives (I feel them spin).
My favourites are the microwave oven, my laptop fan and the security things at the exit of shops
Microwave ovens. Very strong field that can be felt from 2 ft away. Feels like a vibrating surface.
microwave because it has the strongest field. like a vibration in the air.
microwaves - it sometimes feels like the tip of my finger is vibrating
My favourite is the feeling when a cashier scans a product and breaks the RFID tag on it; it feels like a sharp burst of field.
I have been able to feel all of those.Laptop power packs are my favorite, because of the clear, strong sensation.
Subway power generators under the city
I can feel microwave ovens and magnets on my laptop, speakers and shoulder bag.
So far I have only felt a microwave oven and the end of an extension cord that has several power packs plugged in. I would describe the feeling as a light, happy fluttering.
I have a friend whose car engine makes my hands shake. It's really surprising.
When I first received the implants, the were very sensitive but now that they are fully healed, the tingling sensations have diminished quite a bit. I can feel rotating electric motors like wood routers from about 3 inches away, but microwaves and laptop supplies only produce a very minor buzzing. My favorite feeling comes from an automotive battery charger I own. High amperage DC voltage has a very "chunky" feeling, almost like being mildly electrocuted, as opposed to the field from an electric motor, which feels more "fuzzy", like a warm, fast-moving wind across the skin.
I have felt all of the above. It feels like a tingling when it's something with a consistent current running through it, and almost like a clicking when it's something non-constant. I normally feel

the clicking when I'm on my laptop, and I'm fairly certain that it's the hard drive that I'm feeling(it doesn't feel like a fan). I can feel roughly how hard the drive is working by the frequency of the clicking (which is not a constant frequency). For instance, I can feel it speed up when I scroll through a webpage using the scroll bar or when I have code compiling. My favorite thing with a constant AC current is my friend's blacklight, which had a really interesting feel to it. The tingling felt more pronounced, like the frequency was slower. Feeling the high-voltage rail of the metro through the metro floor is also cool.
So far no, but the implant site hasn't healed fully yet.
Yes to all of those, and pretty much anything with a power supply. One of my favorites is computer fans. My sensitivity has increased which allows me to not only feel the wave, but feel the "shape" of the wave. Microwaves give off a chaotic wave, but things like computer fans give off a nice dome/donut shape. It is very hard for me to explain what it feels like. The sensation is similar to a "buzzing" like when one of your extremities falls asleep, but I get more information such as intensity, "shape", and direction of the wave. I work on computers and had my favorite experience while working on a computer. My clients computer would not boot, and they diagnosed a dead hard drive and stated they didn't even think it was spinning. By hovering my hand over the laptop, I was able to feel the laptop spinning, and spinning at what I believed to be a normal speed. That allowed me to skip some of the troubleshooting process and diagnose/fix the issue quicker.
My favorite is when an alarm goes off at Home Depot I can feel it. (Lol)
Yes. Pencil sharpener at about 3 inches away, any closer is a tad too intense.
Yes, I cant really say I have a favorite. Different things produce different sensations, and its difficult to accurately describe. Maybe similar to the tingly feeling you get when your foot has fallen asleep and is waking up, but without the pain/discomfort part. this tingly thing can sort of oscillate or change intensity depending on the type of thing producing the field.. I dunno.
My magnet is much weaker than I'd like. I can feel magnets, of course. Also; laptop power packs, fans in my laptop, electric hair clippers, and a super-strong generator used to irradiate tissue samples. I wish I felt more. My favorite is probably the hair clippers, as the motor inside is powerful and just under the plastic.
YES I find that laptop power converters feel almost pleasant. I can feel high powered electric lines from the ground which is probably my favorite.
Yes, I can feel all three of those, but my favorite is shaded pole fans because it is so powerful. It feels like a wiggly vibrating push.
Yes. Strong microwaves are cool but those box shaped plugs are my favorite because it is a strong steady current.
I feel a lot. My favorite is randomly finding something on the street. I live in NYC, the underground infrastructure is massive. I often feel mysterious sensations under the sidewalk. Microwaves are pretty awesome too. I can feel mine from ~27" away. Vibration tingle. Somewhere between a cell phone vibrating somewhere nearby and a small electric shock.
yes! My favorite is tattoo machines. Second favorite is finding magnets I didn't expect in my daily life.
absolutely, but I usually don't notice magnetic fields unless I'm looking for them. Alternating fields are much more noticeable and produce a tingling sensation. I can also differentiate between magnetic and non-magnetic materials, and even determine the thickness of sheet steel based on how much pressure I feel from the implant when I touch my finger to the steel. My most favorite sensation is when I use opposite poles of a magnet to make my implant flip over. That's a totally bizarre and almost erotic sensation and I've considered asking Steve to give me some magnetic genital beads or designing some custom magnetic jewelry for my apadravya so I can experiment with the use of electromagnets for erotic stimulation.
yes, and i wouldn't say there's a "favorite." I don't go out of my way to hold my hand near something that's affecting the magnet. It's a weird feeling.
Yes, all of the above and more. Most objects feel like a vibration or a buzz emanating from my finger tip. These vibrations can vary in frequency and amplitude. I can locate hidden magnetic

objects by feeling for the magnet pulling in one direction or the other depending on the location of the magnet. My favorite is probably the microwave because it is my strongest household item, and it allows me to show others what it feels like by having them squeeze my finger at the magnet while I'm holding my finger close to the microwave.
Yes, Even after only three weeks I can locate the magnetic sensors in some laptops/iPads that are used to put them to sleep when the display/cover is closed, and I can manipulate them to put computers to sleep with a wave of my hand. I also can feel a "buzzing" sensation from power inverters such as an XBox360 power supply, and the security tag deactivation at electronics store checkout registers (Which is so strongit's slightly uncomfortable). My favorite is the magnet in my laptop's screen, I find myself frequently playing with it while working, just fascinated by the sensation.
yes, my favorite are 220v transformers because they throw off the biggest changing field I've felt. Using my implants to find magnets & know how powerful they are is fun and on occasion useful.
My bedroom fan, first EM field I felt. 6 to 9 inches away, was fun to play with. Other metals while at work at been interesting, including materials I thought would be magnetic, and the surprising amount of steel in the environment. Vacuum power cables at my job are fun to handle while I work. Feel:Imagine a tiny speaker pressed against your finger. At low frequencies, and lower power, you can feel it without doubt. Higher and you can feel it fade out. Lower and same thing. Metal and magnets you feel a pull until you get too close and start to feel a painful pinch (same with powerful EM fields, which feel like a painful pinch/push x times a second).
yes, my computer.
I've been able to feel microwaves, halogen transformers, the magnets in fridge doors, electric motors (for instance in a desk-fan), also the motion detector unit of automated pissoirs. My favorites are the desk-fan, since that enables me to let other people feel the vibration of my implant and then the fridge magnets, since I always thought fridges were hold shut by some vacuum contraption.
I was able to feel a slight vibration once from an indoor power source box. But, being able to FEEL such vibrations from a microwave, et cetera, is more possible when implanted into the finger. This is due to the high nerve count located within the finger.

Table C-8: Text Responses from "Have you been able to 'feel' things like microwave ovens, computer fans or laptop power packs? If so, which is your favourite and why? What does it feel like?"

Direct Quote From Respondents
No, but I can't go into MRI
No, they haven't, and it's not a problem now.
I have had no problems at all, and I work as a nurse at very a very large hospital, I can feel the MRI scanner from across the building but I have had no problems so far.
Not yet
No. I would like to add though that Steve Haworth and his assistants Mandy and Kelly were professionals the entire way through and made me well aware of all risks.
(I wish there was an "Additional Comments" section...i think asking how long the magnet took to "heal" is an unclear question. The magnet actually takes MONTHS to heal. If anyone answers anything less, they were unclear about the healing process. The majority of the soreness might let up in a few weeks, but that does NOT mean it's "healed."Also, you're not going to find anyone who has been stopped by security. Not strong enough.-Dann

I attempted an MRI with magnet implant after being told by the MRI office that I could leave my magnet in, as it would only demagnetize it. I wasn't that far from the machine; maybe 3 to 5 feet away and my magnet started acting up. Flipping about and pulling on the skin; I even tried to proceed by holding it down, but I felt a pinching and burning sensation and the MRI was stopped. After that I removed my magnet in order to complete the MRI. I soon plan to re-implant my magnet as well. For the record, the magnet was produced by Samppa Von Cyborg.

Table C-9: Text responses from "Have your magnet/s or implants ever prevented you from receiving medical treatment, for example an MRI? If so, what was the outcome?"

Appendix D – CERMAG GMET H001 Product Specification

STANDARD EQUIPMENT	GMET H001 GAUSSMETER TRANSVERSE HALL EFFECT PROBE IMPACT RESISTANT STORAGE CASE INSTRUCTION MANUAL BATTERY
ADDITIONAL EQUIPMENT	AXIAL HALL EFFECT PROBE EXTERNAL POWER SUPPLY RS232 COMMUNICATION LEAD AND SOFTWARE TO CONNECT TO AN IBM COMPATABLE PC ZERO FLUX CHAMBER REFERENCE MAGNETS
MEASURING RANGE 1	1 TO 3000 GAUSS (0.0001 TO 0.3 TESLA)* RESOLUTION 1 GAUSS (0.0001 TESLA)
MEASURING RANGE 2	10 TO 30000 GAUSS (0.001 TO 3 TESLA)* RESOLUTION 10 GAUSS (0.001 TESLA)
ACCURACY	+/- 2.0% OR 10 GAUSS (WHICHEVER GREATER) TO 20 000 GAUSS (2.0 TESLA)
DISPLAY REFRESH RATE	0.05 TO 5 SECONDS (PROGRAMMABLE)
MEASUREMENT UNITS	GAUSS TESLA AMPERE METERS OR OERSTED
PROBE TYPES	TRANSVERSELY OR AXIALLY ORIENTATED HALL EFFECT INCORPORATING ONBOARD EEPROM TO STORE CALIBRATION DATA
OPERATING TEMPERATURE LIMITS	$0^{O}C$ TO $+50^{O}C$
STORAGE TEMPERATURE LIMITS	$-20^{O}C$ TO $+70^{O}C$
INTERNAL BATTERY TYPE	HEAVY DUTY 9V ALKALINE (PP3 FORMAT)
BATTERY LIFE	UP TO 20 HOURS CONTINUOUS USE
EXTERNAL POWER SUPPLY SPECIFICATION (NOT SUPPLIED)	9 TO 12V DC REGULATED
DISPLAY TYPE	16 CHARACTER X 2 LINES LCD
METER SIZE	195MM X 101MM X 44MM
WEIGHT	0.42 KG (INCLUDING BATTERY)
COMMUNICATION PORT	RS232C AT 9600 BAUD TO CONNECT TO AN IBM COMPATABLE PC (LEAD NOT SUPPLIED)
SOFTWARE (NOT SUPPLIED)	MICROSOFT WINDOWS BASED UTILITIES AND CONFIGURATION SOFTWARE
APPLICATIONS	MEASUREMENT OF MAGNETIC FLUX DENSITY FOR QUALITY ASSURANCE AND GOODS INWARD INSPECTION FOR APPLICATIONS INCLUDING: MAGNETIC ACTUATORS MAGNETIC SEPARATORS ELECTRIC MOTORS NOT SUITABLE FOR AC MAGNETIC FIELDS

- **DUE TO MEASUREMENT RESTRICTIONS AXIAL PROBES ARE ONLY CALIBRATED TO 5000 GAUSS**
- **PROBES AND METERS ARE CALIBRATED AS A UNIT THEREFORE THE METER MUST ONLY BE USED WITH THE PROBE(S) SUPPLIED WITH IT.**

Figure D-1: CERMAG GMET H001 Product Specification

Appendix E – mbed RT code

```
#include "mbed.h"
#include "TextLCD.h"
#include "Speaker.h"

TextLCD lcd(p15, p16, p17, p18, p19, p20); // rs, e, d4-d7
DigitalIn SW1(p5);
DigitalIn SW2(p6);
Timer t;
DigitalOut led1(LED1);
Speaker mySpeaker(p21);
Serial pc(USBTX, USBRX); // tx, rx
int main()
 {
   lcd.printf("RT e V1\nReady...");
   while(1)
   {
    int y = rand() %5;
    if(SW1)
    {
    lcd.cls();
    lcd.printf("Ready?\n");
    wait(y +2);
    led1 = 1;
    mySpeaker.PlayNote(200.0,1,0.5);
    t.start();
    }

    if(SW2)
    {
    t.stop();
    led1 = 0;
    mySpeaker.PlayNote(200.0,0,0.5);
    lcd.cls();
    lcd.printf("Time in Secs\n%f",t.read());
    pc.printf("%f,",t.read());
    wait (0.5);
    while(!SW2)
    {}
    wait(0.5);
    t.reset();
    lcd.cls();
    lcd.printf("RT e V1\nReady...");
    }

   }
  }
```

Appendix F – Initial Investigation – Frequency Discrimination Raw Data

		Trial Number										
Waveform	Signal 2 (Hz)	1	2	3	4	5	6	7	8	9	10	AVG
Sine	20	0	0	0	0	0	0	0	0	0	0	0
	24	0	0	0	0	0	0	0	0	0	0	0
	28	0	0	0	0	1	0	0	0	0	1	0.2
	32	1	1	1	0	1	0	1	1	0	1	0.7
	36	1	1	0	1	1	1	1	1	1	1	0.9
	40	1	1	1	1	1	1	1	1	1	1	1
Square	20	0	0	0	0	0	0	0	0	0	0	0
	24	0	0	0	0	0	0	0	0	0	0	0
	28	0	1	1	0	1	0	1	1	1	1	0.7
	32	1	1	1	1	1	1	1	1	0	1	0.9
	36	1	1	1	1	1	1	1	1	1	1	1
	40	1	1	1	1	1	1	1	1	1	1	1
Sawtooth	20	0	0	0	0	0	0	0	0	0	0	0
	24	0	0	0	0	0	0	0	0	0	0	0
	28	0	0	0	0	0	0	0	0	0	0	0
	32	1	1	1	1	1	1	1	1	1	1	1
	36	1	1	1	1	1	1	0	1	1	1	0.9
	40	1	1	1	1	0	1	1	0	1	1	0.8

Table F-1: Frequency DL raw data 20 Hz

		Trial Number										
Waveform	Signal 2 (Hz)	1	2	3	4	5	6	7	8	9	10	AVG
Sine	50	0	0	0	0	0	0	0	0	0	0	0
	55	1	0	0	1	0	0	0	0	0	0	0.2
	60	1	1	1	0	0	0	0	0	0	0	0.3
	65	0	0	0	1	0	1	0	0	0	0	0.2
	70	1	1	0	0	0	1	1	1	0	0	0.5
	75	1	0	0	0	0	1	0	0	1	1	0.4
	80	1	1	0	1	1	1	1	1	1	1	0.9
	90	1	1	1	1	0	1	1	1	1	1	0.9
	100	0	1	1	1	1	1	1	1	1	1	0.9
Square	50	0	0	0	0	0	0	0	0	0	0	0
	55	0	0	0	0	0	0	0	1	1	0	0.2

	60	0	0	0	0	1	0	0	0	0	1	0.2
	65	1	0	1	0	0	0	0	0	0	0	0.2
	70	0	1	0	1	0	1	1	1	0	1	0.6
	75	1	1	1	0	1	1	1	1	1	1	0.9
	80	1	1	1	1	0	1	1	1	1	0	0.8
	90	1	1	1	1	1	1	1	0	1	1	0.9
	100	1	1	1	1	1	0	1	1	1	0	0.8
Sawtooth	50	0	0	0	0	0	0	0	0	0	0	0
	55	0	0	0	0	1	0	0	0	0	0	0.1
	60	0	0	0	0	0	0	0	0	0	0	0
	65	1	1	0	0	1	1	0	1	1	0	0.6
	70	1	1	1	1	0	1	1	1	1	1	0.9
	75	1	1	1	1	1	1	1	1	1	1	1
	80	1	1	1	1	1	1	1	1	1	1	1
	90	1	1	1	1	1	1	1	1	1	1	1
	100	1	1	1	1	1	1	1	1	1	1	1

Table F-2: Frequency DL raw data 50 Hz

		Trial Number										
Waveform	Signal 2 (Hz)	1	2	3	4	5	6	7	8	9	10	AVG
Sine	100	0	0	0	1	1	0	1	0	0		0.3
	125	0	0	0	0	0	0	0	0	0	0	0
	150	0	0	0	0	0	1	0	1	1	0	0.3
	175	1	1	1	1	1	1	0	1	1	0	0.8
	200	0	1	1	1	0	0	1	1	1	1	0.7
Square	100	0	0	1	1	0	0	0	1	1	0	0.4
	125	0	1	0	0	0	1	0	0	0	0	0.2
	150	1	0	1	0	1	0	0	0	1	1	0.5
	175	1	1	0	0	0	0	0	1	1	1	0.5
	200	1	0	0	1	0	1	1	0	1	0	0.5
Sawtooth	100	0	0	1	0	0	0	0	0	0	1	0.2
	125	0	0	0	0	1	0	0	0	1	1	0.3
	150	0	1	0	1	0	0	0	0	1	1	0.4
	175	0	1	1	0	0	0	1	1	0	0	0.4
	200	0	1	0	0	0	1	1	1	0	0	0.4

Table F-3: Frequency DL raw data 100 Hz

		Trial Number										
Waveform	Signal 2 (Hz)	1	2	3	4	5	6	7	8	9	10	AVG
Sine	200	0	0	0	0	0	0	1	0	0	0	0.1
	225	0	0	0	0	0	0	0	0	0	0	0
	250	1	1	0	0	1	1	0	0	0	1	0.5
	275	1	0	1	1	1	1	1	0	1	0	0.7
	300	1	1	1	1	1	1	1	1	1	1	1
Square	200	0	0	0	0	0	0	0	0	0	0	0
	225	0	0	0	0	0	0	0	0	0	0	0
	250	1	1	1	1	0	0	1	0	0	1	0.6
	275	0	1	1	1	1	1	1	0	1	1	0.8

	300	1	1	1	1	1	1	1	1	1	1	1
Sawtooth	**200**	0	0	0	0	0	0	0	0	0	0	0
	225	0	1	0	0	0	0	0	0	0	0	0.1
	250	0	1	1	1	0	1	0	0	0	1	0.5
	275	1	1	1	1	1	1	1	1	1	1	1
	300	1	1	1	1	1	1	1	1	1	1	1

Table F-4: Frequency DL raw data 200 Hz

Appendix G – Initial Investigation – Temporal gap detection results

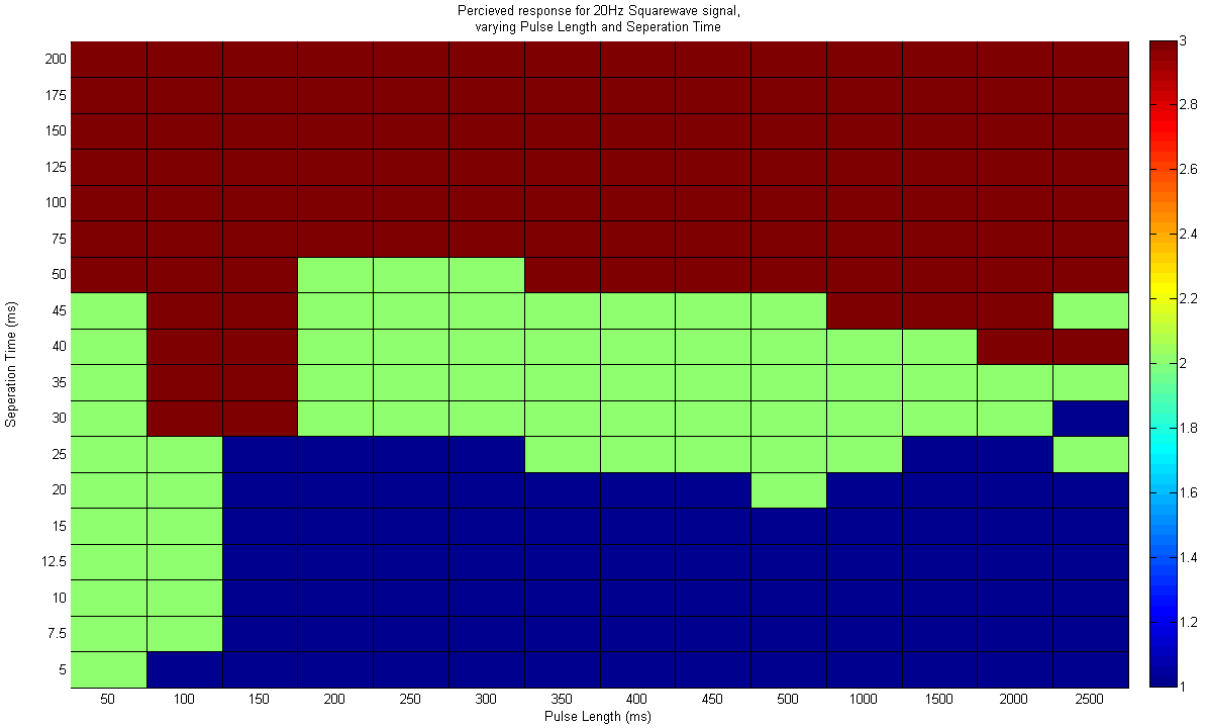

Figure G-1: 3 Pulse 20 Hz Temporal Gap Detection Results (Not to scale)

