Vibrotactile Feedback for Application on Mobile Touch Screen Devices: Effects with Age

By:

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A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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Faculty of Engineering
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January 2016

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Summary

This thesis has investigated vibrotactile interactions for touch screen devices related to age, the study developed distinguishable vibrotactile patterns for evaluation by younger and older people, in order to inform the design process for the development of a haptic language.

The study of haptic perception validated that the optimal sensation to vibration for both age groups is in the range of 100-300 Hz, which guides the design of the future vibrotactile patterns development.

As part of the human perception study carried out, it was found that two of the seven semantic differential pairs tested, *'slow-fast'* and *'light-heavy',* are suitable to describe the feelings of haptic feedback for younger people however there was no clear agreement for older people. It is recommended that the magnitude estimation techniques can be used for the future experimental design.

Finally, this study shows that haptic language could be developed using vibration with the respect to the parameters of amplitude, frequency, and frequency ramping. The amplitude of vibration plays a key role in determining whether people can adequately sense the message, whereas the frequency can be used to imply meaning.

The study found that a signal at 200 Hz could be understood to have a positive meaning for the vibrotactile interaction. Frequency ramping could be an essential parameter to design a negative vibrotactile interaction, compared to amplitude ramping that has no significant influence for perception. Most people would require a certain level of training to learn a haptic language because humans have no pre-conception of vibrations other than as an alert. It is suggested that a scenario should be provided to the subjects for the valuation.

Key words: haptic language, finger sensitivity, vibrotactile feedback, touch screen devices

Acknowledgements

I would like to thank my supervisors Dr Jennifer Rowson and Dr Matt Carré, for their support throughout the past four years. I would also like to thank Shun Hing Education and Charity Fund, the Foundation set up in memory of Dr William Mong and Dr Shan Fu, Shanghai Jiaotong University, China, offer me the opportunity to study PhD at the University of Sheffield.

I would also like to thank many people who have given me support and advice during my PhD, including: Jamie Booth for help with equipment design; Ben Kitchener for support with electrical issues; PhD students and research assistants within the Human Interaction Group (HIG) and in Department of Mechanical Engineering who have been volunteering for my testing; Jean Stevenson for help with recruiting senior people from University Third Age (U3A) society and all those who volunteered to help with experiments.

Finally, I would like to thank my great parents, Mrs Kailan Chu (储开兰) and Mr Zhigang Zhang (张志刚), to whom this thesis is dedicated, for their love and constant support through my life.

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1 Introduction

This thesis investigates haptic interactions for touch screen devices in relation to age. Haptic interactions use a person's sense of touch in order to convey a sensation where the meaning can be recognized or easily learned. Haptics can be used: to mimic the surface texture, force feedback or provide vibrations. For instance, medical students can do a surgical training through a haptic interface on the computer that provides the feeling like blood vessels or muscle tissue. Aircraft pilots can operate a controller with force feedback that simulates the upward force of engine. Users can enter texts on a smartphone (e.g. iPhone) that vibrates to create the sensation of a physical button. Therefore, this work has investigated the limits of finger sensitivity for perceiving and discriminating in vibration with respect to amplitude and frequency, and then proposed a variety of vibrations for human evaluation in order to inform the design of haptic language on touch screen devices.

As technology of touch screen devices is being developed and expanded, people are becoming more reliant on it for communication and information. A UK statistic revealed that 66% of people aged between 16 to 24 years old and 60% of 25 to 34 years old had a smartphone by the end of 2012, compared to 19% of 55 to 64 years old and 3% of over 65 years old [1]. Similar results were found in the usage of tablets. This trend for smartphones and tablets has emerged since 2007 and it can be predicted that they will dominate the future market of electronic devices.