	Separation Time (ms)													
Pulse Length (ms)	50	100	150	200	250	300	350	400	450	500	1000	1500	2000	2500
5	2	1	1	1	1	1	1	1	1	1	1	1	1	1
7.5	2	2	1	1	1	1	1	1	1	1	1	1	1	1
10	2	2	1	1	1	1	1	1	1	1	1	1	1	1
12.5	2	2	1	1	1	1	1	1	1	1	1	1	1	1
15	2	2	1	1	1	1	1	1	1	1	1	1	1	1
20	2	2	1	1	1	1	1	1	1	2	1	1	1	1
25	2	2	1	1	1	1	2	2	2	2	2	1	1	2
30	2	3	3	2	2	2	2	2	2	2	2	2	2	1
35	2	3	3	2	2	2	2	2	2	2	2	2	2	2
40	2	3	3	2	2	2	2	2	2	2	2	2	3	3
45	2	3	3	2	2	2	2	2	2	2	3	3	3	2
50	3	3	3	2	2	2	3	3	3	3	3	3	3	3

75	3	3	3	3	3	3	3	3	3	3	3	3	3	3
100	3	3	3	3	3	3	3	3	3	3	3	3	3	3
125	3	3	3	3	3	3	3	3	3	3	3	3	3	3
150	3	3	3	3	3	3	3	3	3	3	3	3	3	3
175	3	3	3	3	3	3	3	3	3	3	3	3	3	3
200	3	3	3	3	3	3	3	3	3	3	3	3	3	3

Table G-1: Results of 3 Pulse 20 Hz Temporal Gap Detection Results

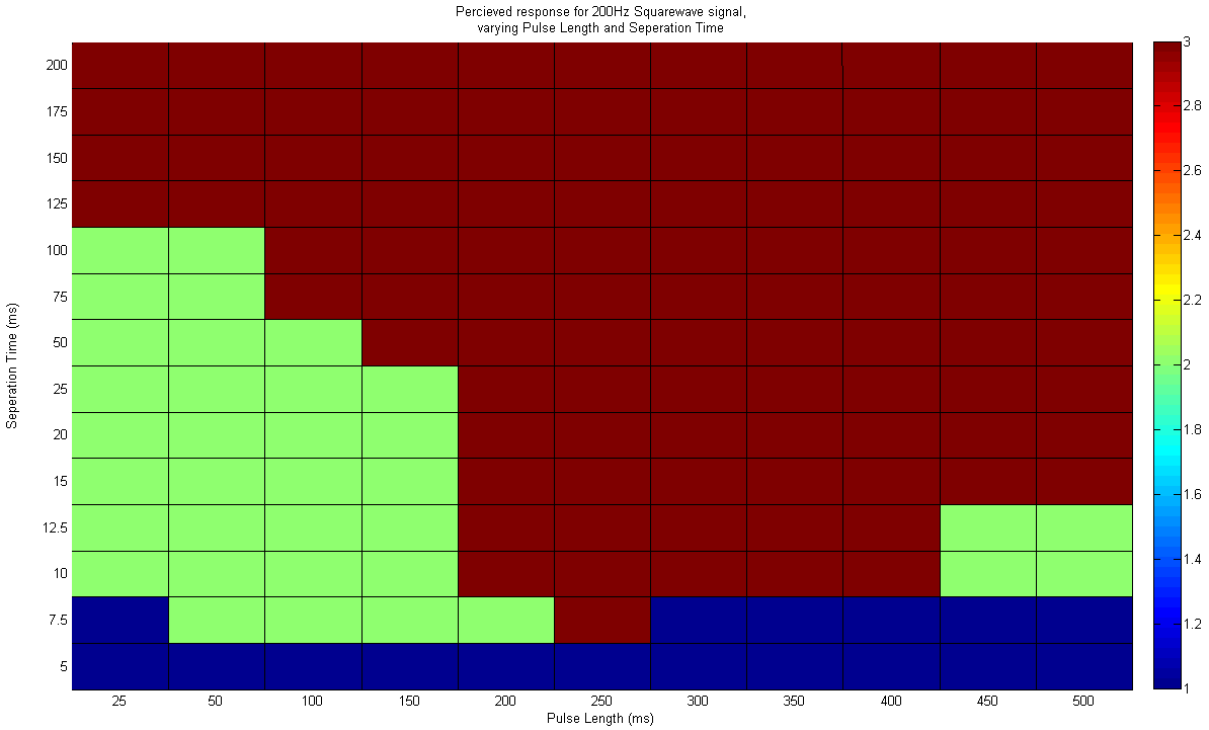

Figure G-2: 3 Pulse 200 Hz Temporal Gap Detection Results (Not to scale)

	Separation Time (ms)										
Pulse Length (ms)	25	50	100	150	200	250	300	350	400	450	500
5	1	1	1	1	1	1	1	1	1	1	1
7.5	1	2	2	2	2	3	1	1	1	1	1
10	2	2	2	2	3	3	3	3	3	2	2
12.5	2	2	2	2	3	3	3	3	3	2	2
15	2	2	2	2	3	3	3	3	3	3	3
20	2	2	2	2	3	3	3	3	3	3	3
25	2	2	2	2	3	3	3	3	3	3	3
50	2	2	2	3	3	3	3	3	3	3	3
75	2	2	3	3	3	3	3	3	3	3	3
100	2	2	3	3	3	3	3	3	3	3	3
125	3	3	3	3	3	3	3	3	3	3	3
150	3	3	3	3	3	3	3	3	3	3	3
175	3	3	3	3	3	3	3	3	3	3	3
200	3	3	3	3	3	3	3	3	3	3	3

Table G-2: Results of 3 Pulse 200 Hz Temporal Gap Detection Results

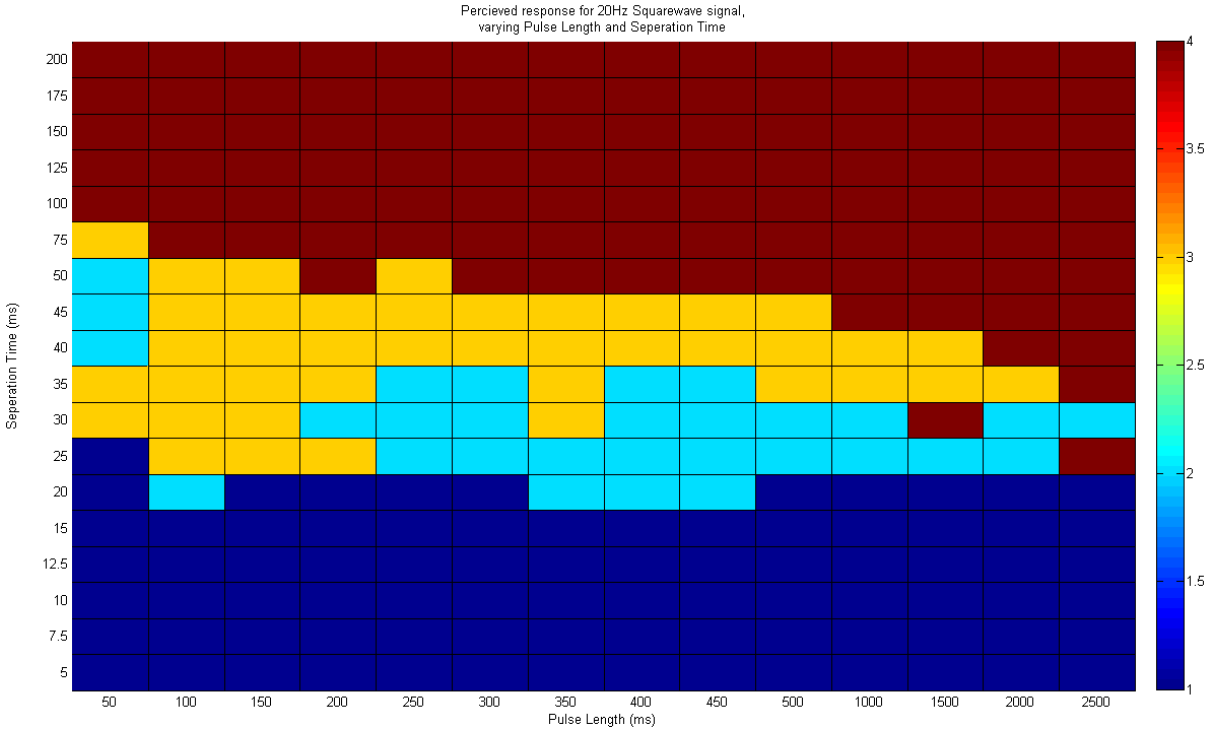

Figure G-3: 4 Pulse 20 Hz Temporal Gap Detection Results (Not to scale)

	Separation Time (ms)													
Pulse Length (ms)	50	100	150	200	250	300	350	400	450	500	1000	1500	2000	2500
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	1	2	1	1	1	1	2	2	2	1	1	1	1	1
25	1	3	3	3	2	2	2	2	2	2	2	2	2	4
30	3	3	3	2	2	2	3	2	2	2	2	4	2	2
35	3	3	3	3	2	2	3	2	2	3	3	3	3	4
40	2	3	3	3	3	3	3	3	3	3	3	3	4	4
45	2	3	3	3	3	3	3	3	3	3	4	4	4	4
50	2	3	3	4	3	4	4	4	4	4	4	4	4	4
75	3	4	4	4	4	4	4	4	4	4	4	4	4	4
100	4	4	4	4	4	4	4	4	4	4	4	4	4	4
125	4	4	4	4	4	4	4	4	4	4	4	4	4	4
150	4	4	4	4	4	4	4	4	4	4	4	4	4	4
175	4	4	4	4	4	4	4	4	4	4	4	4	4	4
200	4	4	4	4	4	4	4	4	4	4	4	4	4	4

Table G-3: Results of 4 Pulse 20 Hz Temporal Gap Detection Results

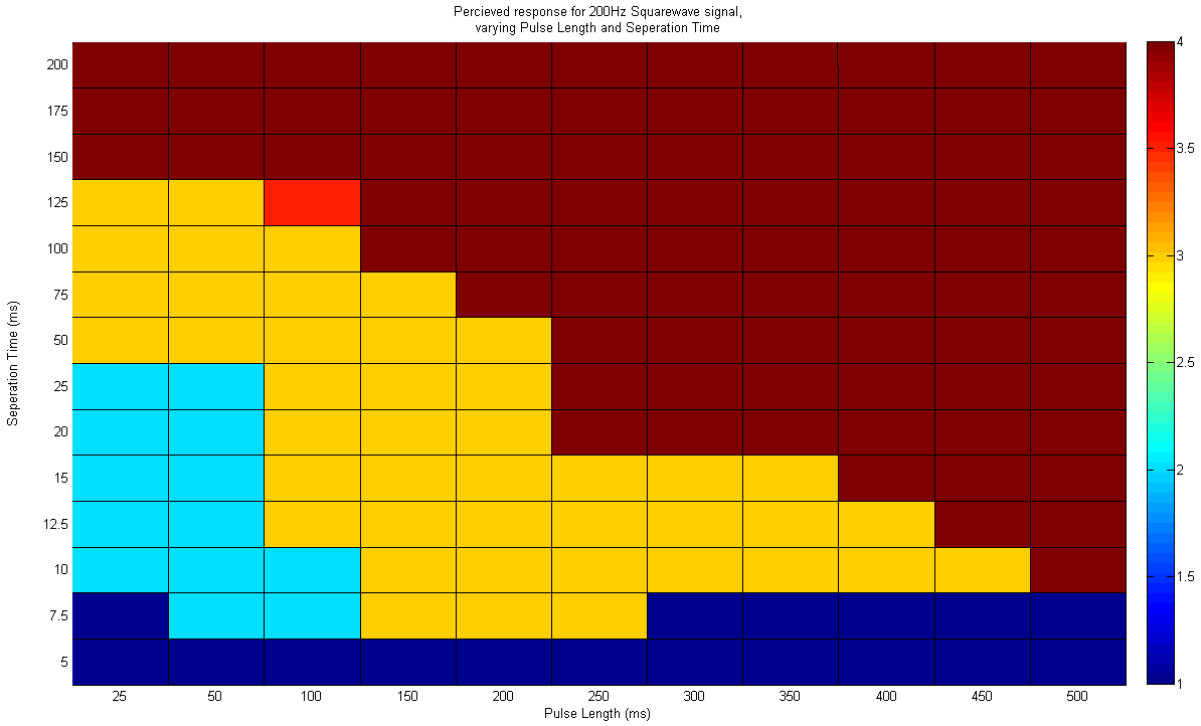

Figure G-4: 4 Pulse 200 Hz Temporal Gap Detection Results (Not to scale)

	Separation Time (ms)										
Pulse Length (ms)	25	50	100	150	200	250	300	350	400	450	500
5	1	1	1	1	1	1	1	1	1	1	1
7.5	1	2	2	3	3	3	1	1	1	1	1
10	2	2	2	3	3	3	3	3	3	3	4
12.5	2	2	3	3	3	3	3	3	3	4	4
15	2	2	3	3	3	3	3	3	4	4	4
20	2	2	3	3	3	4	4	4	4	4	4
25	2	2	3	3	3	4	4	4	4	4	4
50	3	3	3	3	3	4	4	4	4	4	4
75	3	3	3	3	4	4	4	4	4	4	4
100	3	3	3	4	4	4	4	4	4	4	4
125	3	3	3.5	4	4	4	4	4	4	4	4
150	4	4	4	4	4	4	4	4	4	4	4
175	4	4	4	4	4	4	4	4	4	4	4
200	4	4	4	4	4	4	4	4	4	4	4

Table G-4: Results of 4 Pulse 200 Hz Temporal Gap Detection Results

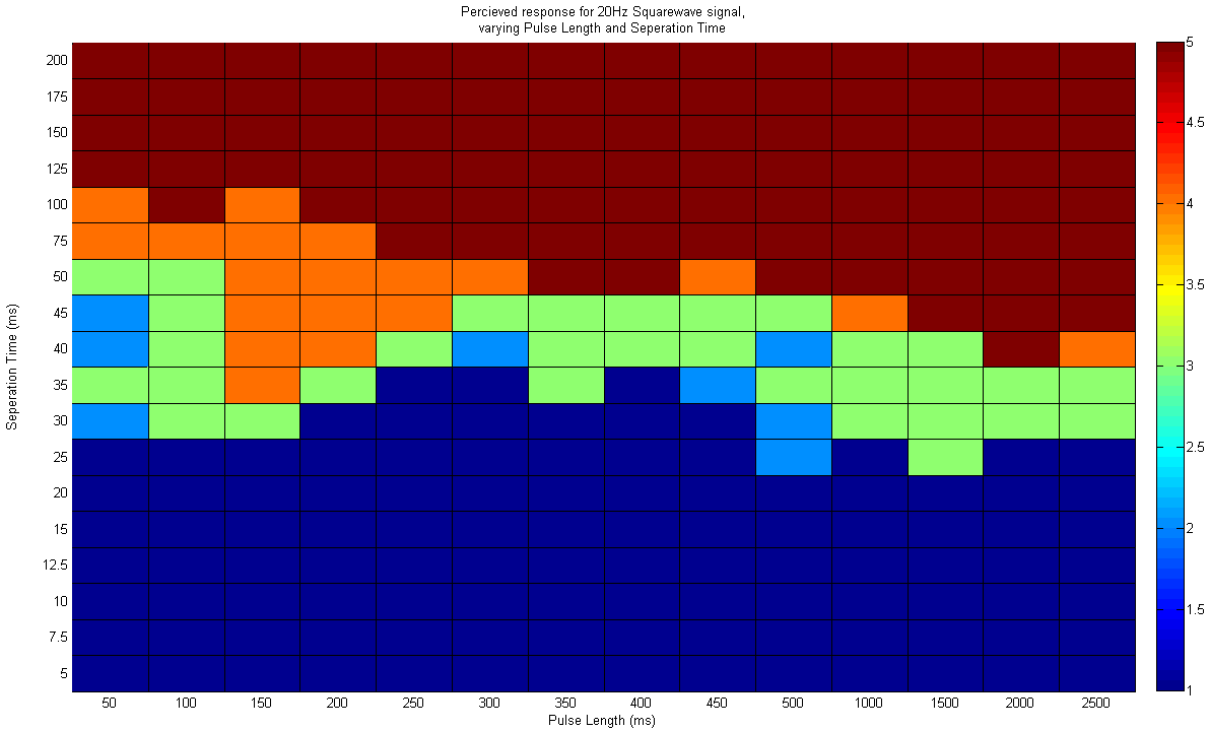

Figure G-5: 5 Pulse 20 Hz Temporal Gap Detection Results (Not to scale)

	Separation Time (ms)													
Pulse Length (ms)	50	100	150	200	250	300	350	400	450	500	1000	1500	2000	2500
5	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12.5	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	2	1	3	1	1
30	2	3	3	1	1	1	1	1	1	2	3	3	3	3
35	3	3	4	3	1	1	3	1	2	3	3	3	3	3
40	2	3	4	4	3	2	3	3	3	2	3	3	5	4
45	2	3	4	4	4	3	3	3	3	3	4	5	5	5
50	3	3	4	4	4	4	5	5	4	5	5	5	5	5
75	4	4	4	4	5	5	5	5	5	5	5	5	5	5
100	4	5	4	5	5	5	5	5	5	5	5	5	5	5
125	5	5	5	5	5	5	5	5	5	5	5	5	5	5
150	5	5	5	5	5	5	5	5	5	5	5	5	5	5
175	5	5	5	5	5	5	5	5	5	5	5	5	5	5
200	5	5	5	5	5	5	5	5	5	5	5	5	5	5

Table G-5: Results of 5 Pulse 20 Hz Temporal Gap Detection Results

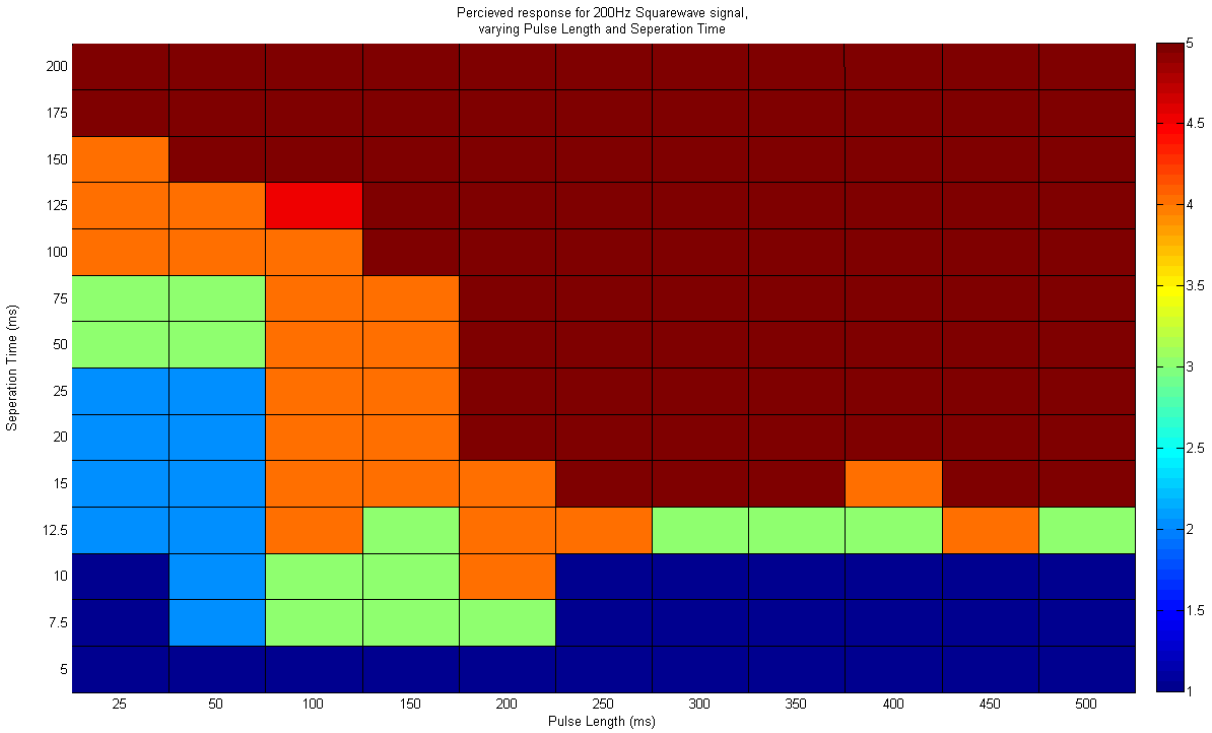

Figure G-6: 5 Pulse 200 Hz Temporal Gap Detection Results (Not to scale)

	Separation Time (ms)										
Pulse Length (ms)	25	50	100	150	200	250	300	350	400	450	500
5	1	1	1	1	1	1	1	1	1	1	1
7.5	1	2	3	3	3	1	1	1	1	1	1
10	1	2	3	3	4	1	1	1	1	1	1
12.5	2	2	4	3	4	4	3	3	3	4	3
15	2	2	4	4	4	5	5	5	4	5	5
20	2	2	4	4	5	5	5	5	5	5	5
25	2	2	4	4	5	5	5	5	5	5	5
50	3	3	4	4	5	5	5	5	5	5	5
75	3	3	4	4	5	5	5	5	5	5	5
100	4	4	4	5	5	5	5	5	5	5	5
125	4	4	4.5	5	5	5	5	5	5	5	5
150	4	5	5	5	5	5	5	5	5	5	5
175	5	5	5	5	5	5	5	5	5	5	5
200	5	5	5	5	5	5	5	5	5	5	5

Table G-6: Results of 5 Pulse 200 Hz Temporal Gap Detection Results

Appendix H – Initial Investigation – 2 Pulse Temporal Gap Detection

20 Hz Signals

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0
35	0	0	1	1	1	1	0	1	1	1	0.7
40	1	1	1	1	0	0	1	1	1	1	0.8
45	1	1	1	1	0	1	1	1	1	1	0.9
50	1	1	1	1	1	1	1	1	1	1	1
55	1	1	1	1	1	1	1	1	1	1	1
60	1	1	1	1	1	1	1	1	1	1	1

Table H-1: 2 Pulse Temporal Gap Detection, 20Hz Signal, 250ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	1	0	0	0.1
40	0	0	0	0	1	0	1	0	1	0	0.3
45	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1
55	1	1	1	1	1	1	1	1	1	1	1
60	1	1	1	1	1	1	1	1	1	1	1

Table H-2: 2 Pulse Temporal Gap Detection, 20Hz Signal, 300ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	1	0.1
30	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0
40	1	0	1	1	1	0	1	0	1	1	0.7
45	1	1	1	1	0	0	0	0	1	1	0.6
50	1	1	1	1	0	1	0	1	1	1	0.8
55	1	1	1	1	1	1	1	1	1	1	1
60	1	1	1	1	1	1	1	1	1	1	1

Table H-3: 2 Pulse Temporal Gap Detection, 20Hz Signal, 350ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	0	0	0	0	0
45	0	0	1	1	1	0	0	1	0	0	0.4
50	1	0	1	0	0	0	0	1	1	0	0.4
55	1	0	1	1	0	1	1	1	1	1	0.8
60	1	1	1	1	1	1	1	1	1	1	1

Table H-4: 2 Pulse Temporal Gap Detection, 20Hz Signal, 400ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0
40	0	1	0	1	0	0	0	0	0	0	0.2
45	0	1	0	0	0	0	0	0	1	0	0.2
50	0	1	1	1	1	0	1	0	1	0	0.6
55	1	1	1	1	0	1	1	1	1	0	0.8
60	1	1	1	1	1	1	1	1	1	1	1

Table H-5: 2 Pulse Temporal Gap Detection, 20Hz Signal, 450ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	1	0	1	0	0	0	0.2
35	1	0	0	1	1	0	1	0	0	0	0.4
40	0	0	1	1	1	1	0	1	0	1	0.6
45	1	1	1	0	1	1	1	0	1	1	0.8
50	1	1	1	1	1	1	1	1	1	1	1
55	1	1	1	1	1	1	1	1	1	1	1
60	1	1	1	1	1	1	1	1	1	1	1

Table H-6: 2 Pulse Temporal Gap Detection, 20Hz Signal, 500ms Pulse Length

200Hz Signals

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	1	0	0	0	0	0	0	0.1
15	0	1	0	1	0	1	1	0	1	0	0.5
20	1	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1
35	1	1	1	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	1	1	1	1	1
45	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1

Table H-7: 2 Pulse Temporal Gap Detection, 200Hz Signal, 25ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	1	0	0	0	0	0	0	0.1
20	1	1	1	1	1	1	1	0	1	0	0.8
25	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1
35	1	1	1	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	1	1	1	1	1
45	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1

Table H-8: 2 Pulse Temporal Gap Detection, 200Hz Signal, 50ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	1	0	0	0	0	0	0	0	0	0	0.1
12.5	1	1	0	0	1	0	0	0	0	0	0.3
15	1	1	0	0	1	0	0	0	0	0	0.3
20	1	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1
35	1	1	1	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	1	1	1	1	1
45	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1

Table H-9: 2 Pulse Temporal Gap Detection, 200Hz Signal, 100ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	1	0	0	0	0	0	0.1
10	0	0	1	1	1	1	1	0	0	0	0.5
12.5	0	0	1	0	1	0	1	0	1	1	0.5
15	0	1	1	1	1	1	1	1	1	0	0.8
20	1	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1
35	1	1	1	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	1	1	1	1	1
45	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1

Table H-10: 2 Pulse Temporal Gap Detection, 200Hz Signal, 150ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	1	0	1	0	0	0.2
12.5	1	0	0	1	0	1	0	1	0	1	0.5
15	1	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1
35	1	1	1	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	1	1	1	1	1
45	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1

Table H-11: 2 Pulse Temporal Gap Detection, 200Hz Signal, 200ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG

0	0	0	0	0	0	0	0	0	0	0
5	0	0	1	0	0	0	0	0	0	0	0.1
7.5	0	1	0	0	0	0	1	1	0	0	0.3
10	1	1	1	1	1	0	1	1	1	1	0.9
12.5	1	1	1	1	1	1	1	1	1	1	1
15	1	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1
35	1	1	1	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	1	1	1	1	1
45	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1

Table H-12: 2 Pulse Temporal Gap Detection, 200Hz Signal, 2500ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	1	0	0	0	0	0	0	0.1
10	0	0	0	1	0	0	0	0	0	0	0.1
12.5	1	0	0	1	1	1	0	0	0	1	0.5
15	1	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1
35	1	1	1	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	1	1	1	1	1
45	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1

Table H-13: 2 Pulse Temporal Gap Detection, 200Hz Signal, 300ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	0	0	1	0	0	0	0	0	1	0	0.2
12.5	0	1	0	0	0	1	0	0	1	0	0.3
15	1	1	1	1	1	1	1	0	1	1	0.9
20	1	1	1	1	1	1	1	1	1	1	1
25	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1
35	1	1	1	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	1	1	1	1	1
45	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1

Table H-14: 2 Pulse Temporal Gap Detection, 200Hz Signal, 350ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	0	0	1	0	0	0	0	0	0	0	0.1
12.5	1	0	1	0	0	1	0	0	1	0	0.4

15	1	1	1	1	1	1	0	0	1	1	0.8
20	1	1	1	1	1	1	0	1	1	1	0.9
25	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	1	1	1	1	1
35	1	1	1	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	1	1	1	1	1
45	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1

Table H-15: 2 Pulse Temporal Gap Detection, 200Hz Signal, 400ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0
15	1	0	0	0	1	0	0	0	0	1	0.3
20	1	1	0	1	0	0	0	0	0	0	0.3
25	1	1	1	1	1	1	0	1	1	1	0.9
30	1	1	1	1	1	1	1	1	0	1	0.9
35	1	1	1	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	1	1	1	1	1
45	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1

Table H-16: 2 Pulse Temporal Gap Detection, 200Hz Signal, 450ms Pulse Length

Separation time/Trial #	1	2	3	4	5	6	7	8	9	10	AVG
0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0
15	1	1	0	0	0	1	0	0	0	0	0.3
20	1	1	1	0	1	1	0	1	0	0	0.6
25	1	1	1	1	1	1	1	1	1	1	1
30	1	1	1	1	1	1	0	1	1	1	0.9
35	1	1	1	1	1	1	1	1	1	1	1
40	1	1	1	1	1	1	1	1	1	1	1
45	1	1	1	1	1	1	1	1	1	1	1
50	1	1	1	1	1	1	1	1	1	1	1

Table H-17: 2 Pulse Temporal Gap Detection, 200Hz Signal, 500ms Pulse Length

Appendix I –QUEST Match Amp Function

```
function Amp2 = matchamp(Freq1,Freq2,Waveform)
%match amplitude of freq2 to freq1 in frequency domain
Y1 = findmaxFFT(Freq1,Waveform,1);
min = 0.75;
max = 1.25;
Y2 = findmaxFFT(Freq2,Waveform,1);
while (Y1 ~= Y2)
    mmd = max - min;
    R = min+mmd*rand(1,1);
    Y2 = findmaxFFT(Freq2,Waveform,R);
    if (Y2>Y1)
        max = R;
    elseif (Y1>Y2)
        min = R;
    end
end
Amp2 = R;
```

Appendix J –QUEST Methodology

Frequency Discrimination	Temporal Discrimination	Amplitude Discrimination	Amplitude Detection
Baseline Frequency	Signal Frequency	Signal Frequency	Signal Frequency
Target Frequency	Baseline Duration	Baseline Amplitude	Target Amplitude
Trial Number	Target Duration	Target Amplitude	Trial Number
Interval 1 Frequency	Trial Number	Trial Number	QUEST Mean
Interval 2 Frequency	Interval 1 Duration	Interval 1 Amplitude	QUEST STD
Current Target	Interval 2 Duration	Interval 2 Amplitude	Correct/Incorrect
QUEST Mean	Current Target	Current Target	Waveform
QUEST STD	QUEST Mean	QUEST Mean	Final Estimate Mean
Participants Answer	QUEST STD	QUEST STD	Final Estimate STD
Correct/Incorrect	Participants Answer	Participants Answer	
Waveform	Correct/Incorrect	Correct/Incorrect	
Final Estimate Mean	Waveform	Waveform	
Final Estimate STD	Final Estimate Mean	Final Estimate Mean	
	Final Estimate STD	Final Estimate STD	

Table J-1: Data Matrix saved per 2IFC QUEST experiments

Temporal Gap Detection		
Pulse Frequency	Trial Count Per Pulse Number	Pulse Length
Current Target	QUEST Mean	Total Trial Number
Pulse Number	Actual Pulse Number	QUEST STD
Correct/Incorrect	Waveform	Participants Answer

Table J-2: Data matrix for the 5AFC QUEST experiment i.e. Temporal Gap Detection

Experiment Type	Variable 1	Variable 2	Variable 3	Variable 4	Variable 5
Frequency Discrimination	Frequency 1	Frequency 2	Amplitude 1	Amplitude 2	Waveform
Temporal Discrimination	Duration 1	Duration 2	Waveform	Frequency	Amplitude
Amplitude Discrimination	Amplitude 1	Amplitude 2	Waveform	Frequency	
Amplitude Detection	Amplitude 1	Amplitude 2	Waveform	Frequency	

Table J-3: Variables for each experiment creation and play functions

Appendix K – RT Data & Mixed Model Output

K.1 All Participant Data

	All Participant RT Data (ms)						
					Ex-Gauss Parameters		
UID	Type	Means	STD	Median	μ	σ	τ
I1LI	Audio	1.43E+02	1.86E+01	1.44E+02	1.42E+02	1.81E+01	5.15E-01
	MIVS	2.59E+02	2.57E+01	2.60E+02	2.59E+02	2.51E+01	6.96E-01
	Visual F.	1.91E+02	2.00E+01	1.92E+02	1.74E+02	1.04E+01	1.73E+01
	Visual P.	2.66E+02	5.22E+01	2.48E+02	2.09E+02	8.18E+00	5.71E+01
I2LP	Audio	1.96E+02	4.96E+01	1.76E+02	1.50E+02	3.87E-11	4.57E+01
	MIVS	3.25E+02	8.30E+01	3.13E+02	2.58E+02	5.29E+01	6.62E+01
	Visual F.	2.81E+02	4.88E+01	2.82E+02	2.78E+02	4.75E+01	2.34E+00
	Visual P.	3.16E+02	6.94E+01	2.98E+02	2.60E+02	2.00E+01	5.63E+01
I3LI	Audio	1.63E+02	1.29E+01	1.66E+02	1.62E+02	1.26E+01	3.58E-01
	MIVS	2.12E+02	2.56E+01	2.12E+02	2.05E+02	2.41E+01	6.43E+00
	Visual F.	2.43E+02	2.76E+01	2.47E+02	2.36E+02	2.61E+01	6.68E+00
	Visual P.	3.34E+02	7.90E+01	3.17E+02	2.72E+02	2.59E-07	6.20E+01
I4RM1	Audio	2.40E+02	4.45E+01	2.37E+02	2.07E+02	3.06E+01	3.23E+01
	MIVS	2.60E+02	3.81E+01	2.57E+02	2.58E+02	3.71E+01	2.61E+00
	Visual F.	2.43E+02	2.97E+01	2.37E+02	2.21E+02	2.00E+01	2.19E+01
	Visual P.	2.92E+02	6.82E+01	2.72E+02	2.33E+02	1.61E+01	5.88E+01
I4RM2	Audio	1.93E+02	2.31E+01	1.97E+02	1.85E+02	2.10E+01	8.24E+00
	MIVS	2.48E+02	1.91E+01	2.42E+02	2.29E+02	7.96E+00	1.90E+01
	Visual F.	2.62E+02	3.81E+01	2.51E+02	2.20E+02	5.41E+00	4.21E+01
	Visual P.	3.84E+02	7.29E+01	3.91E+02	2.95E+02	1.53E-05	9.42E+01
I4RM3	Audio	1.89E+02	2.31E+01	1.87E+02	1.89E+02	2.25E+01	6.32E-01
	MIVS	2.38E+02	2.78E+01	2.41E+02	2.25E+02	2.36E+01	1.36E+01
	Visual F.	2.52E+02	3.98E+01	2.43E+02	2.07E+02	9.00E+00	4.53E+01
	Visual P.	4.33E+02	1.43E+02	3.96E+02	2.62E+02	2.22E-06	1.70E+02
I5RM1	Audio	2.16E+02	2.62E+01	2.23E+02	2.15E+02	2.56E+01	7.05E-01
	MIVS	2.46E+02	3.35E+01	2.43E+02	2.45E+02	3.27E+01	9.00E-01
	Visual F.	2.49E+02	3.71E+01	2.42E+02	2.14E+02	1.36E+01	3.57E+01
	Visual P.	3.45E+02	5.26E+01	3.48E+02	3.39E+02	5.08E+01	6.61E+00
I5RM2	Audio	1.79E+02	2.28E+01	1.82E+02	1.77E+02	2.21E+01	2.59E+00
	MIVS	2.04E+02	2.38E+01	1.99E+02	1.95E+02	2.17E+01	8.27E+00
	Visual F.	2.51E+02	5.30E+01	2.40E+02	2.03E+02	2.37E-10	4.85E+01
	Visual P.	3.37E+02	7.81E+01	3.04E+02	2.58E+02	3.60E-07	8.73E+01
I5RM3	Audio	1.64E+02	1.70E+01	1.64E+02	1.63E+02	1.65E+01	4.58E-01

	MIVS	2.12E+02	2.66E+01	2.00E+02	1.89E+02	4.98E-11	2.72E+01
	Visual F.	2.13E+02	1.80E+01	2.14E+02	2.01E+02	1.28E+01	1.20E+01
	Visual P.	3.04E+02	4.65E+01	2.95E+02	2.52E+02	8.87E-06	5.20E+01
I6LR	Audio	1.93E+02	4.94E+01	1.84E+02	1.35E+02	5.48E-09	5.85E+01
	MIVS	2.03E+02	1.88E+01	2.00E+02	1.85E+02	8.39E+00	1.79E+01
	Visual F.	2.13E+02	2.59E+01	2.06E+02	1.83E+02	4.80E+00	2.99E+01
	Visual P.	3.19E+02	7.12E+01	3.10E+02	2.48E+02	5.68E-06	8.76E+01
I7LR	Audio	1.89E+02	2.70E+01	1.85E+02	1.53E+02	1.57E-07	3.62E+01
	MIVS	2.25E+02	2.14E+01	2.20E+02	2.04E+02	8.23E+00	2.10E+01
	Visual F.	2.06E+02	2.46E+01	1.98E+02	1.78E+02	4.72E+00	2.86E+01
	Visual P.	3.00E+02	1.07E+02	2.72E+02	2.04E+02	1.18E+01	9.60E+01
O1RI	Audio	1.58E+02	1.92E+01	1.57E+02	1.39E+02	8.32E+00	1.83E+01
	MIVS	2.41E+02	3.02E+01	2.39E+02	2.31E+02	2.78E+01	9.61E+00
S1LI	Audio	2.15E+02	4.84E+01	1.99E+02	1.59E+02	7.91E-06	5.11E+01
	MIVS	2.24E+02	2.40E+01	2.23E+02	2.04E+02	1.29E+01	1.93E+01
	Visual F.	2.56E+02	3.81E+01	2.47E+02	2.33E+02	2.98E+01	2.30E+01
	Visual P.	4.72E+02	7.95E+01	4.81E+02	4.67E+02	7.73E+01	4.79E+00
S2LP	Audio	1.65E+02	2.30E+01	1.58E+02	1.45E+02	1.00E+01	1.95E+01
	MIVS	2.17E+02	2.44E+01	2.15E+02	1.96E+02	1.35E+01	2.03E+01
	Visual F.	1.93E+02	2.02E+01	1.88E+02	1.74E+02	1.04E+01	1.87E+01
	Visual P.	3.31E+02	9.36E+01	3.20E+02	2.48E+02	4.07E+01	8.33E+01
S3LI	Audio	1.85E+02	3.78E+01	1.77E+02	1.44E+02	4.87E+00	4.13E+01
	MIVS	2.38E+02	3.94E+01	2.30E+02	2.23E+02	3.54E+01	1.51E+01
	Visual F.	2.09E+02	2.12E+01	2.07E+02	1.92E+02	1.31E+01	1.72E+01
	Visual P.	3.32E+02	6.10E+01	3.28E+02	3.21E+02	5.85E+01	1.06E+01
S4RM	Audio	1.85E+02	3.98E+01	1.75E+02	1.50E+02	2.35E+01	3.52E+01
	MIVS	2.52E+02	2.99E+01	2.50E+02	2.46E+02	2.86E+01	5.88E+00
	Visual F.	2.18E+02	3.41E+01	2.18E+02	2.17E+02	3.34E+01	9.20E-01
	Visual P.	3.01E+02	4.02E+01	2.95E+02	2.74E+02	2.93E+01	2.73E+01
S5RM	Audio	1.50E+02	2.03E+01	1.47E+02	1.43E+02	1.83E+01	7.40E+00
	MIVS	2.61E+02	3.51E+01	2.59E+02	2.43E+02	2.92E+01	1.81E+01
	Visual F.	2.27E+02	4.29E+01	2.16E+02	1.84E+02	1.54E-06	4.68E+01
	Visual P.	2.86E+02	4.59E+01	2.78E+02	2.40E+02	1.69E+01	4.61E+01
S6LR	Audio	2.22E+02	4.75E+01	2.00E+02	1.74E+02	1.05E+01	4.81E+01
	MIVS	2.67E+02	3.48E+01	2.60E+02	2.47E+02	2.80E+01	1.92E+01
	Visual F.	2.79E+02	6.10E+01	2.65E+02	2.28E+02	2.84E+01	5.11E+01
	Visual P.	3.56E+02	5.77E+01	3.58E+02	3.10E+02	3.55E+01	4.61E+01
S7LR	Audio	2.04E+02	3.36E+01	1.98E+02	1.64E+02	8.97E-07	4.60E+01
	MIVS	2.52E+02	4.43E+01	2.56E+02	2.48E+02	4.30E+01	3.95E+00
	Visual F.	2.60E+02	5.22E+01	2.55E+02	2.57E+02	5.08E+01	3.28E+00
	Visual P.	4.03E+02	9.48E+01	3.79E+02	3.18E+02	4.01E+01	8.52E+01

Table K-1: Statistics from each of the participants RT data (ms), displaying the mean, standard deviation and median, along with the parameters for the fitted Ex-Gaussian distribution function for each data set, i.e. the mean, standard deviation and skewness value. Visual F. – Visual Focal Area, Visual P. – Peripheral Visual Area.