As people age, the abilities of their senses (vision, hearing, taste, smell, touch) decline and become less accurate with advanced ageing [2]. The distribution of population (Figure 1.1) in England and Wales shifted from a pear shape into an apple one in hundred years [3]. The reason is that people are living longer with the dramatically improvement of healthcare service for decades yet the birth rate remains at the same level. This process leads to an increase of the number of people above 65 years that is projected to reach 12.67 million, as well as people between 55 to 64 years old reach 8.20 million in UK by 2020 [4]. Most 60-year older people in the developed countries will live average 23 additional years [5].

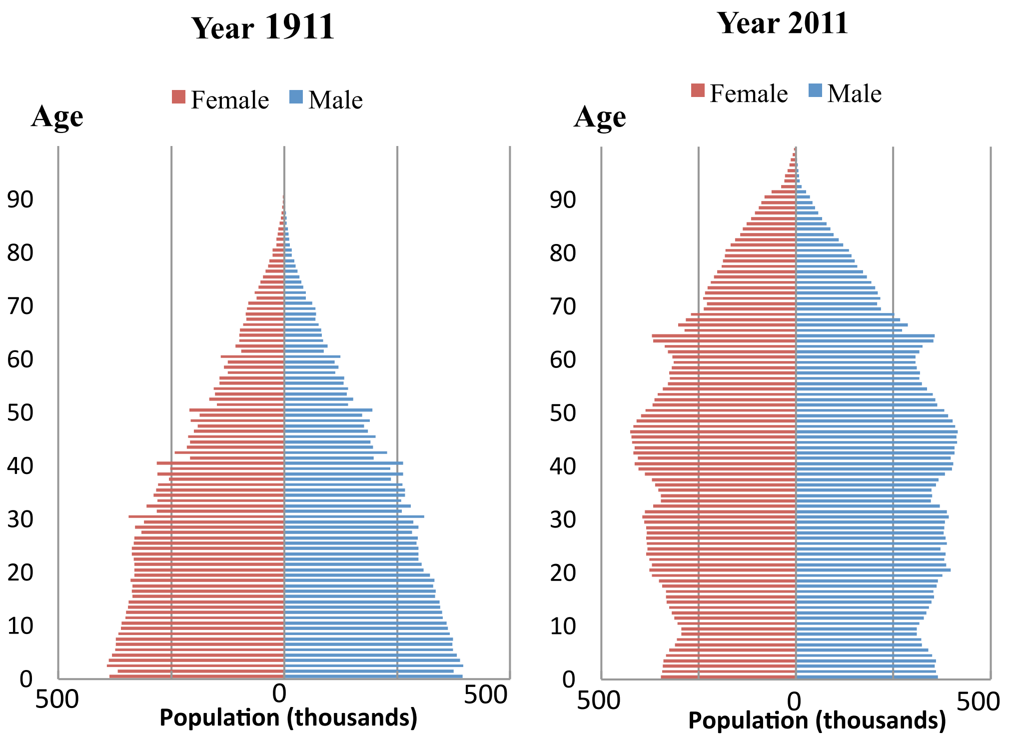


Figure 1.1 - The population structure of England and Wales between 1911 and 2011 (Data source: census 2011)

Older people are willing to use modern technology, but devices are often complex to operate and not designed to be age-friendly. Current populations who are reaching into retirement are largely happy using modern technology. However, the problem is that if the electronic devices are not sufficiently well designed with their projected abilities in mind they will not be able to continue using them.

Therefore, products such as large font books, big button phones, and easy-grip cooking utensils have all been developed to help older people for daily activities.

Touch screen devices have included assistive aids to improve the usability. Visual, audio and haptic feedbacks are commonly established on smartphones yet haptic feedback has little variety other than a single frequency of vibration with the same amplitude. There is no haptic feedback in most tablets. The reason is that haptic interaction is more complicated to develop on touch screen devices than visual and auditory cues [6] as well as the touch sensation declines with ageing [7, 8]. Hence, current haptic technology has limitation of design and development, which leads to a huge challenge to develop a haptic language with ageing in mind for applications such as smartphones.

1.1 Mobile phone evolution

The first handheld mobile phone was invented by Motorola in 1973. Since then, the wireless telephone technology has been increasingly developed from the first generation until the fourth generation. In 2012, UK launched its 4G mobile networks by EE Company.