K.2 Histograms

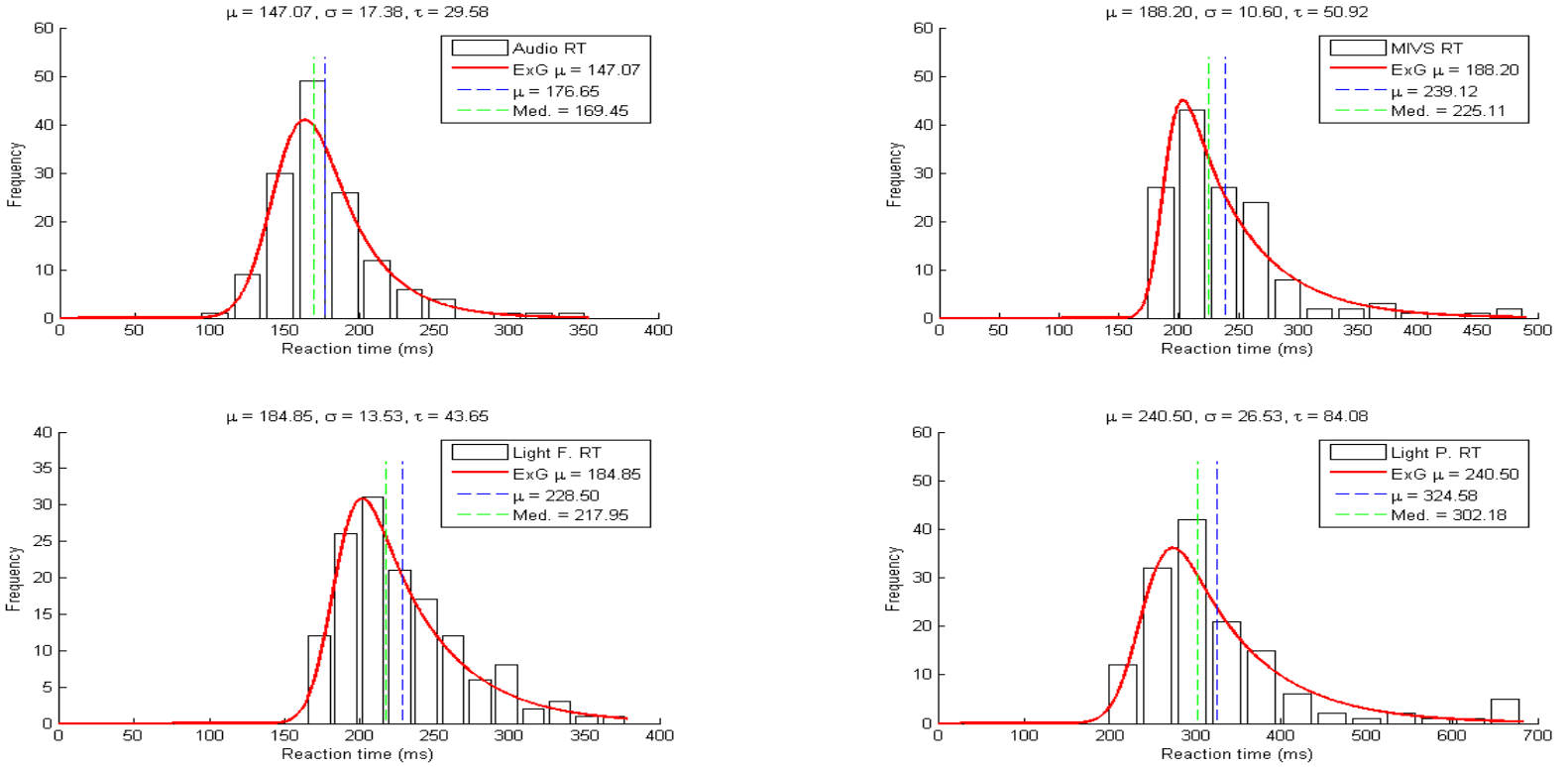

Figure K-1: Histograms of the implanted participants RT data within the main study. The fitted ex-Gaussian distribution, mean (μ) and median (Med.) of the data are presented for comparison of the measures of central tendency. The parameters used for the ex-Gaussian distribution function (defined in equation 7.1) are given as titles to each graph. The y-axis labelled frequency is frequency of occurrence. (Top Left) – Audio RT Data, (Top Right) – MIVS RT Data, (Bottom Left) – Visual Focal area RT Data (Bottom Right) – Peripheral Vision RT Data.

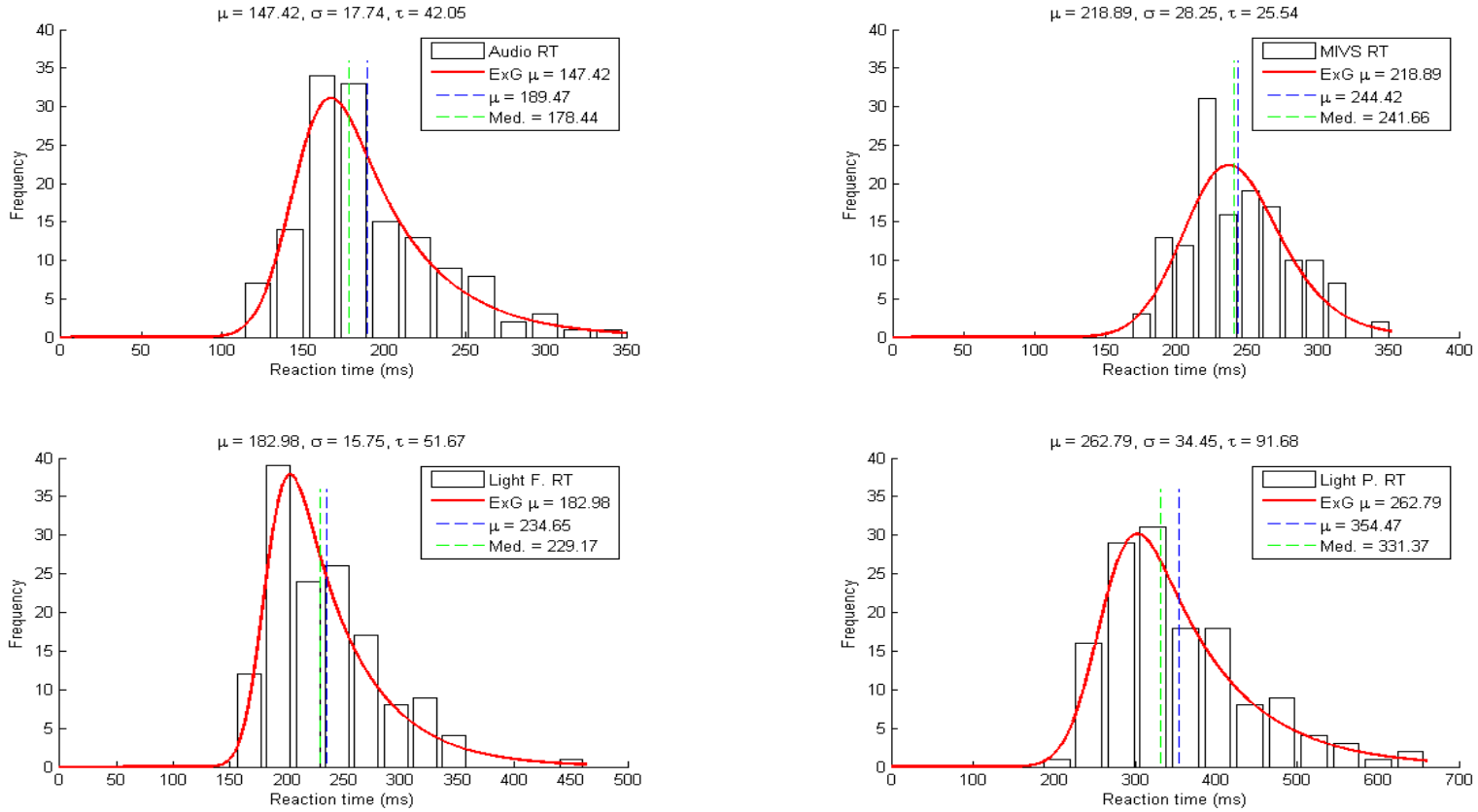

Figure K-2: Histograms of the superficial participants RT data within the main study. The fitted ex-Gaussian distribution, mean (μ) and median (Med.) of the data are presented for comparison of the measures of central tendency. The parameters used for the ex-Gaussian distribution function (defined in equation 7.1) are given as titles to each graph. The y-axis labelled frequency is frequency of occurrence. (Top Left) – Audio RT Data, (Top Right) – MIVS RT Data, (Bottom Left) – Visual Focal area RT Data (Bottom Right) – Peripheral Vision RT Data

K.3 SPSS Mixed Model Output Modelling All Main Study RT Data

Variable name definitions:

- ITypeN – Implant Type, 1 = Implanted, 2 = Superficial
- SensMod – Sensory Modality, 1 = Audio, 2 = MIVS, 3 = Visual Focal, 4 = Peripheral Vision
- IDN – Unique ID
- exGaussMean – Ex-Gaussian Mean

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables
Fixed Effects	Intercept	1		1	
	ITypeN	2		1	
	SensMod	4		3	
	ITypeN * SensMod	8		3	
Random Effects	Intercept	1	Variance Components	1	IDN
Residual				1	
Total		16		10	

a. Dependent Variable: exGaussMean.

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		1086.074392	255.990189	4.243	.000	684.273066	1723.811214
Intercept [subject = IDN]	Variance	251.479097	222.897848	1.128	.259	44.263077	1428.769541

a. Dependent Variable: exGaussMean.

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	12	1256.805	.000
ITypeN	1	12	2.744	.124
SensMod	3	36	32.525	.000
ITypeN * SensMod	3	36	3.270	.032

a. Dependent Variable: exGaussMean.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	311.131704	13.823135	43.398	22.508	.000	283.262082	339.001327
[ITypeN=1]	-67.208971	19.548865	43.398	-3.438	.001	-106.622569	-27.795373

[ITypeN=2]	0[b]	0	.	.	.	.	.
[SensMod=1]	-157.000699	17.615532	36	-8.913	.000	-192.726653	-121.274744
[SensMod=2]	-81.264085	17.615532	36	-4.613	.000	-116.990040	-45.538130
[SensMod=3]	-99.042015	17.615532	36	-5.622	.000	-134.767970	-63.316060
[SensMod=4]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [SensMod=1]	69.445272	24.912124	36	2.788	.008	18.921142	119.969402
[ITypeN=1] * [SensMod=2]	55.071727	24.912124	36	2.211	.034	4.547597	105.595857
[ITypeN=1] * [SensMod=3]	63.323046	24.912124	36	2.542	.015	12.798916	113.847176
[ITypeN=1] * [SensMod=4]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [SensMod=1]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [SensMod=2]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [SensMod=3]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [SensMod=4]	0[b]	0	.	.	.	.	.

a. Dependent Variable: exGaussMean.

b. This parameter is set to zero because it is redundant.

Estimates[a]

I-Type	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Implanted	206.556	8.644	12	187.723	225.389
Superficial	226.805	8.644	12	207.972	245.638

a. Dependent Variable: exGaussMean.

Estimates[a]

Sen-Mod	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Audio	155.249	9.774	43.398	135.542	174.956
MIVS	223.799	9.774	43.398	204.092	243.506
LightF	210.147	9.774	43.398	190.440	229.854
LightPer	277.527	9.774	43.398	257.820	297.234

a. Dependent Variable: exGaussMean.

Pairwise Comparisons[a]

(I) Sen-Mod	(J) Sen-Mod	Mean Difference (I-J)	Std. Error	df	Sig.[c]	95% Confidence Interval for Difference[c]	
						Lower Bound	Upper Bound
Audio	MIVS	-68.550*	12.456	36	.000	-103.222	-33.878
	LightF	-54.898*	12.456	36	.001	-89.570	-20.225
	LightPer	-122.278*	12.456	36	.000	-156.950	-87.606
MIVS	Audio	68.550*	12.456	36	.000	33.878	103.222
	LightF	13.652	12.456	36	.861	-21.020	48.325
	LightPer	-53.728*	12.456	36	.001	-88.400	-19.056
LightF	Audio	54.898*	12.456	36	.001	20.225	89.570
	MIVS	-13.652	12.456	36	.861	-48.325	21.020
	LightPer	-67.380*	12.456	36	.000	-102.053	-32.708
LightPer	Audio	122.278*	12.456	36	.000	87.606	156.950
	MIVS	53.728*	12.456	36	.001	19.056	88.400
	LightF	67.380*	12.456	36	.000	32.708	102.053

Based on estimated marginal means

3. ITypeN * SensMod[a]

ITypeN	SensMod	Mean	Std. Error	df	95% Confidence Interval	
					Lower Bound	Upper Bound
Implanted	Audio	156.367	13.823	43.398	128.498	184.237
	MIVS	217.730	13.823	43.398	189.861	245.600
	Light	208.204	13.823	43.398	180.334	236.073
	LightPer	243.923	13.823	43.398	216.053	271.792
Superficial	Audio	154.131	13.823	43.398	126.261	182.001
	MIVS	229.868	13.823	43.398	201.998	257.737
	Light	212.090	13.823	43.398	184.220	239.959
	LightPer	311.132	13.823	43.398	283.262	339.001

a. Dependent Variable: exGaussMean.

*. The mean difference is significant at the .05 level.

a. Dependent Variable: exGaussMean.

c. Adjustment for multiple comparisons: Šidák.

Appendix L – Amplitude Detection Data & Statistical Models

L.1 Box plots from Outlier removal

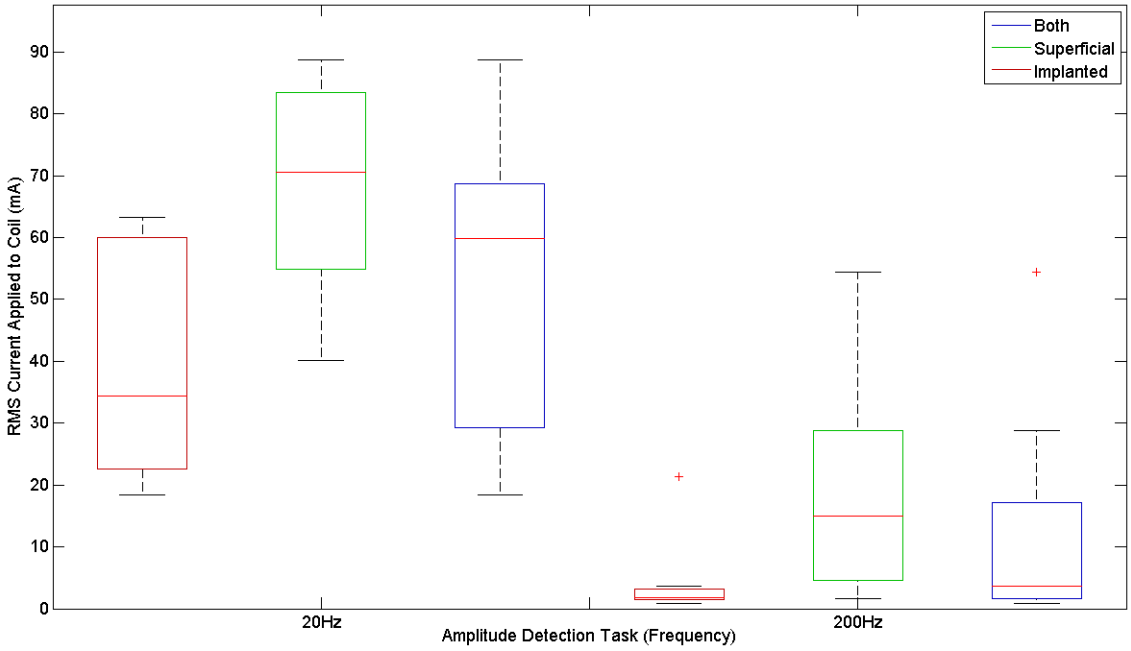

Figure L-1: Current supplied to coil at the amplitude detection threshold for all participants within the main study (categorised by group) post outlier removal

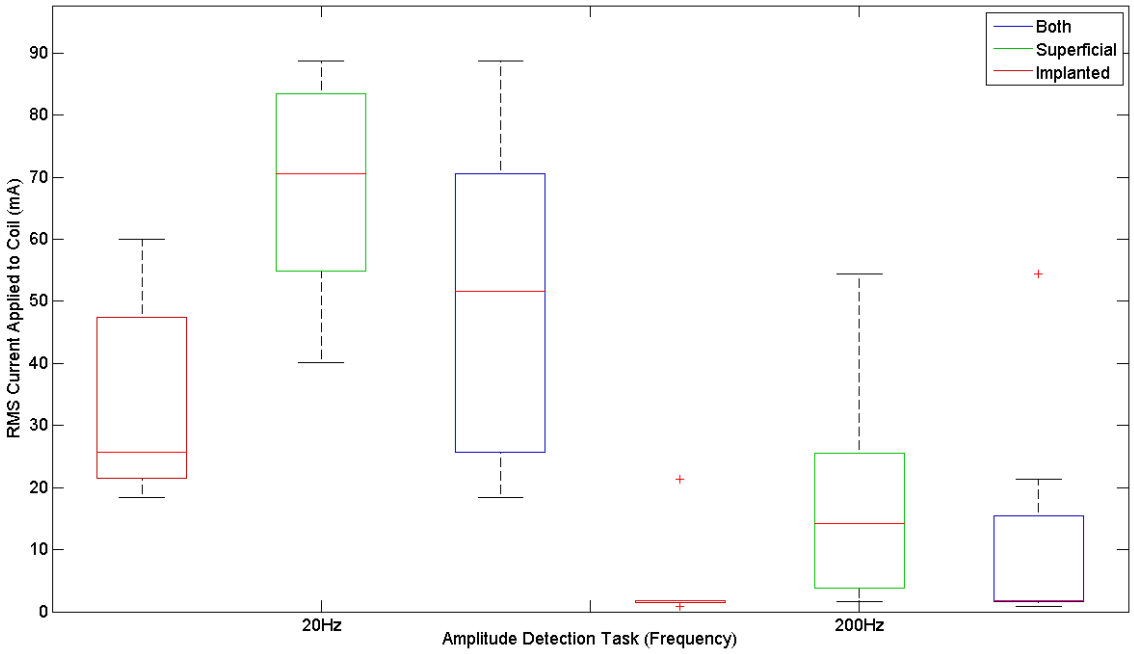

Figure L-2: Current supplied to coil at the amplitude detection threshold for all participants within the main study (categorised by group) post outlier removal + I2LP & S2LP

L.2 First Model – SPSS Mixed Model Output, Modelling Main Study Amplitude Detection Experimental Data with Outliers Removed

Variable name definitions:

- ITypeN – Implant Type, 1 = Implanted, 2 = Superficial
- Freq – Stimulus Frequency
- IDN – Unique ID

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables
Fixed Effects	Intercept	1		1	
	ITypeN	2		1	
	Freq	2		1	
	ITypeN * Freq	4		1	
Random Effects	Intercept	1	Variance Components	1	IDN
	Residual			1	
	Total	10		6	

a. Dependent Variable: Obs.