Figure 1.2 - Mobile phone models from 1980 to 2010

Mobile phone models in Figure 1.2 have been developed by Kyle Bean, a graduate from University of Brighton. From the left to right, the features of each phone are as following:

- 1985 – Motorola dynaTAC [330(h)×45(w)×89(d) mm , 790g]
- 1988 – Nokia-Mobira Cityman 1320 [185(h) × 43(w) ×79(d) mm, 750g]
- 1991 – AEG Teleport-C [160(h) × 35(w) ×75(d) mm, 594g]
- 1993 – Ericsson GH198 [141(h) × 29(w) ×59(d) mm, 330g]
- 1996 – Motorola MicroTAC 650 [140(h) × 26(w) ×56(d) mm, 221g]
- 1998 – Siemens C10 [137(h) × 22(w) ×55(d) mm, 165g]
- 2001 – Nokia 3210 [123.8(h) × 22.5(w) ×50.5(d) mm, 151g]
- 2005 – Motorola Razr V3 [98 (h) × 13.9(w) ×53(d) mm, 95g]
- 2009 – Samsung Tocco [95.9 (h) × 11.5(w) ×55(d) mm, 100.6g]

It can be seen that the most obvious physical change is that the size of mobile phones becomes smaller with the development of microchip processor and improvements of battery technology. Another change is that mechanical keyboard is replaced by a touch screen with the development of software engineering. The touch screen design provides more intuitive, engaging, and natural experience. This evolution has expanded the usage of mobile phones that once were only for the most important businessmen and are now accessible to all, from a 10-year child to an 80-year adult.

1.1.1 Analogue mobile phones

Car telephone devices were widely used before the first true mobile phones were invented. However, that had heavy battery packs and worked as a separate handset connected via a length of wire. Motorola truly revolutionized the industry with the launch of the first mobile phone DynaTAC 8000X shown in Figure 1.2. From 1980s to 1990s, mobiles phones have been hugely improved in performance and usability.

1.1.2 Digital mobile phones

The second generation of mobile phones started to replace the previous one by using digital instead of analogue transmission since the late 1990s. The digital mobile phones established a new feature of text messaging, called SMS, and also introduced the functions to access media contents such as ringtone on mobile phones.

Besides, the size of 2G mobile phones became smaller and the weight was reduced toward 100-200 gram. This improvement was accomplished because of the technological innovation such as advanced batteries and the improvements of energy-efficient electronics. The larger distribution network of phone stations provided also helped to increase the usage of mobile service.

1.1.3 Mobile broadband networks

Though 2G phones began to increase in usage for people’s daily lives all over the world, a new trend commenced in terms of demand for larger data access (e.g. connect to the internet) and higher processing speed. The 2G networks were not well designed to fulfill this job. Therefore the third generation (3G) mobile phones have been developed.

The main innovation of 3G mobile phones is that the technology of circuit switching has been replaced by packet switching for data transmission in 2G networks. For instance, 3G networks process data at rates of 0.2 Mbit/s up to 20s Mbit/s. The first commercial 3G networks were developed by NTT DoCoMo in Japan in May 2001, using the WCDMA technology. Then, Apple launched its first 3G smartphones in 2007. Thereafter, 9% of the total mobile phone subscribers started to use 3G networks worldwide.

1.1.4 Mobile ultra-broadband networks

In 2012, 4G networks were launched in the UK. 4G systems provide mobile ultra-broadband Internet access as a successor of 3G networks. OFCOM targets its number reaching 98% of UK population in the near future.

In summary, mobile phones became smaller and lighter from the first generation till now. The touch screen replaced the mechanical keyboard and the usage is projected to be widespread. Mobile networks became digital and provided larger data access and higher processing speed. As technology continues to be advanced, mobile phones will become thinner and lighter. The size of touch screen will be increased. Smartphones and tablets will be seen as essential tools to the whole population for social networking.