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	11.379	76.586	.000
ITypeN	1	11.379	8.938	.012
Freq	1	10.860	46.019	.000
ITypeN * Freq	1	10.860	1.434	.257

a. Dependent Variable: Obs.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	19.902167	6.824156	19.245	2.916	.009	5.631317	34.173016
[ITypeN=1]	-15.228738	9.299757	19.245	-1.638	.118	-34.676627	4.219151
[ITypeN=2]	0[b]	0	.	.	.	.	.
[Freq=20]	48.701859	8.993097	10.921	5.415	.000	28.890796	68.512922
[Freq=200]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [Freq=20]	-14.615186	12.203919	10.860	-1.198	.257	-41.518180	12.287807
[ITypeN=1] * [Freq=200]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=20]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=200]	0[b]	0	.	.	.	.	.

a. Dependent Variable: Obs.
b. This parameter is set to zero because it is redundant.

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		216.119739	96.355483	2.243	.025	90.197011	517.841345
Intercept [subject = IDN]	Variance	63.294871	87.743814	.721	.471	4.181893	957.996943

a. Dependent Variable: Obs.

Estimates[a]

I-Type	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Implanted	21.717	5.105	11.298	10.518	32.916
Superficial	44.253	5.547	11.449	32.103	56.404

a. Dependent Variable: Obs.

Estimates[a]

Freq	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound

20	53.682	5.041	19.655	43.156	64.209
200	12.288	4.650	19.245	2.564	22.012

a. Dependent Variable: Obs.

4. I-Type * Freq[a]

I-Type	Freq	Mean	Std. Error	df	95% Confidence Interval	
					Lower Bound	Upper Bound
Implanted	20	38.760	6.799	19.626	24.560	52.960
	200	4.673	6.318	19.245	-8.539	17.886
Superficial	20	68.604	7.443	19.678	53.061	84.147
	200	19.902	6.824	19.245	5.631	34.173

a. Dependent Variable: Obs.

L.3 Second Model - SPSS Mixed Model Output, Modelling Main Study Amplitude Detection Experiment Data with Outliers, I2LP and S2LP Removed

Variable name definitions:

- ITypeN – Implant Type, 1 = Implanted, 2 = Superficial
- Freq – Stimulus Frequency
- IDN – Unique ID

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables
Fixed Effects	Intercept	1		1	
	ITypeN	2		1	
	Freq	2		1	
	ITypeN * Freq	4		1	
Random Effects	Intercept	1	Variance Components	1	IDN
	Residual			1	
	Total	10		6	

a. Dependent Variable: Obs.

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	9.205	57.168	.000
ITypeN	1	9.205	8.321	.018
Freq	1	8.901	40.056	.000
ITypeN * Freq	1	8.901	2.860	.125

a. Dependent Variable: Obs.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	18.118600	7.494628	15.913	2.418	.028	2.223649	34.013551
[ITypeN=1]	-13.277100	10.147775	15.913	-1.308	.209	-34.798965	8.244765
[ITypeN=2]	0[b]	0	.	.	.	.	.
[Freq=20]	50.081400	8.965548	8.565	5.586	.000	29.641729	70.521071
[Freq=200]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [Freq=20]	-21.121158	12.488764	8.901	-1.691	.125	-49.420653	7.178337
[ITypeN=1] * [Freq=200]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=20]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=200]	0[b]	0	.	.	.	.	.

a. Dependent Variable: Obs.

b. This parameter is set to zero because it is redundant.

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		200.952626	97.106991	2.069	.039	77.940788	518.110718
Intercept [subject = IDN]	Variance	79.894647	97.507385	.819	.413	7.305823	873.707798

a. Dependent Variable: Obs.

Estimates[a]

I-Type	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Implanted	19.322	5.676	9.619	6.607	32.036
Superficial	43.159	6.006	8.849	29.537	56.782

a. Dependent Variable: Obs.

Estimates[a]

Freq	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
20	51.001	5.282	16.225	39.817	62.185
200	11.480	5.074	15.913	.719	22.241

a. Dependent Variable: Obs.

4. I-Type * Freq[a]

I-Type	Freq	Mean	Std. Error	df	95% Confidence Interval	
					Lower Bound	Upper Bound
Implanted	20	33.802	7.444	16.494	18.060	49.544
	200	4.842	6.842	15.913	-9.669	19.352

Superficial	20	68.200	7.495	15.913	52.305	84.095
	200	18.119	7.495	15.913	2.224	34.014

a. Dependent Variable: Obs.

Appendix M – Amplitude Discrimination Data & Mixed Model

M.1 QUEST Result from Outlier

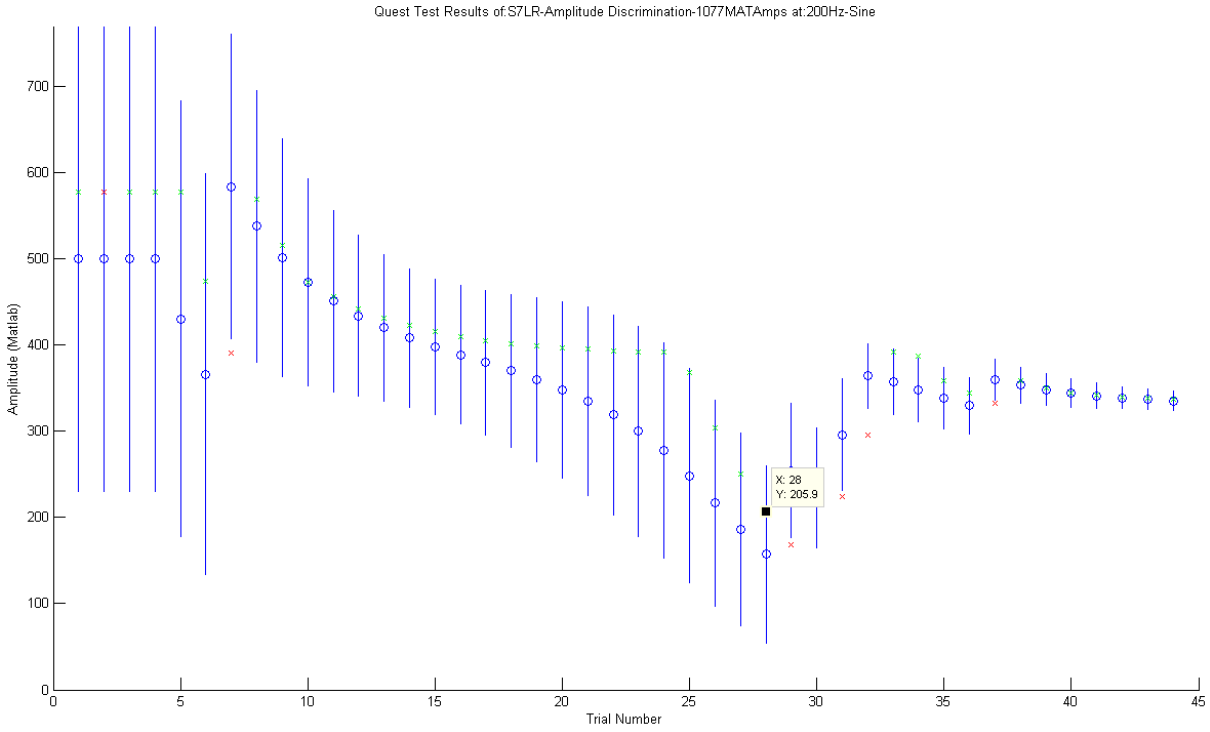

Figure M-1: S7LR 200Hz Amplitude discrimination experiment QUEST output

M.2 Mixed Model Output SPSS Mixed Model Output, Modelling Main Study Amplitude Discrimination Experiment Data with Outlier Removed

Variable name definitions:

- ITypeN & I-Type – Implant Type, 1 = Implanted, 2 = Superficial
- Freq – Stimulus Frequency
- IDN – Unique ID

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables
Fixed Effects	Intercept	1	Variance Components	1	IDN
	Freq	2		1	
	ITypeN	2		1	
	Freq * ITypeN	4		1	
Random Effects	Intercept	1		1	
Residual				1	
Total		10		6	

a. Dependent Variable: Obs.

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	10.777	74.820	.000
Freq	1	10.090	5.102	.047
ITypeN	1	10.777	.032	.862
Freq * ITypeN	1	10.090	.351	.567

a. Dependent Variable: Obs.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	.180655	.031468	17.111	5.741	.000	.114295	.247014
[Freq=20]	-.030043	.026313	10.307	-1.142	.279	-.088436	.028349
[Freq=200]	0[b]	0	.	.	.	.	.
[ITypeN=1]	.017634	.043545	16.207	.405	.691	-.074581	.109849
[ITypeN=2]	0[b]	0	.	.	.	.	.
[Freq=20] * [ITypeN=1]	-.021365	.036061	10.090	-.592	.567	-.101617	.058888
[Freq=20] * [ITypeN=2]	0[b]	0	.	.	.	.	.
[Freq=200] * [ITypeN=1]	0[b]	0	.	.	.	.	.
[Freq=200] * [ITypeN=2]	0[b]	0	.	.	.	.	.

a. Dependent Variable: Obs.
b. This parameter is set to zero because it is redundant.

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		.002128	.000959	2.219	.026	.000880	.005147
Intercept [subject = IDN]	Variance	.004213	.002406	1.751	.080	.001376	.012901

a. Dependent Variable: Obs.

Estimates[a]

Freq	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
20	.149	.021	15.237	.103	.194
200	.189	.022	16.207	.143	.236

a. Dependent Variable: Obs.

Estimates[a]

I-Type	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Implanted	.173	.027	10.504	.112	.233
Superficial	.166	.028	11.051	.104	.227

a. Dependent Variable: Obs.

4. Freq * I-Type[a]

Freq	I-Type	Mean	Std. Error	df	95% Confidence Interval	
					Lower Bound	Upper Bound
20	Implanted	.147	.030	15.237	.083	.211
	Superficial	.151	.030	15.237	.087	.215
200	Implanted	.198	.030	15.237	.134	.262
	Superficial	.181	.031	17.111	.114	.247

a. Dependent Variable: Obs.

Appendix N – Frequency Discrimination Data & Model

N.1 QUEST Outputs for all Participants

		Frequency DL 20 Hz Baseline			Frequency DL 50 Hz Baseline			Frequency DL 100 Hz Baseline			Frequency DL 200 Hz Baseline		
		Sine	Sq.	Saw.	Sine	Sq.	Saw.	Sine	Sq.	Saw.	Sine	Sq.	Saw.
I1LI	M	3.80	2.16	3.20	8.20	8.10	5.69	20.12	15.91	7.27	50.07	52.73	24.06
	STD	0.08	0.06	0.47	0.13	0.32	0.68	0.16	0.72	3.33	0.82	0.40	3.49
I2LP	M	3.17	3.67	3.42	9.13	30.59	6.21	29.07	32.60	27.09	24.81	18.85	41.59
	STD	0.41	0.24	0.12	3.21	0.19	0.60	0.32	1.41	1.80	0.31	1.22	0.50
I3LI	M	2.55	1.65	3.19	6.65	4.91	4.66	44.74	12.79	10.09	21.73	13.13	24.59
	STD	0.26	0.07	0.06	0.11	1.44	0.36	0.23	5.68	2.92	0.38	1.57	0.85
I4RM1	M	3.25	0.73	3.86	14.47	8.16	4.23	11.82	38.87	27.02	44.73	43.85	92.40
	STD	0.50	0.44	0.06	0.83	0.30	0.08	2.68	2.39	0.48	4.37	0.52	3.17
I4RM2	M	3.64	1.95	3.05	8.53	17.31	9.50	14.67	24.08	10.89	29.04	19.48	55.00
	STD	0.06	0.11	0.28	0.10	0.19	0.42	2.36	10.16	0.85	0.45	1.00	3.13
I4RM3	M	1.64	3.84	3.64	4.17	8.89	4.50	73.34	72.31	11.90	29.96	37.16	56.42
	STD	0.08	0.06	0.42	1.34	4.81	0.11	0.90	6.89	5.77	1.00	0.32	0.44
I5RM1	M	4.81	1.33	5.15	15.35	13.47	4.60	18.28	18.87	21.66	20.71	30.12	42.40
	STD	0.08	0.40	0.07	6.59	1.80	0.11	1.24	1.15	1.10	7.79	1.40	1.09
I5RM2	M	2.59	1.99	2.74	16.63	2.90	6.26	12.28	18.77	22.37	47.32	21.33	37.28
	STD	0.06	0.06	0.52	0.45	2.15	0.11	0.22	1.99	0.57	7.43	2.55	0.65
I5RM3	M	2.42	2.17	1.89	8.90	22.56	9.59	13.93	24.16	27.03	29.59	43.26	22.66
	STD	0.07	0.06	0.35	0.66	0.26	0.17	4.94	7.87	0.26	6.01	0.28	0.21
I6LR	M	5.97	2.85	2.65	26.94	17.34	16.36	19.54	47.54	53.83	31.53	32.53	27.81
	STD	0.07	0.35	0.78	0.60	4.55	0.49	1.22	3.31	0.14	2.23	0.19	0.27
I7LR	M	11.16	2.69	2.91	5.17	29.29	6.51	28.45	59.91	97.32	79.71	64.72	99.67
	STD	0.10	0.15	0.12	0.29	0.18	2.74	7.03	0.08	0.60	0.22	2.18	0.17
O1RI	M	4.00	2.03	2.00	9.13	16.13	6.68	11.64	28.62	15.48	46.61	22.42	32.02
	STD	0.22	0.78	0.09	4.16	1.07	0.36	2.78	13.23	5.02	0.72	3.93	1.66
S1LI	M	4.26	2.04	2.60	9.06	5.86	6.40	21.76	48.93	14.88	36.01	9.35	41.36
	STD	0.20	0.31	0.30	1.20	0.50	0.41	1.00	0.11	5.05	4.52	0.12	0.17
S2LP	M	8.74	1.87	2.82	13.44	16.11	8.34	56.56	48.21	90.20	92.28	88.92	65.77
	STD	1.15	0.64	0.25	0.24	0.80	1.23	5.07	1.04	5.74	0.78	2.97	0.45
S3LI	M	3.03	5.46	2.55	10.19	3.53	6.24	5.10	26.68	5.69	9.10	12.25	14.88
	STD	0.06	0.33	0.16	0.14	0.13	0.08	0.51	0.14	0.45	0.21	0.69	2.55
S4RM	M	4.26	1.52	1.88	12.63	2.95	6.77	5.35	86.46	25.30	69.70	48.22	51.10
	STD	0.07	0.10	0.11	1.41	1.06	0.56	1.36	1.65	0.42	0.19	1.37	13.88

S5RM	M	2.40	2.22	2.76	7.76	10.00	5.36	63.15	33.08	16.54	52.15	7.62	34.14
	STD	0.52	0.10	0.29	0.34	0.10	0.21	0.22	0.94	2.28	15.45	3.05	0.46
S6LR	M	2.24	2.57	2.70	10.35	16.52	7.72	5.71	9.60	10.07	31.16	59.64	90.71
	STD	0.56	0.71	0.55	0.99	1.44	0.34	1.90	0.42	1.85	0.74	9.81	5.41
S7LR	M	7.12	2.95	1.18	18.55	5.97	2.95	97.76	99.98	99.99	68.69	45.21	78.39
	STD	0.06	0.06	0.64	1.28	2.85	1.97	0.47	0.03	0.02	15.27	4.09	4.05

Table N-1: QUEST output estimates given by the algorithm for all of the participant's frequency discrimination experimentation (Hz), M – Mean, STD – Standard Deviation

N.2 20Hz Model - SPSS Mixed Model Output, Modelling All 20Hz Main Study Frequency Discrimination Experiment Data

Variable name definitions:

- ITypeN – Implant Type, 1 = Implanted, 2 = Superficial
- WaveFormN – Waveform, 1 = Sawtooth, 2 = Sine, 3 = Square
- IDN – Unique ID

Between-Subjects Factors

		Value Label	N
I-Type	1	Implanted	21
	2	Superficial	21
WaveFormN	1	Sawtooth	14
	2	Sine	14
	3	Square	14

Tests of Between-Subjects Effects
Dependent Variable: WeberFraction

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.080[a]	5	.016	1.907	.117
Intercept	1.130	1	1.130	135.390	.000
ITypeN	.001	1	.001	.085	.772
WaveFormN	.076	2	.038	4.540	.017
ITypeN * WaveFormN	.003	2	.002	.185	.832
Error	.301	36	.008		
Total	1.510	42			
Corrected Total	.380	41			

a. R Squared = .209 (Adjusted R Squared = .100)

Parameter Estimates
Dependent Variable: WeberFraction

Parameter	B	Std. Error	t	Sig.	95% Confidence Interval

					Lower Bound	Upper Bound
Intercept	.133	.035	3.850	.000	.063	.203
[ITypeN=1]	.003	.049	.060	.953	-.096	.102
[ITypeN=2]	0[a]	.	.	.	.	.
[WaveFormN=1]	-.015	.049	-.309	.759	-.114	.084
[WaveFormN=2]	.096	.049	1.965	.057	-.003	.195
[WaveFormN=3]	0[a]	.	.	.	.	.
[ITypeN=1] * [WaveFormN=1]	.028	.069	.413	.682	-.112	.169
[ITypeN=1] * [WaveFormN=2]	-.013	.069	-.182	.857	-.153	.128
[ITypeN=1] * [WaveFormN=3]	0[a]	.	.	.	.	.
[ITypeN=2] * [WaveFormN=1]	0[a]	.	.	.	.	.
[ITypeN=2] * [WaveFormN=2]	0[a]	.	.	.	.	.
[ITypeN=2] * [WaveFormN=3]	0[a]	.	.	.	.	.

a. This parameter is set to zero because it is redundant.

Estimates
Dependent Variable: WeberFraction

I-Type	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Implanted	.168	.020	.128	.209
Superficial	.160	.020	.119	.200

Estimates
Dependent Variable: WeberFraction

WaveFormN	Mean	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Sawtooth	.134	.024	.084	.183
Sine	.224	.024	.175	.274
Square	.134	.024	.085	.184

Pairwise Comparisons
Dependent Variable: WeberFraction

(I) WaveFormN	(J) WaveFormN	Mean Difference (I-J)	Std. Error	Sig.[b]	95% Confidence Interval for Difference[b]	
					Lower Bound	Upper Bound
Sawtooth	Sine	-.091*	.035	.038	-.177	-.004
	Square	-.001	.035	1.000	-.087	.086
Sine	Sawtooth	.091*	.035	.038	.004	.177
	Square	.090*	.035	.040	.003	.176
Square	Sawtooth	.001	.035	1.000	-.086	.087
	Sine	-.090*	.035	.040	-.176	-.003

Based on estimated marginal means
*. The mean difference is significant at the .05 level.
b. Adjustment for multiple comparisons: Šidák.

4. I-Type * WaveFormN
Dependent Variable: WeberFraction

I-Type	WaveFormN	Mean	Std. Error	95% Confidence Interval	
				Lower Bound	Upper Bound
Implanted	Sawtooth	.149	.035	.079	.219
	Sine	.219	.035	.149	.289
	Square	.136	.035	.066	.206
Superficial	Sawtooth	.118	.035	.048	.188
	Sine	.229	.035	.159	.299
	Square	.133	.035	.063	.203

N.3 50 Hz Model- SPSS Mixed Model Output, Modelling All 50Hz Main Study Frequency Discrimination Experiment Data

Variable name definitions:

- ITypeN – Implant Type, 1 = Implanted, 2 = Superficial
- WaveFormN – Waveform, 1 = Sawtooth, 2 = Sine, 3 = Square
- IDN – Unique ID

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables
Fixed Effects	Intercept	1		1	
	ITypeN	2		1	
	WaveFormN	3		2	
	ITypeN * WaveFormN	6		2	
Random Effects	Intercept[b]	1	Variance Components	1	IDN
	Residual			1	
	Total	13		8	

a. Dependent Variable: WeberFraction.