1.2 Usage trend of mobile phones

Mobile phones have become a common communication tool in people's daily lives and have been available in the UK since 1980s. According to the report from OFCOM [9], there were 95% of UK adults aged 16 above have a mobile phone until 2014. Meanwhile, the smartphone and tablet ownership is 61% and 44% respectively.

1.2.1 Usage by ages

Continuous Household Survey (CHS) [10] conducted a survey about mobile phone ownership by age in the Northern Ireland. The results (Figure 1.3) revealed that 70% of people who are over 60 years old have a mobile phone in 2009, comparing to younger group aged 16-29 accomplishing the same goal in 2001. The percentage in the population aged 16-59 was much higher than people aged 60 above from 1990 to 2009 and the number in older group was growing slower than any other age groups.

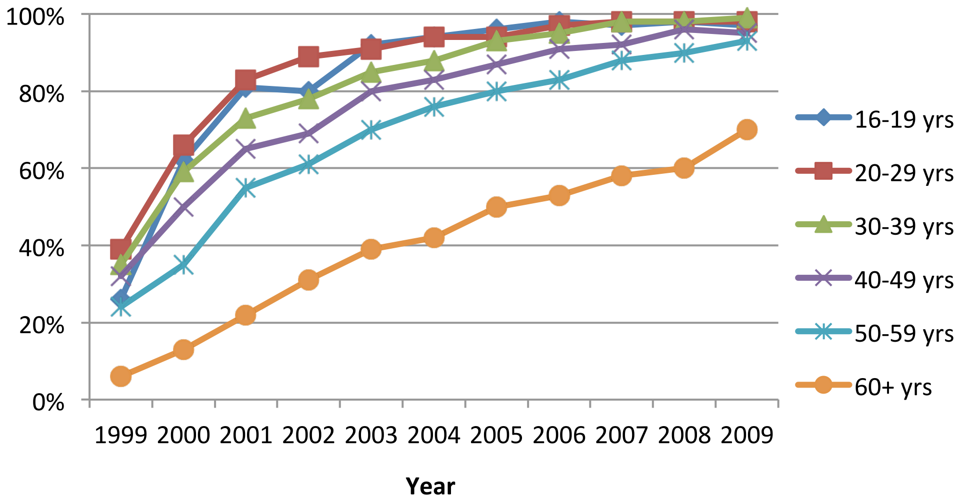


Figure 1.3 - UK mobile phones ownership for all ages (data source: Continuous Household Survey)

1.2.2 Usage by smartphones

OFCOM has published the ownership of smartphones in the UK by 2012 [1]. Figure 1.4 shows a comparison of subscribers of mobile phone and smartphone within the population of 16-24 years old, 55-64 years old and 65 years above. The number of smartphone ownership reached 66%, 19% and 5% respectively in 2012. The mobile phone take up remained the same level (over 90%) in younger group whereas the percentage in older group reached 70% in 2011 and decreased to 68% in 2012. However, the smartphone take up in younger population accomplished the goal of 50% in 2011, compared to only 7% of people aged 55-64 and less than 1% of people over 65 years in 2011. The latest OFCM report [9] revealed that the number of tablet usages reaches 49% of the population aged 16-24, 35% of people aged 55-64 and 22% of people over 65 years in 2014. The number is predicted to increase over 50% in the next five years. When these people reach their retirement, the number of smartphone and tablet ownership for older people will increase dramatically.

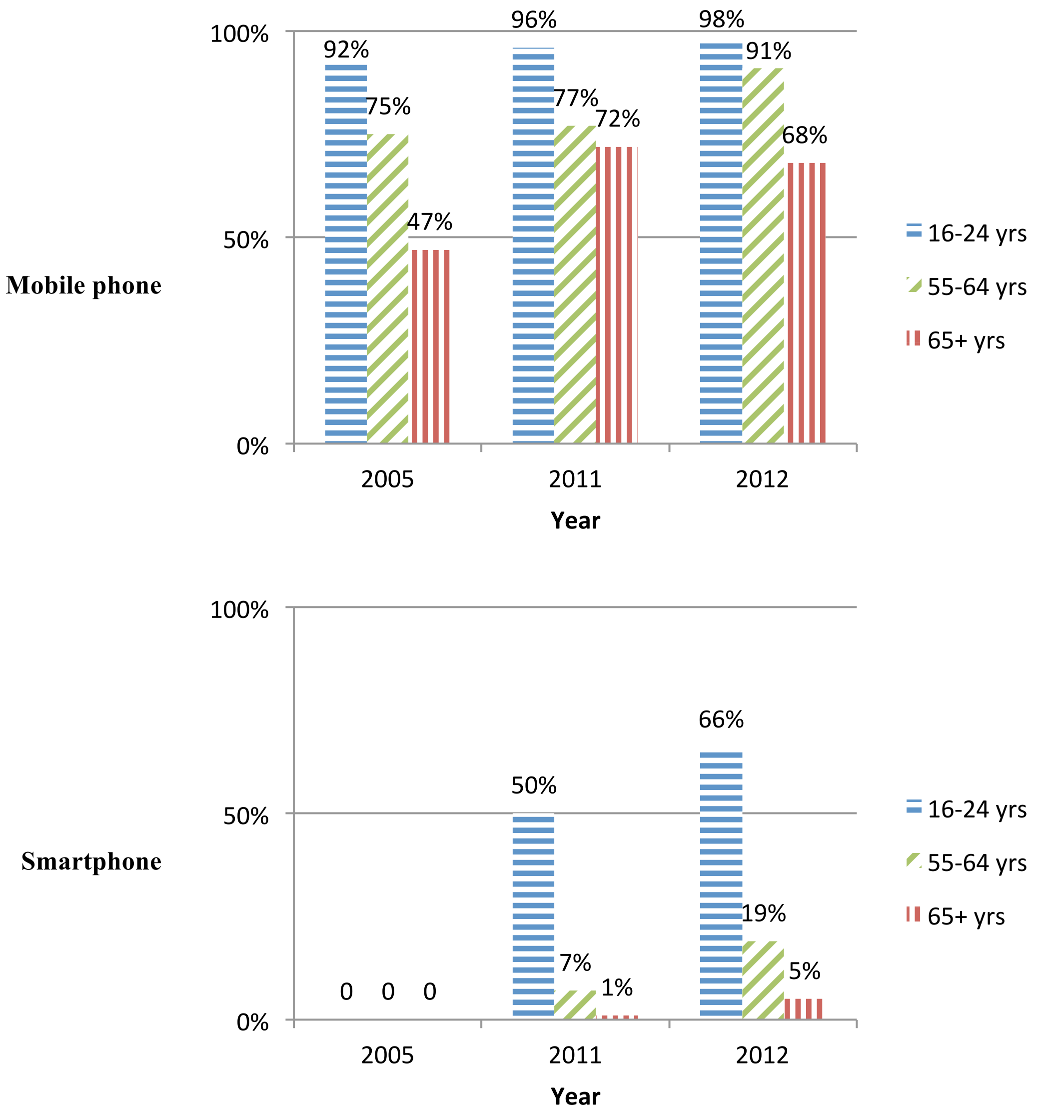


Figure 1.4 - Mobile phone and smartphone take up between younger and older people in the UK

From Figure 1.4 it is clear that younger and older people have greatly different adaption to smartphone. OFCOM [11] concluded that the access to a wider range of new communication technologies is more likely accepted in the younger generation rather than older generation after comparing the subscription of eight modern electronic devices such as 3G handset and digital TV. The reason why older people don’t adopt to new technology is that they don’t feel the new technology is designed for them and most of them have less education of modern technology. Hence, older people think these new electronic devices don’t make their life easier.