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	12	80.844	.000
ITypeN	1	12	1.447	.252
WaveFormN	2	24	4.222	.027
ITypeN * WaveFormN	2	24	3.221	.058

a. Dependent Variable: WeberFraction.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	.174075	.047348	33.398	3.676	.001	.077788	.270363
[ITypeN=1]	.173560	.066961	33.398	2.592	.014	.037389	.309730
[ITypeN=2]	0[b]	0	.	.	.	.	.
[WaveFormN=1]	-.048966	.059990	24	-.816	.422	-.172780	.074849
[WaveFormN=2]	.060133	.059990	24	1.002	.326	-.063681	.183947
[WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [WaveFormN=1]	-.145801	.084839	24	-1.719	.099	-.320901	.029298
[ITypeN=1] * [WaveFormN=2]	-.210135	.084839	24	-2.477	.021	-.385235	-.035035
[ITypeN=1] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [WaveFormN=1]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [WaveFormN=2]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [WaveFormN=3]	0[b]	0	.	.	.	.	.

a. Dependent Variable: WeberFraction.
b. This parameter is set to zero because it is redundant.

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		.012596	.003636	3.464	.001	.007153	.022180
Intercept [subject = IDN]	Variance	.003097	.003216	.963	.335	.000405	.023700

a. Dependent Variable: WeberFraction.

Estimates[a]

I-Type	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Implanted	.233	.032	12	.162	.303
Superficial	.178	.032	12	.107	.248

a. Dependent Variable: WeberFraction.

Estimates[a]

WaveFormN	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Sawtooth	.139	.033	33.398	.071	.207
Sine	.216	.033	33.398	.148	.284
Square	.261	.033	33.398	.193	.329

a. Dependent Variable: WeberFraction.

Pairwise Comparisons[a]

(I) WaveFormN	(J) WaveFormN	Mean Difference (I-J)	Std. Error	df	Sig.[c]	95% Confidence Interval for Difference[c]	
						Lower Bound	Upper Bound
Sawtooth	Sine	-.077	.042	24	.227	-.186	.032
	Square	-.122*	.042	24	.025	-.231	-.013
Sine	Sawtooth	.077	.042	24	.227	-.032	.186
	Square	-.045	.042	24	.657	-.154	.064
Square	Sawtooth	.122*	.042	24	.025	.013	.231
	Sine	.045	.042	24	.657	-.064	.154

Based on estimated marginal means
*. The mean difference is significant at the .05 level.
a. Dependent Variable: WeberFraction.
c. Adjustment for multiple comparisons: Šidák.

4. I-Type * WaveFormN[a]

I-Type	WaveFormN	Mean	Std. Error	df	95% Confidence Interval	
					Lower Bound	Upper Bound
Implanted	Sawtooth	.153	.047	33.398	.057	.249
	Sine	.198	.047	33.398	.101	.294
	Square	.348	.047	33.398	.251	.444
Superficial	Sawtooth	.125	.047	33.398	.029	.221
	Sine	.234	.047	33.398	.138	.330
	Square	.174	.047	33.398	.078	.270

a. Dependent Variable: WeberFraction.

N.4 100 Hz Model - SPSS Mixed Model Output, Modelling All 100Hz Main Study Frequency Discrimination Experiment Data

Variable name definitions:

- ITypeN – Implant Type, 1 = Implanted, 2 = Superficial
- WaveFormN – Waveform, 1 = Sawtooth, 2 = Sine, 3 = Square
- IDN – Unique ID

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables
Fixed Effects	Intercept	1		1	
	ITypeN	2		1	
	WaveFormN	3		2	
	ITypeN * WaveFormN	6		2	
Random Effects	Intercept	1	Variance Components	1	IDN
	Residual			1	

Total	13		8	

a. Dependent Variable: WeberFraction.

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Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	12	31.053	.000
ITypeN	1	12	.245	.630
WaveFormN	2	24	.767	.475
ITypeN * WaveFormN	2	24	.173	.843

a. Dependent Variable: WeberFraction.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	.504200	.119028	24.336	4.236	.000	.258717	.749683
[ITypeN=1]	-.125301	.168332	24.336	-.744	.464	-.472467	.221864
[ITypeN=2]	0[b]	0	.	.	.	.	.
[WaveFormN=1]	-.128956	.120266	24	-1.072	.294	-.377172	.119261
[WaveFormN=2]	-.139360	.120266	24	-1.159	.258	-.387577	.108856
[WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [WaveFormN=1]	.085100	.170082	24	.500	.621	-.265931	.436131
[ITypeN=1] * [WaveFormN=2]	.087889	.170082	24	.517	.610	-.263142	.438920
[ITypeN=1] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [WaveFormN=1]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [WaveFormN=2]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [WaveFormN=3]	0[b]	0	.	.	.	.	.

a. Dependent Variable: WeberFraction.
b. This parameter is set to zero because it is redundant.

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		.050624	.014614	3.464	.001	.028750	.089140
Intercept [subject = IDN]	Variance	.048551	.027150	1.788	.074	.016225	.145278

a. Dependent Variable: WeberFraction.

Estimates[a]

I-Type	Mean	Std. Error	df	95% Confidence Interval

				Lower Bound	Upper Bound
Implanted	.347	.097	12	.136	.558
Superficial	.415	.097	12	.204	.625

a. Dependent Variable: WeberFraction.

Estimates[a]

WaveFormN	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Sawtooth	.355	.084	24.336	.182	.529
Sine	.346	.084	24.336	.173	.520
Square	.442	.084	24.336	.268	.615

a. Dependent Variable: WeberFraction.

Pairwise Comparisons[a]

(I) WaveFormN	(J) WaveFormN	Mean Difference (I-J)	Std. Error	df	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
Sawtooth	Sine	.009	.085	24	.999	-.209	.227
	Square	-.086	.085	24	.685	-.305	.132
Sine	Sawtooth	-.009	.085	24	.999	-.227	.209
	Square	-.095	.085	24	.616	-.314	.123
Square	Sawtooth	.086	.085	24	.685	-.132	.305
	Sine	.095	.085	24	.616	-.123	.314

Based on estimated marginal means
a. Dependent Variable: WeberFraction.
b. Adjustment for multiple comparisons: Šidák.

4. I-Type * WaveFormN[a]

I-Type	WaveFormN	Mean	Std. Error	df	95% Confidence Interval	
					Lower Bound	Upper Bound
Implanted	Sawtooth	.335	.119	24.336	.090	.581
	Sine	.327	.119	24.336	.082	.573
	Square	.379	.119	24.336	.133	.624
Superficial	Sawtooth	.375	.119	24.336	.130	.621
	Sine	.365	.119	24.336	.119	.610
	Square	.504	.119	24.336	.259	.750

a. Dependent Variable: WeberFraction.

N.5 200 Hz Model- SPSS Mixed Model Output, Modelling All 200Hz Main Study Frequency Discrimination Experiment Data

Variable name definitions:

- ITypeN – Implant Type, 1 = Implanted, 2 = Superficial

- WaveFormN – Waveform, 1 = Sawtooth, 2 = Sine, 3 = Square
- IDN – Unique ID

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables
Fixed Effects	Intercept	1		1	
	ITypeN	2		1	
	WaveFormN	3		2	
	ITypeN * WaveFormN	6		2	
Random Effects	Intercept	1	Variance Components	1	IDN
	Residual			1	
	Total	13		8	

a. Dependent Variable: WeberFraction.

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	12	53.276	.000
ITypeN	1	12	.514	.487
WaveFormN	2	24	1.513	.241
ITypeN * WaveFormN	2	24	.600	.557

a. Dependent Variable: WeberFraction.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	.193722	.048532	19.825	3.992	.001	.092429	.295015
[ITypeN=1]	-.006303	.068635	19.825	-.092	.928	-.149553	.136948
[ITypeN=2]	0[b]	0	.	.	.	.	.
[WaveFormN=1]	.075095	.041255	24	1.820	.081	-.010050	.160241
[WaveFormN=2]	.062778	.041255	24	1.522	.141	-.022368	.147923
[WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [WaveFormN=1]	-.050513	.058343	24	-.866	.395	-.170927	.069901
[ITypeN=1] * [WaveFormN=2]	-.059199	.058343	24	-1.015	.320	-.179612	.061215
[ITypeN=1] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [WaveFormN=1]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [WaveFormN=2]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [WaveFormN=3]	0[b]	0	.	.	.	.	.

a. Dependent Variable: WeberFraction.
b. This parameter is set to zero because it is redundant.

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		.005957	.001720	3.464	.001	.003383	.010489
Intercept [subject = IDN]	Variance	.010531	.005142	2.048	.041	.004044	.027420

a. Dependent Variable: WeberFraction.

Estimates[a]

I-Type	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Implanted	.197	.042	12	.105	.289
Superficial	.240	.042	12	.148	.332

a. Dependent Variable: WeberFraction.

Estimates[a]

WaveFormN	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Sawtooth	.240	.034	19.825	.169	.312
Sine	.224	.034	19.825	.152	.295
Square	.191	.034	19.825	.119	.262

a. Dependent Variable: WeberFraction.

Pairwise Comparisons[a]

(I) WaveFormN	(J) WaveFormN	Mean Difference (I-J)	Std. Error	df	Sig.[b]	95% Confidence Interval for Difference[b]	
						Lower Bound	Upper Bound
Sawtooth	Sine	.017	.029	24	.922	-.058	.092
	Square	.050	.029	24	.272	-.025	.125
Sine	Sawtooth	-.017	.029	24	.922	-.092	.058
	Square	.033	.029	24	.606	-.042	.108
Square	Sawtooth	-.050	.029	24	.272	-.125	.025
	Sine	-.033	.029	24	.606	-.108	.042

Based on estimated marginal means
a. Dependent Variable: WeberFraction.
b. Adjustment for multiple comparisons: Šidák.

4. I-Type * WaveFormN[a]

I-Type	WaveFormN	Mean	Std. Error	df	95% Confidence Interval	
					Lower Bound	Upper Bound
Implanted	Sawtooth	.212	.049	19.825	.111	.313
	Sine	.191	.049	19.825	.090	.292
	Square	.187	.049	19.825	.086	.289
Superficial	Sawtooth	.269	.049	19.825	.168	.370

	Sine	.257	.049	19.825	.155	.358
	Square	.194	.049	19.825	.092	.295

a. Dependent Variable: WeberFraction.

N.6 Frequency Examination Model - - SPSS Mixed Model Output, Modelling All Main Study Frequency Discrimination Experiment Data

Variable name definitions:

- ITypeN – Implant Type, 1 = Implanted, 2 = Superficial
- WaveFormN – Waveform, 1 = Sawtooth, 2 = Sine, 3 = Square
- IDN – Unique ID
- Freq – Frequency

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables
Fixed Effects	Intercept	1		1	
	ITypeN	2		1	
	Freq	4		3	
	WaveFormN	3		2	
	ITypeN * Freq	8		3	
	ITypeN * WaveFormN	6		2	
	Freq * WaveFormN	12		6	
	ITypeN * Freq * WaveFormN	24		6	
Random Effects	Intercept	1	Variance Components	1	IDN
	Residual			1	
	Total	61		26	

a. Dependent Variable: WeberFraction.

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	12	82.703	.000
ITypeN	1	12	.049	.828
Freq	3	132	14.011	.000
WaveFormN	2	132	.979	.378
ITypeN * Freq	3	132	1.147	.333
ITypeN * WaveFormN	2	132	.304	.738
Freq * WaveFormN	6	132	1.372	.231
ITypeN * Freq * WaveFormN	6	132.000	.564	.758

a. Dependent Variable: WeberFraction.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound

Intercept	.193722	.070635	94.251	2.743	.007	.053478	.333966
[ITypeN=1]	-.006303	.099894	94.251	-.063	.950	-.204637	.192032
[ITypeN=2]	0[b]	0	.	.	.	.	.
[Freq=20]	-.060754	.088277	132	-.688	.493	-.235375	.113867
[Freq=50]	-.019647	.088277	132	-.223	.824	-.194267	.154974
[Freq=100]	.310478	.088277	132	3.517	.001	.135857	.485099
[Freq=200]	0[b]	0	.	.	.	.	.
[WaveFormN=1]	.075095	.088277	132	.851	.396	-.099526	.249716
[WaveFormN=2]	.062778	.088277	132	.711	.478	-.111843	.237399
[WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [Freq=20]	.009222	.124843	132	.074	.941	-.237729	.256173
[ITypeN=1] * [Freq=50]	.179863	.124843	132	1.441	.152	-.067089	.426814
[ITypeN=1] * [Freq=100]	-.118999	.124843	132	-.953	.342	-.365950	.127952
[ITypeN=1] * [Freq=200]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=20]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=50]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=100]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=200]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [WaveFormN=1]	-.050513	.124843	132	-.405	.686	-.297464	.196438
[ITypeN=1] * [WaveFormN=2]	-.059199	.124843	132.000	-.474	.636	-.306150	.187752
[ITypeN=1] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [WaveFormN=1]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [WaveFormN=2]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[Freq=20] * [WaveFormN=1]	-.090191	.124843	132	-.722	.471	-.337142	.156760
[Freq=20] * [WaveFormN=2]	.033176	.124843	132	.266	.791	-.213775	.280127
[Freq=20] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[Freq=50] * [WaveFormN=1]	-.124061	.124843	132	-.994	.322	-.371012	.122890
[Freq=50] * [WaveFormN=2]	-.002645	.124843	132	-.021	.983	-.249596	.244306
[Freq=50] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[Freq=100] * [WaveFormN=1]	-.204051	.124843	132	-1.634	.105	-.451002	.042900
[Freq=100] * [WaveFormN=2]	-.202138	.124843	132	-1.619	.108	-.449089	.044813

[Freq=100] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[Freq=200] * [WaveFormN=1]	0[b]	0	.	.	.	.	.
[Freq=200] * [WaveFormN=2]	0[b]	0	.	.	.	.	.
[Freq=200] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [Freq=20] * [WaveFormN=1]	.079010	.176554	132	.448	.655	-.270232	.428252
[ITypeN=1] * [Freq=20] * [WaveFormN=2]	.046663	.176554	132	.264	.792	-.302579	.395905
[ITypeN=1] * [Freq=20] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [Freq=50] * [WaveFormN=1]	-.095289	.176554	132	-.540	.590	-.444530	.253953
[ITypeN=1] * [Freq=50] * [WaveFormN=2]	-.150937	.176554	132	-.855	.394	-.500178	.198305
[ITypeN=1] * [Freq=50] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [Freq=100] * [WaveFormN=1]	.135613	.176554	132	.768	.444	-.213629	.484854
[ITypeN=1] * [Freq=100] * [WaveFormN=2]	.147088	.176554	132.000	.833	.406	-.202154	.496329
[ITypeN=1] * [Freq=100] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [Freq=200] * [WaveFormN=1]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [Freq=200] * [WaveFormN=2]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [Freq=200] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=20] * [WaveFormN=1]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=20] * [WaveFormN=2]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=20] * [WaveFormN=3]	0[b]	0	.	.	.	.	.

[ITypeN=2] * [Freq=50] * [WaveFormN=1]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=50] * [WaveFormN=2]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=50] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=100] * [WaveFormN=1]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=100] * [WaveFormN=2]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=100] * [WaveFormN=3]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=200] * [WaveFormN=1]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=200] * [WaveFormN=2]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=200] * [WaveFormN=3]	0[b]	0	.	.	.	.	.

a. Dependent Variable: WeberFraction.
b. This parameter is set to zero because it is redundant.

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		.027275	.003357	8.124	.000	.021428	.034717
Intercept [subject = IDN]	Variance	.007651	.004061	1.884	.060	.002703	.021653

a. Dependent Variable: WeberFraction.

Pairwise Comparisons[a]

(I) Freq	(J) Freq	Mean Difference (I-J)	Std. Error	df	Sig.[c]	95% Confidence Interval for Difference[c]	
						Lower Bound	Upper Bound
20	50	-.041	.036	132	.829	-.137	.055
	100	-.217*	.036	132	.000	-.313	-.121
	200	-.054	.036	132	.581	-.150	.042
50	20	.041	.036	132	.829	-.055	.137
	100	-.176*	.036	132.000	.000	-.272	-.079
	200	-.013	.036	132	1.000	-.109	.083
100	20	.217*	.036	132	.000	.121	.313
	50	.176*	.036	132.000	.000	.079	.272

	200	.163*	.036	132	.000	.066	.259
	20	.054	.036	132	.581	-.042	.150
200	50	.013	.036	132	1.000	-.083	.109
	100	-.163*	.036	132	.000	-.259	-.066

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Dependent Variable: WeberFraction.

c. Adjustment for multiple comparisons: Šidák.

Appendix O – Temporal Discrimination Data & Model

O.1 QUEST Outputs for all Participants

Temporal DL (ms)							
UID		20 Hz	200 Hz	UID		20 Hz	200 Hz
I1LI	Mean	29.07	35.56	I6LR	Mean	144.89	63.65
	STD	0.18	6.29		STD	5.23	0.35
I2LP	Mean	74.34	68.82	I7LR	Mean	39.63	32.32
	STD	2.29	0.49		STD	0.96	2.69
I3LI	Mean	32.23	59.86	O1RI	Mean	14.26	50.94
	STD	2.53	0.56		STD	6.06	0.24
I4RM1	Mean	46.12	87.93	S1LI	Mean	18.21	38.52
	STD	8.98	26.43		STD	2.66	4.27
I4RM2	Mean	176.38	94.89	S2LP	Mean	128.07	66.19
	STD	4.89	5.89		STD	1.90	1.67
I4RM3	Mean	54.47	77.40	S3LI	Mean	57.04	136.98
	STD	22.05	3.11		STD	3.15	0.30
I5RM1	Mean	37.72	122.58	S4RM	Mean	56.10	87.03
	STD	1.01	0.17		STD	2.77	0.60
I5RM2	Mean	10.14	50.21	S5RM	Mean	19.16	94.32
	STD	0.66	7.41		STD	0.32	3.16
I5RM3	Mean	12.64	91.67	S6LR	Mean	47.18	68.35
	STD	0.20	0.19		STD	1.93	16.50
				S7LR	Mean	118.07	160.60
					STD	1.06	1.89

Table O-1: QUEST output estimates outputs for all participants

O.2 Model - - SPSS Mixed Model Output, Modelling All Main Study Temporal Discrimination Experiment Data

Variable name definitions:

- ITypeN – Implant Type, 1 = Implanted, 2 = Superficial
- Freq – Frequency
- IDN – Unique ID

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables
Fixed Effects	Intercept	1		1	
	ITypeN	2		1	
	Freq	2		1	
	ITypeN * Freq	4		1	
Random Effects	Intercept	1	Variance Components	1	IDN
	Residual			1	
	Total	10		6	

a. Dependent Variable: WeberFraction.

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	12	67.760	.000
ITypeN	1	12	1.445	.252
Freq	1	12	1.964	.186
ITypeN * Freq	1	12	.866	.370

a. Dependent Variable: WeberFraction.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	.372561	.059190	22.507	6.294	.000	.249968	.495153
[ITypeN=1]	-.127267	.083708	22.507	-1.520	.142	-.300639	.046106
[ITypeN=2]	0[b]	0	.	.	.	.	.
[Freq=20]	-.118945	.072128	12	-1.649	.125	-.276098	.038209
[Freq=200]	0[b]	0	.	.	.	.	.
[ITypeN=1] * [Freq=20]	.094949	.102004	12	.931	.370	-.127300	.317197
[ITypeN=1] * [Freq=200]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=20]	0[b]	0	.	.	.	.	.
[ITypeN=2] * [Freq=200]	0[b]	0	.	.	.	.	.

a. Dependent Variable: WeberFraction.
b. This parameter is set to zero because it is redundant.

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		.018209	.007434	2.449	.014	.008180	.040530
Intercept [subject = IDN]	Variance	.006316	.007311	.864	.388	.000653	.061051

a. Dependent Variable: WeberFraction.