In summary, 95% of UK population has a mobile phone in 2014. Smartphones and tablets start to dominate the current market. Older people have less motivation to adopt modern devices than younger people. 66% of people aged 16-24 years had a smartphone, compared to 19% of 55-64 years old and 5% of 65 years above in 2012. However, it can be predicted that current population who are reaching retirement will expand the usage of touch screen devices. The number will increase to 50% of older generation in the next five years. The problem is that if these touch screen devices are not well designed with ageing in mind, the future older people may not continue using them.

1.3 Design for ageing

Ageing issues obviously affect the design of products. Ageing-friendly products are required the assistive aids or re-designs as people age their abilities change and deteriorate for everyday activities. Thus, different products have different solutions, for instance, easy-grip utensils and big button mobile phones.

However, some of them are not designed appropriately for older people. The equivalent design in Figure 1.5 (b) can help old people to have a tea service but looks poor and not suitable to enjoy a sophisticated life-style.

(a) Common tea service **(b) Equivalent assistive devices for tea service**

Figure 1.5 - Products for tea service

Big button mobile phones are often poorly designed as they focus on functional designs not styles. Figure 1.6 shows that a big button phone looks ugly compared to smartphone (e.g. Samsung Galaxy S3).

(a) Smartphone **(b) Big button mobile phone**

Figure 1.6 - Mobile phones for older people

Therefore, in order to design ageing-friendly smartphones, the challenges are that which features of the phones are required to adapt older people's abilities and how to improve the usability in an appropriate way as smartphones are complex devices that have a variety of basic and advanced features (lists of features of Samsung Galaxy S3 can be found at Appendix 1). Calling and messaging are the basic functions, which are easy to re-design for older people such as larger fonts or bigger layout of virtual keyboard. Haptic technology can be one of the solutions to provide an additional aid for advanced features, especially for visual impairments.

1.4 Research drivers

The development of haptic language in vibration can be applied to convey information as an alternative communication channel. For instance, the future smartphones can transfer emotional expressions such as angry or delighted messages by vibrotactile feedback rather than an alert message on current smartphones. The greatest challenges of haptic language development are to define a system from the objective stimuli to represent a variety of subjective responses and develop haptic devices to meet human's capability. In order to achieve the above goal, this study aimed to initially find the finger sensitivity of haptic feedback on touch screen devices in different populations, and develop distinguishable vibrotactile patterns for the evaluation of younger and older people, in order to ensure accessibility for all the populations into later years of life and inform the design process for the development of haptic language. This study would answer the following research questions (RQ1 and RQ2):

> **RQ1**: What is the threshold of finger sensitivity of younger and older people when interacting with haptic feedback in vibration?
>
> **RQ2**: What kind of vibrations with respect to amplitude and frequency changes can be distinguished for younger and older people as a haptic language?

The objectives of this study are divided into four parts:

1. To analyze the vibrations on different smartphones.
2. To validate threshold of finger sensitivity and the discrimination in vibration with respect to amplitude and frequency changes in different populations.
3. To investigate the subjective descriptions of the haptic feedback available on smartphones.
4. To identify the vibrations that could represent common notifications of smartphones for the haptic language development.

1.5 Thesis walkthrough

This thesis commences with an introduction of haptic technology: mobile phone evolution, the usage of smartphone in the UK market, and the ageing issues of smartphone design. Chapter 2 reviews the haptics research, the design of touch screen devices as well as the haptic perception related to the development of haptic language. Chapter 3-6 explains the details of all the experimental design, equipment and results dedicated to each objective. The discussion and conclusions are at the end. The structure of thesis is shown in Figure 1.7.

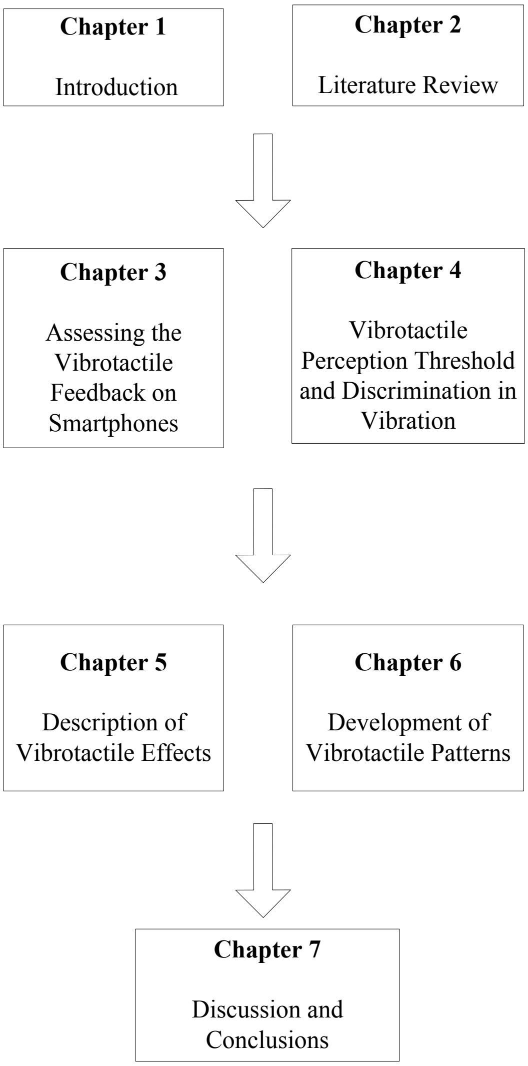


Figure 1.7 - The structure of thesis

2 Literature Review

Haptic language can be utilized through touch screen devices in order to provide physical feedback and convey information. This chapter reviews the previous work in relation to its design. It starts with an overview of haptics research in computer science, robotics and neuroscience. Then, it reviews recent research work related to touch screens, designing for ageing, and interactions with touch screens. It also covers research that has been carried out in the psychology field such as haptic reception and psychophysical methods. The structure of literature review is shown in Figure 2.1.