Estimates[a]

I-Type	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Implanted	.233	.047	12	.131	.336
Superficial	.313	.047	12	.211	.415

a. Dependent Variable: WeberFraction.

Estimates[a]

Freq	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
20	.237	.042	22.507	.151	.324
200	.309	.042	22.507	.222	.396

a. Dependent Variable: WeberFraction.

Appendix P – Temporal Gap Detection Data and Model

P.1 Data

		200 Hz 250 ms Pulse – Pulse Number (Vals ms)				200 Hz 25 ms Pulse – Pulse Number (Vals ms)				20 Hz 250 ms Pulse – Pulse Number (Vals ms)			
		2	3	4	5	2	3	4	5	2	3	4	5
I1LI	Mean	12.20	16.16	15.09	24.68	51.20	123.63	157.21	193.41	33.25	39.67	42.07	40.11
	STD	0.14	0.04	0.05	0.05	0.05	0.24	0.07	1.08	0.05	0.22	0.46	0.09
I2LP	Mean	1.06	1.34	3.39	25.93	36.69	69.63	125.96	217.94	42.63	80.45	70.37	107.59
	STD	0.13	0.05	0.07	8.83	9.00	0.14	0.13	3.34	0.04	1.42	0.12	2.01
I3LI	Mean	6.26	7.95	11.07	22.16	9.84	93.05	158.74	179.37	31.96	34.87	35.64	39.83
	STD	0.29	0.05	5.22	4.76	0.15	0.04	0.50	0.11	0.06	0.05	0.51	0.14
I4RM3	Mean	8.78	15.44	16.49	18.28	16.02	123.59	164.53	200.71	26.06	56.11	64.93	99.14
	STD	0.10	0.78	0.13	0.12	0.20	0.07	1.37	14.38	0.04	10.10	0.06	0.60
I5RM3	Mean	2.80	7.85	10.35	9.95	30.15	88.68	116.37	145.97	24.03	22.20	30.93	36.21
	STD	0.06	0.04	0.04	0.10	4.93	3.56	1.00	25.78	0.09	0.04	1.40	0.04
I6LR	Mean	6.81	22.28	32.54	32.79	18.56	124.54	140.29	166.56	35.59	36.07	41.93	34.46
	STD	0.04	0.06	0.81	0.09	0.06	0.04	0.04	0.10	2.70	0.23	7.12	1.52
I7LR	Mean	2.03	1.88	21.76	19.79	14.26	101.44	104.26	147.65	47.45	72.24	72.34	87.06
	STD	0.04	0.07	0.71	3.59	0.04	0.07	1.99	0.05	0.33	0.09	3.60	4.30
O1RI	Mean	4.49	5.79	11.26	16.23	20.34	87.11	118.69	136.21	10.84	15.00	24.61	42.38
	STD	0.09	0.65	0.06	0.17	0.05	4.08	0.05	0.08	0.16	0.05	0.06	0.07
S1LI	Mean	3.53	10.42	15.85	15.93	39.44	59.65	109.98	175.41	24.67	15.66	23.59	22.83
	STD	0.04	2.04	2.93	0.04	19.46	0.04	2.29	0.06	0.04	0.07	5.72	0.06
S2LP	Mean	16.22	17.41	20.87	33.10	23.27	119.36	243.31	225.77	84.58	112.26	125.72	112.50
	STD	0.07	0.04	0.07	0.04	0.06	0.05	0.61	0.43	2.47	2.27	2.67	19.11
S3LI	Mean	10.53	13.17	17.21	41.59	81.96	130.99	216.52	295.13	51.00	61.22	49.03	67.89
	STD	1.05	0.15	0.09	0.04	0.04	0.46	0.07	0.04	0.06	0.05	0.47	0.05
S4RM	Mean	24.30	19.07	34.26	30.20	25.27	133.34	199.08	175.86	45.11	52.15	97.47	65.47
	STD	2.45	0.06	0.73	0.04	1.78	0.14	2.46	0.41	1.44	0.80	2.46	0.06
S5RM	Mean	8.43	11.48	10.46	13.09	33.31	107.70	126.96	168.54	19.84	21.24	24.81	26.41
	STD	0.06	0.07	0.05	0.87	0.59	0.17	0.04	0.07	0.05	0.04	0.31	2.13
S6LR	Mean	8.79	12.66	11.52	15.61	35.38	81.11	110.02	153.26	32.90	36.20	106.19	104.22
	STD	0.19	0.12	0.36	0.67	0.22	0.20	0.06	0.57	0.04	6.64	1.86	2.56
S7LR	Mean	20.92	26.50	50.86	75.14	68.66	165.23	240.08	250.67	71.49	72.18	121.12	103.83
	STD	0.05	0.10	0.55	0.04	0.11	1.66	0.04	0.33	0.05	0.23	0.12	0.10

Table P-1: QUEST output estimates for Temporal Gap Detection Experiments

P.2 Model One - SPSS Mixed Model Output, Modelling All Main Study TND with Respect to Experiment Data for Pulse Type = 250 ms, Investigation of Frequency Effects

Variable name definitions:

- ITypeN – Implant Type, 1 = Implanted, 2 = Superficial
- IDN – Unique ID
- Freq – Frequency
- PulseNo – Pulse Number

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables
Fixed Effects	Intercept	1		1	
	Freq	2		1	
	Implanted	2		1	
	PulseNo	4		3	
	Freq * Implanted	4		1	
	Freq * PulseNo	8		3	
	Implanted * PulseNo	8		3	
	Freq * Implanted * PulseNo	16		3	
Random Effects	Intercept	1	Variance Components	1	ID
	Residual			1	
	Total	46		18	

a. Dependent Variable: Value.

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	12	75.356	.000
Freq	1	84.000	148.736	.000
Implanted	1	12	1.497	.245
PulseNo	3	84.000	9.850	.000
Freq * Implanted	1	84.000	.753	.388
Freq * PulseNo	3	84.000	.854	.468
Implanted * PulseNo	3	84.000	.646	.588
Freq * Implanted * PulseNo	3	84.000	.631	.597

a. Dependent Variable: Value.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval

						Lower Bound	Upper Bound
Intercept	32.093429	8.424254	41.764	3.810	.000	15.089752	49.097105
[Freq=1]	39.784286	8.988994	84	4.426	.000	21.908685	57.659886
[Freq=2]	0[b]	0	.	.	.	.	.
[Implanted=1]	-10.153571	11.913695	41.764	-.852	.399	-34.200401	13.893258
[Implanted=2]	0[b]	0	.	.	.	.	.
[PulseNo=2]	-18.848171	8.988994	84.000	-2.097	.039	-36.723772	-.972571
[PulseNo=3]	-16.279000	8.988994	84.000	-1.811	.074	-34.154601	1.596601
[PulseNo=4]	-9.090429	8.988994	84	-1.011	.315	-26.966029	8.785172
[PulseNo=5]	0[b]	0	.	.	.	.	.
[Freq=1] * [Implanted=1]	1.759857	12.712357	84	.138	.890	-23.520060	27.039774
[Freq=1] * [Implanted=2]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=1]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=2]	0[b]	0	.	.	.	.	.
[Freq=1] * [PulseNo=2]	-5.945400	12.712357	84.000	-.468	.641	-31.225317	19.334517
[Freq=1] * [PulseNo=3]	-2.614000	12.712357	84.000	-.206	.838	-27.893917	22.665917
[Freq=1] * [PulseNo=4]	15.488286	12.712357	84	1.218	.226	-9.791631	40.768203
[Freq=1] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Freq=2] * [PulseNo=2]	0[b]	0	.	.	.	.	.
[Freq=2] * [PulseNo=3]	0[b]	0	.	.	.	.	.
[Freq=2] * [PulseNo=4]	0[b]	0	.	.	.	.	.
[Freq=2] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Implanted=1] * [PulseNo=2]	2.613271	12.712357	84.000	.206	.838	-22.666645	27.893188
[Implanted=1] * [PulseNo=3]	4.753386	12.712357	84.000	.374	.709	-20.526531	30.033303
[Implanted=1] * [PulseNo=4]	2.963914	12.712357	84.000	.233	.816	-22.316003	28.243831
[Implanted=1] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=2]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=3]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=4]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Freq=1] * [Implanted=1] * [PulseNo=2]	-6.880414	17.977988	84	-.383	.703	-42.631616	28.870787

[Freq=1] * [Implanted=1] * [PulseNo=3]	-.543814	17.977988	84	-.030	.976	-36.295016	35.207387
[Freq=1] * [Implanted=1] * [PulseNo=4]	-21.673914	17.977988	84.000	-1.206	.231	-57.425116	14.077287
[Freq=1] * [Implanted=1] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Freq=1] * [Implanted=2] * [PulseNo=2]	0[b]	0	.	.	.	.	.
[Freq=1] * [Implanted=2] * [PulseNo=3]	0[b]	0	.	.	.	.	.
[Freq=1] * [Implanted=2] * [PulseNo=4]	0[b]	0	.	.	.	.	.
[Freq=1] * [Implanted=2] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=1] * [PulseNo=2]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=1] * [PulseNo=3]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=1] * [PulseNo=4]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=1] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=2] * [PulseNo=2]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=2] * [PulseNo=3]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=2] * [PulseNo=4]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=2] * [PulseNo=5]	0[b]	0	.	.	.	.	.

a. Dependent Variable: Value.

b. This parameter is set to zero because it is redundant.

Estimates of Covariance Parameters[a]

Parameter	Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Residual	282.807054	43.638076	6.481	.000	209.000338	382.677993

Intercept [subject = ID]	Variance	213.969392	101.930634	2.099	.036	84.111752	544.310395

a. Dependent Variable: Value.

Estimates[a]

Implanted	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Implanted	31.469	5.968	12	18.466	44.472
Superficial	41.797	5.968	12	28.794	54.800

a. Dependent Variable: Value.

Estimates[a]

Freq	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
20Hz	56.013	4.509	15.599	46.433	65.592
200Hz	17.254	4.509	15.599	7.674	26.833

a. Dependent Variable: Value.

Estimates[a]

PulseNo	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
2 Pulses	25.114	5.038	23.766	14.711	35.518
3 Pulses	32.003	5.038	23.766	21.600	42.407
4 Pulses	42.066	5.038	23.766	31.662	52.470
5 Pulses	47.349	5.038	23.766	36.945	57.753

a. Dependent Variable: Value.

6. Freq * PulseNo[a]

Freq	PulseNo	Mean	Std. Error	df	95% Confidence Interval	
					Lower Bound	Upper Bound
20Hz	2 Pulses	40.754	5.957	41.764	28.730	52.777
	3 Pulses	50.893	5.957	41.764	38.869	62.916
	4 Pulses	64.724	5.957	41.764	52.700	76.747
	5 Pulses	67.681	5.957	41.764	55.657	79.704
200Hz	2 Pulses	9.475	5.957	41.764	-2.548	21.499
	3 Pulses	13.114	5.957	41.764	1.091	25.138
	4 Pulses	19.408	5.957	41.764	7.385	31.432
	5 Pulses	27.017	5.957	41.764	14.993	39.040

a. Dependent Variable: Value.

8. Freq * Implanted * PulseNo[a]

Freq	Implanted	PulseNo	Mean	Std. Error	df	95% Confidence Interval	
						Lower Bound	Upper Bound
20Hz	Implanted	2 Pulses	34.423	12.330	39.704	9.497	59.350
		3 Pulses	48.801	12.330	39.704	23.874	73.727
		4 Pulses	51.172	12.330	39.704	26.245	76.098
		5 Pulses	63.484	12.330	39.704	38.557	88.411

200Hz	Superficial	2 Pulses	47.084	12.330	39.704	22.158	72.011
		3 Pulses	52.985	12.330	39.704	28.058	77.911
		4 Pulses	78.276	12.330	39.704	53.349	103.202
		5 Pulses	71.878	12.330	39.704	46.951	96.804
	Implanted	2 Pulses	25.245	12.330	39.704	.318	50.171
		3 Pulses	103.509	12.330	39.704	78.583	128.436
		4 Pulses	138.194	12.330	39.704	113.268	163.121
		5 Pulses	178.801	12.330	39.704	153.875	203.728
	Superficial	2 Pulses	43.898	12.330	39.704	18.972	68.825
		3 Pulses	113.912	12.330	39.704	88.985	138.838
		4 Pulses	177.993	12.330	39.704	153.066	202.919
		5 Pulses	206.377	12.330	39.704	181.451	231.304

a. Dependent Variable: Value.

P.3 Model Two - SPSS Mixed Model Output, Modelling All Main Study TND with Respect to Experiment Data for Number of Cycles = 5, Investigation of Frequency Effects

Variable name definitions:

- ITypeN – Implant Type, 1 = Implanted, 2 = Superficial
- IDN – Unique ID
- Freq – Frequency
- PulseNo – Pulse Number

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables
Fixed Effects	Intercept	1		1	
	Freq	2		1	
	Implanted	2		1	
	PulseNo	4		3	
	Freq * Implanted	4		1	
	Freq * PulseNo	8		3	
	Implanted * PulseNo	8		3	
	Freq * Implanted * PulseNo	16		3	
Random Effects	Intercept	1	Variance Components	1	ID
	Residual			1	
	Total	46		18	

a. Dependent Variable: Value.

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.
Intercept	1	12	204.248	.000
Freq	1	84.000	217.831	.000
Implanted	1	12	2.192	.164
PulseNo	3	84.000	78.331	.000
Freq * Implanted	1	84.000	1.453	.231
Freq * PulseNo	3	84.000	37.824	.000
Implanted * PulseNo	3	84.000	1.425	.241
Freq * Implanted * PulseNo	3	84.000	.117	.950

a. Dependent Variable: Value.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	206.377143	12.330436	39.704	16.737	.000	181.450616	231.303670
[Freq=1]	-134.499429	12.931549	84.000	-10.401	.000	-160.215232	-108.783625
[Freq=2]	0[b]	0	.	.	.	.	.
[Implanted=1]	-27.575714	17.437869	39.704	-1.581	.122	-62.827147	7.675718
[Implanted=2]	0[b]	0	.	.	.	.	.
[PulseNo=2]	-162.478857	12.931549	84.000	-12.565	.000	-188.194660	-136.763054
[PulseNo=3]	-92.465429	12.931549	84.000	-7.150	.000	-118.181232	-66.749625
[PulseNo=4]	-28.384286	12.931549	84.000	-2.195	.031	-54.100089	-2.668482
[PulseNo=5]	0[b]	0	.	.	.	.	.
[Freq=1] * [Implanted=1]	19.182000	18.287972	84.000	1.049	.297	-17.185638	55.549638
[Freq=1] * [Implanted=2]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=1]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=2]	0[b]	0	.	.	.	.	.
[Freq=1] * [PulseNo=2]	137.685286	18.287972	84.000	7.529	.000	101.317648	174.052924
[Freq=1] * [PulseNo=3]	73.572429	18.287972	84.000	4.023	.000	37.204791	109.940066
[Freq=1] * [PulseNo=4]	34.782143	18.287972	84.000	1.902	.061	-1.585495	71.149781
[Freq=1] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Freq=2] * [PulseNo=2]	0[b]	0	.	.	.	.	.
[Freq=2] * [PulseNo=3]	0[b]	0	.	.	.	.	.
[Freq=2] * [PulseNo=4]	0[b]	0	.	.	.	.	.
[Freq=2] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Implanted=1] * [PulseNo=2]	8.922271	18.287972	84.000	.488	.627	-27.445366	45.289909
[Implanted=1] * [PulseNo=3]	17.173286	18.287972	84.000	.939	.350	-19.194352	53.540924

[Implanted=1] * [PulseNo=4]	-12.222857	18.287972	84.000	-.668	.506	-48.590495	24.144781
[Implanted=1] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=2]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=3]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=4]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Freq=1] * [Implanted=1] * [PulseNo=2]	-13.189414	25.863098	84.000	-.510	.611	-64.621021	38.242192
[Freq=1] * [Implanted=1] * [PulseNo=3]	-12.963714	25.863098	84.000	-.501	.618	-64.395321	38.467892
[Freq=1] * [Implanted=1] * [PulseNo=4]	-6.487143	25.863098	84.000	-.251	.803	-57.918749	44.944464
[Freq=1] * [Implanted=1] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Freq=1] * [Implanted=2] * [PulseNo=2]	0[b]	0	.	.	.	.	.
[Freq=1] * [Implanted=2] * [PulseNo=3]	0[b]	0	.	.	.	.	.
[Freq=1] * [Implanted=2] * [PulseNo=4]	0[b]	0	.	.	.	.	.
[Freq=1] * [Implanted=2] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=1] * [PulseNo=2]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=1] * [PulseNo=3]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=1] * [PulseNo=4]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=1] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=2] * [PulseNo=2]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=2] * [PulseNo=3]	0[b]	0	.	.	.	.	.

[Freq=2] * [Implanted=2] * [PulseNo=4]	0[b]	0	.	.	.	.	.
[Freq=2] * [Implanted=2] * [PulseNo=5]	0[b]	0	.	.	.	.	.

a. Dependent Variable: Value.
b. This parameter is set to zero because it is redundant.

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		585.287357	90.311800	6.481	.000	432.539619	791.976677
Intercept [subject = ID]	Variance	478.990158	225.697237	2.122	.034	190.215376	1206.167324

a. Dependent Variable: Value.

Estimates[a]

Implanted	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Implanted	80.454	8.881	12	61.103	99.805
Superficial	99.050	8.881	12	79.699	118.401

a. Dependent Variable: Value.

6. Freq * PulseNo[a]

Freq	PulseNo	Mean	Std. Error	df	95% Confidence Interval	
					Lower Bound	Upper Bound
20Hz	2 Pulses	40.754	8.719	39.704	23.128	58.379
	3 Pulses	50.893	8.719	39.704	33.267	68.518
	4 Pulses	64.724	8.719	39.704	47.098	82.349
	5 Pulses	67.681	8.719	39.704	50.055	85.307
200Hz	2 Pulses	34.572	8.719	39.704	16.946	52.197
	3 Pulses	108.711	8.719	39.704	91.085	126.336
	4 Pulses	158.094	8.719	39.704	140.468	175.719
	5 Pulses	192.589	8.719	39.704	174.964	210.215

a. Dependent Variable: Value.

8. Freq * Implanted * PulseNo[a]

Freq	Implanted	PulseNo	Mean	Std. Error	df	95% Confidence Interval	
						Lower Bound	Upper Bound
20Hz	Implanted	2 Pulses	34.423	12.330	39.704	9.497	59.350
		3 Pulses	48.801	12.330	39.704	23.874	73.727
		4 Pulses	51.172	12.330	39.704	26.245	76.098
		5 Pulses	63.484	12.330	39.704	38.557	88.411
	Superficial	2 Pulses	47.084	12.330	39.704	22.158	72.011
		3 Pulses	52.985	12.330	39.704	28.058	77.911
		4 Pulses	78.276	12.330	39.704	53.349	103.202

200Hz	Implanted	5 Pulses	71.878	12.330	39.704	46.951	96.804
		2 Pulses	25.245	12.330	39.704	.318	50.171
		3 Pulses	103.509	12.330	39.704	78.583	128.436
		4 Pulses	138.194	12.330	39.704	113.268	163.121
		5 Pulses	178.801	12.330	39.704	153.875	203.728
	Superficial	2 Pulses	43.898	12.330	39.704	18.972	68.825
		3 Pulses	113.912	12.330	39.704	88.985	138.838
		4 Pulses	177.993	12.330	39.704	153.066	202.919
		5 Pulses	206.377	12.330	39.704	181.451	231.304

a. Dependent Variable: Value.

P.4 Model Three - SPSS Mixed Model Output, Modelling All Main Study TND with Respect to Experiment Data for Pulse Type = 200 Hz, Investigation of Number of Cycles Effects

Variable name definitions:

- ITypeN – Implant Type, 1 = Implanted, 2 = Superficial
- IDN – Unique ID
- NumberOfCycles – Number of Cycles
- PulseNo – Pulse Number

Model Dimension[a]

		Number of Levels	Covariance Structure	Number of Parameters	Subject Variables
Fixed Effects	Intercept	1		1	
	Implanted	2		1	
	PulseNo	4		3	
	Implanted * PulseNo	8		3	
	NumberOfCycles	2		1	
	Implanted * NumberOfCycles	4		1	
	PulseNo * NumberOfCycles	8		3	
	Implanted * PulseNo * NumberOfCycles	16		3	
Random Effects	Intercept	1	Variance Components	1	ID
	Residual			1	
	Total	46		18	

a. Dependent Variable: Value.

Type III Tests of Fixed Effects[a]

Source	Numerator df	Denominator df	F	Sig.

Intercept	1	12	220.319	.000
Implanted	1	12	2.790	.121
PulseNo	3	84	93.686	.000
Implanted * PulseNo	3	84	.750	.526
NumberOfCycles	1	84	734.352	.000
Implanted * NumberOfCycles	1	84	4.448	.038
PulseNo * NumberOfCycles	3	84	61.110	.000
Implanted * PulseNo * NumberOfCycles	3	84	.571	.635

a. Dependent Variable: Value.

Estimates of Fixed Effects[a]

Parameter	Estimate	Std. Error	df	t	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Intercept	32.093429	9.937198	48.067	3.230	.002	12.114076	52.072782
[Implanted=1]	-10.153571	14.053320	48.067	-.723	.473	-38.408643	18.101501
[Implanted=2]	0[b]	0	.	.	.	.	.
[PulseNo=2]	-18.848171	11.088463	84	-1.700	.093	-40.898796	3.202453
[PulseNo=3]	-16.279000	11.088463	84	-1.468	.146	-38.329625	5.771625
[PulseNo=4]	-9.090429	11.088463	84	-.820	.415	-31.141053	12.960196
[PulseNo=5]	0[b]	0	.	.	.	.	.
[Implanted=1] * [PulseNo=2]	2.613271	15.681455	84	.167	.868	-28.571021	33.797564
[Implanted=1] * [PulseNo=3]	4.753386	15.681455	84	.303	.763	-26.430907	35.937678
[Implanted=1] * [PulseNo=4]	2.963914	15.681455	84	.189	.851	-28.220378	34.148207
[Implanted=1] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=2]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=3]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=4]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=5]	0[b]	0	.	.	.	.	.
[NumberOfCycles=5]	174.283714	11.088463	84	15.718	.000	152.233089	196.334339
[NumberOfCycles=50]	0[b]	0	.	.	.	.	.
[Implanted=1] * [NumberOfCycles=5]	-17.422143	15.681455	84	-1.111	.270	-48.606436	13.762150
[Implanted=1] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.
[Implanted=2] * [NumberOfCycles=5]	0[b]	0	.	.	.	.	.
[Implanted=2] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.
[PulseNo=2] * [NumberOfCycles=5]	-143.630686	15.681455	84	-9.159	.000	-174.814978	-112.446393
[PulseNo=2] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.
[PulseNo=3] * [NumberOfCycles=5]	-76.186429	15.681455	84	-4.858	.000	-107.370721	-45.002136
[PulseNo=3] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.
[PulseNo=4] * [NumberOfCycles=5]	-19.293857	15.681455	84	-1.230	.222	-50.478150	11.890436
[PulseNo=4] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.

[PulseNo=5] * [NumberOfCycles=5]	0[b]	0	.	.	.	.	.
[PulseNo=5] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.
[Implanted=1] * [PulseNo=2] * [NumberOfCycles=5]	6.309000	22.176926	84	.284	.777	-37.792250	50.410250
[Implanted=1] * [PulseNo=2] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.
[Implanted=1] * [PulseNo=3] * [NumberOfCycles=5]	12.419900	22.176926	84	.560	.577	-31.681350	56.521150
[Implanted=1] * [PulseNo=3] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.
[Implanted=1] * [PulseNo=4] * [NumberOfCycles=5]	-15.186771	22.176926	84	-.685	.495	-59.288021	28.914478
[Implanted=1] * [PulseNo=4] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.
[Implanted=1] * [PulseNo=5] * [NumberOfCycles=5]	0[b]	0	.	.	.	.	.
[Implanted=1] * [PulseNo=5] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=2] * [NumberOfCycles=5]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=2] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=3] * [NumberOfCycles=5]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=3] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=4] * [NumberOfCycles=5]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=4] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=5] * [NumberOfCycles=5]	0[b]	0	.	.	.	.	.
[Implanted=2] * [PulseNo=5] * [NumberOfCycles=50]	0[b]	0	.	.	.	.	.

a. Dependent Variable: Value.

b. This parameter is set to zero because it is redundant.

Estimates of Covariance Parameters[a]

Parameter		Estimate	Std. Error	Wald Z	Sig.	95% Confidence Interval	
						Lower Bound	Upper Bound
Residual		430.339046	66.402756	6.481	.000	318.029571	582.309670
Intercept [subject = ID]	Variance	260.896292	128.738970	2.027	.043	99.184430	686.265732

a. Dependent Variable: Value.

Estimates[a]

Implanted	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
Implanted	62.453	6.705	12	47.844	77.061

Superficial	78.292	6.705	12	63.683	92.901

a. Dependent Variable: Value.

3. Implanted * PulseNo[a]

Implanted	PulseNo	Mean	Std. Error	df	95% Confidence Interval	
					Lower Bound	Upper Bound
Implanted	2 Pulses	15.475	8.247	26.469	-1.462	32.412
	3 Pulses	56.962	8.247	26.469	40.025	73.899
	4 Pulses	77.004	8.247	26.469	60.067	93.941
	5 Pulses	100.371	8.247	26.469	83.434	117.308
Superficial	2 Pulses	28.572	8.247	26.469	11.635	45.509
	3 Pulses	64.863	8.247	26.469	47.926	81.800
	4 Pulses	100.498	8.247	26.469	83.561	117.435
	5 Pulses	119.235	8.247	26.469	102.298	136.172

a. Dependent Variable: Value.

Estimates[a]

NumberOfCycles	Mean	Std. Error	df	95% Confidence Interval	
				Lower Bound	Upper Bound
5	123.491	5.130	16.385	112.636	134.346
50	17.254	5.130	16.385	6.399	28.109

a. Dependent Variable: Value.

6. Implanted * NumberOfCycles[a]

Implanted	NumberOfCycles	Mean	Std. Error	df	95% Confidence Interval	
					Lower Bound	Upper Bound
Implanted	5	111.437	7.255	16.385	96.086	126.789
	50	13.468	7.255	16.385	-1.883	28.819
Superficial	5	135.545	7.255	16.385	120.194	150.896
	50	21.039	7.255	16.385	5.688	36.390

a. Dependent Variable: Value.

7. PulseNo * NumberOfCycles[a]

PulseNo	NumberOfCycles	Mean	Std. Error	df	95% Confidence Interval	
					Lower Bound	Upper Bound
2 Pulses	5	34.572	7.027	48.067	20.444	48.699
	50	9.475	7.027	48.067	-4.652	23.603
3 Pulses	5	108.711	7.027	48.067	94.583	122.838
	50	13.114	7.027	48.067	-1.013	27.242
4 Pulses	5	158.094	7.027	48.067	143.966	172.221
	50	19.408	7.027	48.067	5.281	33.536
5 Pulses	5	192.589	7.027	48.067	178.462	206.717
	50	27.017	7.027	48.067	12.889	41.144

a. Dependent Variable: Value.

8. Implanted * PulseNo * NumberOfCycles[a]

Implanted	PulseNo	NumberOfCycles	Mean	Std. Error	df	95% Confidence Interval

						Lower Bound	Upper Bound
Implanted	2 Pulses	5	25.245	9.937	48.067	5.265	45.224
		50	5.705	9.937	48.067	-14.274	25.684
	3 Pulses	5	103.509	9.937	48.067	83.530	123.489
		50	10.414	9.937	48.067	-9.565	30.394
	4 Pulses	5	138.194	9.937	48.067	118.215	158.174
		50	15.813	9.937	48.067	-4.166	35.793
	5 Pulses	5	178.801	9.937	48.067	158.822	198.781
		50	21.940	9.937	48.067	1.961	41.919
Superficial	2 Pulses	5	43.898	9.937	48.067	23.919	63.878
		50	13.245	9.937	48.067	-6.734	33.225
	3 Pulses	5	113.912	9.937	48.067	93.932	133.891
		50	15.814	9.937	48.067	-4.165	35.794
	4 Pulses	5	177.993	9.937	48.067	158.014	197.972
		50	23.003	9.937	48.067	3.024	42.982
	5 Pulses	5	206.377	9.937	48.067	186.398	226.356
		50	32.093	9.937	48.067	12.114	52.073

a. Dependent Variable: Value.

Appendix Q – 3-Month Study Plots

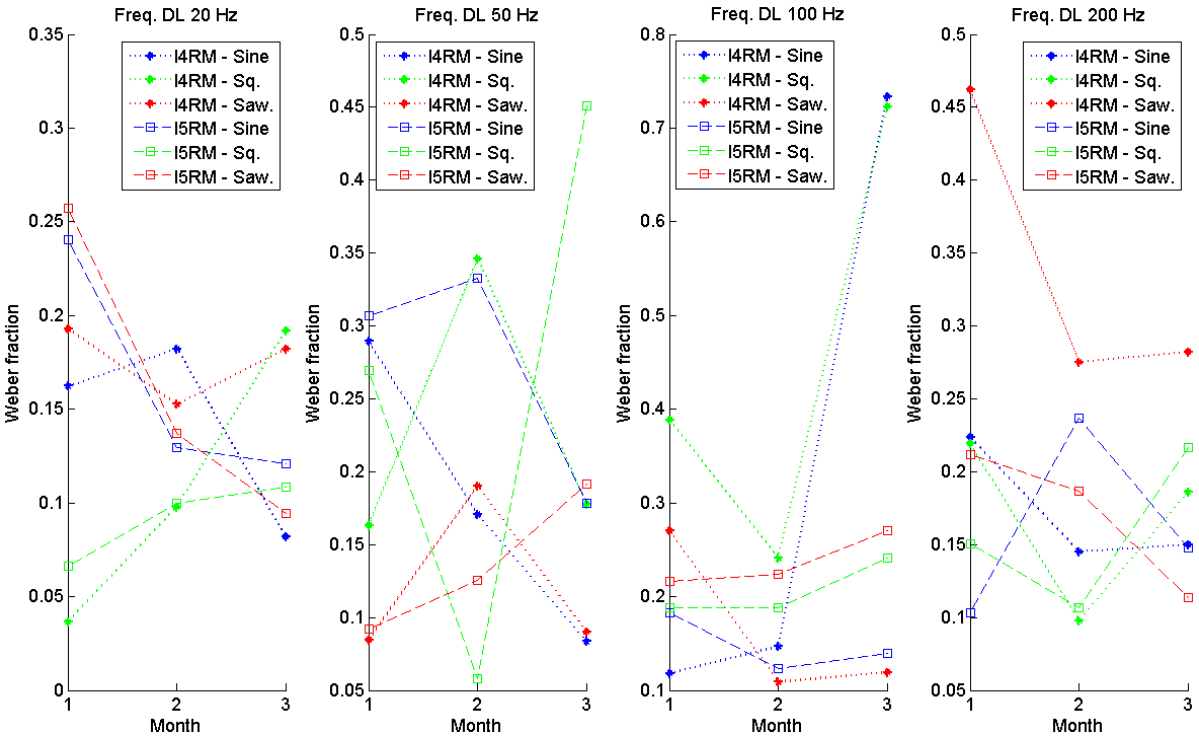

Figure Q-1: Participant's data from the frequency discrimination experiment as part of the 3-month study

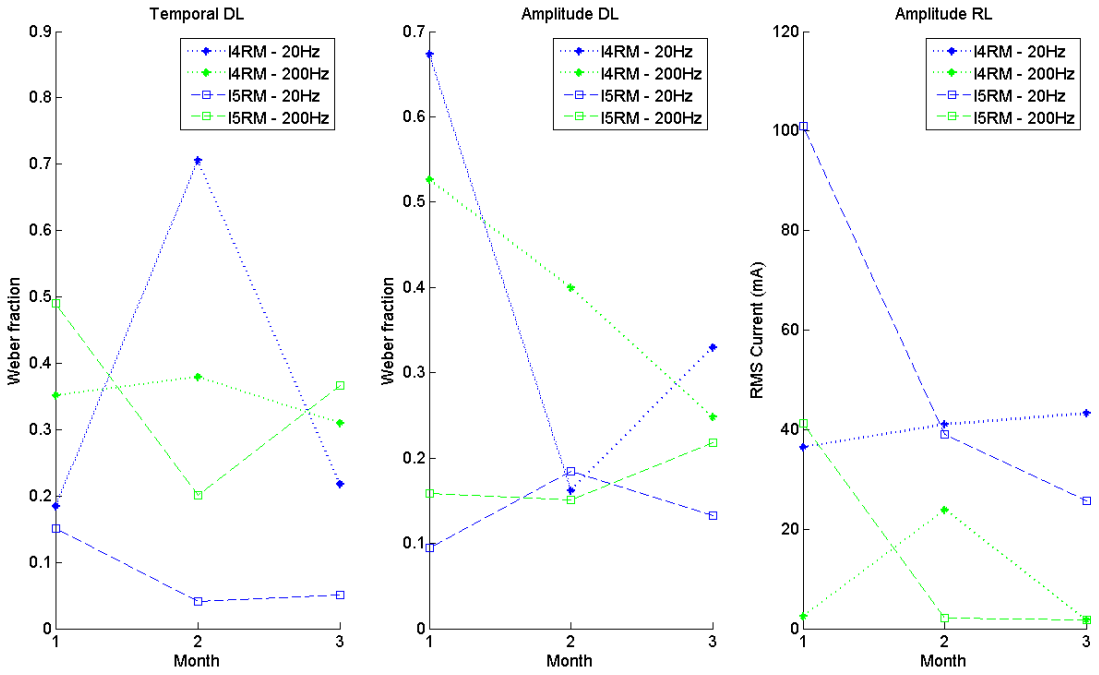

Figure Q-2: Participant's data from the temporal discrimination (DL) amplitude discrimination (DL) and amplitude detection experiments as part of the 3-month study

Appendix R – SSUS Table of Comparisons

Test	Type	SSUS Mean	Im. Mean	Im. STD	Su. Mean	Su. STD	Both Mean	Both STD	Z Score 1	Sig	Z Score 2	Sig	Z Score 3	Sig	Closest Too
1	Audio	139.31	154.24	17.29	152.28	12.06	154.24	17.29	-0.86	0.39	-1.07	0.28	-0.86	0.39	Im
	MIVS	231.39	219.44	28.79	230.06	20.35	219.44	28.79	0.42	0.68	0.07	0.95	0.42	0.68	Su
2	20 Hz	29.84	121.76	238.69	300.98	508.35	121.76	238.69	-0.39	0.70	-0.53	0.59	-0.39	0.70	Im
	200 Hz	6.67	4.92	6.88	116.51	279.12	4.92	6.88	0.25	0.80	-0.39	0.69	0.25	0.80	Im
3	20 Hz	0.12	0.14	0.09	0.15	0.08	0.14	0.09	-0.25	0.80	-0.32	0.75	-0.25	0.80	Im
	200 Hz	0.13	0.19	0.08	0.24	0.24	0.19	0.08	-0.81	0.42	-0.47	0.64	-0.81	0.42	Su
4	20 Sine	0.20	0.22	0.15	0.23	0.11	0.22	0.15	-0.11	0.91	-0.22	0.83	-0.11	0.91	Im
	20 Sq.	0.10	0.13	0.04	0.13	0.06	0.13	0.04	-0.77	0.44	-0.44	0.66	-0.77	0.44	Su
	20 Saw.	0.10	0.14	0.03	0.12	0.03	0.14	0.03	-1.34	0.18	-0.54	0.59	-1.34	0.18	Su
	50 Sine	0.18	0.20	0.14	0.23	0.07	0.20	0.14	-0.09	0.93	-0.66	0.51	-0.09	0.93	Im
	50 Sq.	0.32	0.34	0.19	0.19	0.12	0.34	0.19	-0.11	0.91	1.11	0.27	-0.11	0.91	Im
	50 Saw.	0.13	0.15	0.08	0.13	0.03	0.15	0.08	-0.22	0.83	0.23	0.82	-0.22	0.83	Su
	100 Sine	0.12	0.30	0.20	0.33	0.35	0.30	0.20	-0.91	0.36	-0.62	0.53	-0.91	0.36	Su
	100 Sq.	0.29	0.37	0.21	0.48	0.31	0.37	0.21	-0.38	0.70	-0.62	0.54	-0.38	0.70	Im
	100 Saw.	0.15	0.31	0.31	0.35	0.38	0.31	0.31	-0.52	0.61	-0.51	0.61	-0.52	0.61	Su
	200 Sine	0.23	0.20	0.10	0.25	0.13	0.20	0.10	0.38	0.70	-0.16	0.87	0.38	0.70	Su
	200 Sq.	0.11	0.18	0.09	0.18	0.14	0.18	0.09	-0.75	0.45	-0.49	0.62	-0.75	0.45	Su
	200 Saw.	0.16	0.21	0.13	0.26	0.13	0.21	0.13	-0.35	0.73	-0.74	0.46	-0.35	0.73	Im

5	20 Hz	0.06	0.20	0.17	0.23	0.18	0.20	0.17	-0.83	0.41	-0.97	0.33	-0.83	0.41	Im
	200 Hz	0.20	0.24	0.08	0.35	0.17	0.24	0.08	-0.45	0.65	-0.88	0.38	-0.45	0.65	Im
6	2P. (T1)	4.49	5.55	3.74	12.15	7.58	5.55	3.74	-0.28	0.78	-1.01	0.31	-0.28	0.78	Im
	3P. (T1)	5.79	9.84	7.42	14.56	6.33	9.84	7.42	-0.55	0.59	-1.39	0.17	-0.55	0.59	Im
	4P. (T1)	11.26	15.24	8.79	21.53	14.15	15.24	8.79	-0.45	0.65	-0.73	0.47	-0.45	0.65	Im
	5P. (T1)	16.23	21.23	6.88	30.11	20.91	21.23	6.88	-0.73	0.47	-0.66	0.51	-0.73	0.47	Su
	2P. (T2)	20.34	24.63	13.82	40.95	22.44	24.63	13.82	-0.31	0.76	-0.92	0.36	-0.31	0.76	Im
	3P. (T2)	87.11	101.46	20.59	110.56	33.85	101.46	20.59	-0.70	0.49	-0.69	0.49	-0.70	0.49	Su
	4P. (T2)	118.69	135.76	22.65	170.58	59.73	135.76	22.65	-0.75	0.45	-0.87	0.39	-0.75	0.45	Im
	5P. (T2)	136.21	173.48	29.30	197.61	54.34	173.48	29.30	-1.27	0.20	-1.13	0.26	-1.27	0.20	Su
	2P. (T3)	10.84	31.47	11.41	42.55	25.68	31.47	11.41	-1.81	0.07	-1.24	0.22	-1.81	0.07	Su
	3P. (T3)	15.00	44.58	23.15	48.24	33.59	44.58	23.15	-1.28	0.20	-0.99	0.32	-1.28	0.20	Su
	4P. (T3)	24.61	47.85	18.68	71.57	45.45	47.85	18.68	-1.24	0.21	-1.03	0.30	-1.24	0.21	Su
	5P. (T3)	42.38	60.85	31.29	68.19	35.88	60.85	31.29	-0.59	0.56	-0.72	0.47	-0.59	0.56	Im
													Total	56.25%	Im.

Table R-1: Table of Z-Scores comparing the SSUS participant to the main study participants. Test numbers 1 – RT (ms), 2 – Amplitude Detection (mA), 3 – Amplitude Discrimination (WF), 4 – Frequency Discrimination (WF), 5 – Temporal Discrimination (WF), 6 – Temporal Gap Detection (ms), Im. – Implanted, Su. – Superficial, ZScore 1 – SSUS vs. Implanted, ZScore 2 – SSUS vs Superficial, Z Score 3 – SSUS vs Both. (N.B. number denoted in type from test 4 refer to baseline frequency in Hz)

"There is one more thing...

...It's been emotional."

Big Chris – Vinnie Jones – Lock, Stock and Two Smoking Barrels (1998)