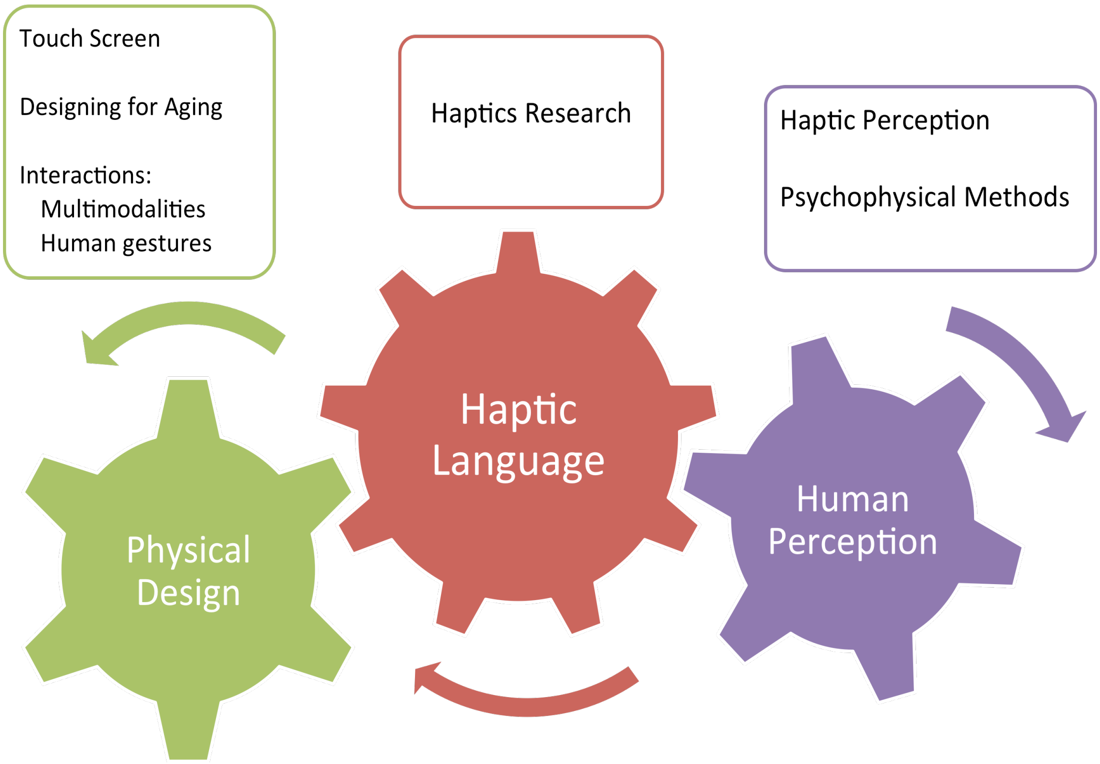


Figure 2.1 - The overview of literature review

2.1 Haptics research

Haptics is a technology that utilizes motions, vibrations or forces to improve the human sense of touch. Haptic research covers a multidisciplinary field, which includes computer science, robotics, and neuroscience. The first haptic devices were used in nuclear engineering research in US by Goertz [12] in 1952 and in Europe by Vertut et al. [13] in 1976. The following sections summarize the main research work of haptic technology.

2.1.1 Haptics in computer science

Haptics has been carried out mainly in computer science and can be applied to a number of applications with computers. In recent years, computers have become faster, smaller, smarter and cheaper enabling the development of new algorithms required exploiting haptics in simulations of complex interacting scenarios with realistic displays, forces, deformations and sounds. Virtual reality simulators already use haptic feedback in flying, driving and surgical simulation and training. For instance, a force feedback (providing by electromagnetic motors) system measures the movements of the user’s fingers, hand, and/or arm and senses any forces he/she exerts; calculates the effect of exerted forces and the resultant forces that should act on the user; then presents the resultant forces to the user’s fingers, wrist, and/or arm [14]. Pyo et al. [15] proposed an haptic interface to simulate friction force for realistic 3D haptic rendering. They used the electrostatic parallel actuator to generate mechanical vibration in combination with the dielectric elastomeric actuator to generate electro-vibration, which feels like rubbery when fingertip slides over the surface. Haptics is also used in the development of new interfaces. Ryu et al. [16] developed a 3×3 haptic keypad system using an array of actuators for interacting with a graphic display unit. Another application is a locomotion device that creates sense of walking in virtual environments. Cakmak and Hager have developed a prototype (Figure 2.2) for walking, running, jumping and sitting in a virtual environment in 2014 [17]. The prototype consists of a ring construction rotated through 360 degrees and a belt system fixed onto the user in combination with different sensors located in the ground floor.

Figure 2.2 – A locomotion device called Cyberith Virtualizer

Haptics has been well developed in the entertainment industry since 1970s. These reviews [18, 19] gave an overview of haptics development in PC and console gaming industry. Nintendo Wii utilized haptic feedback into its controller to enhance the gaming experience [20]. New technologies and innovations need to be fully investigated in this area. The big challenge is that the haptic system has to be intuitive and robust with the cheaper expenses for different scenarios and can also provide a real-time, realistic, and enjoyable feedback for players.

Touch screen devices enable users to provide input to the computer through fingertips. Hollinworth [21] investigated the possibility of using *gestural input* through multi-touch screen for older people. Roudaut et al. [22] proposed a *gesture output* device. When user moves their finger in a gesture such as a path of 'N' on the device, it replies a gesture such as a heart-shaped path in order to inform new emails or messages from a friend. Gomes et al. [23] proposed a *flexible* smartphone that changes its shape to inform users different notifications. Yet, these techniques are either a concept or in prototype stage, that have not been established in current touch screen devices. The most common haptic feedback on touch screen devices is vibrations. The devices are limited with vibrations at the same amplitude and the single frequency. There is astonishingly little variety in the approaches of haptic feedback on touch screens other than vibrations. One trend is that further research focuses on providing a physical key-click feedback when typing on a virtual keyboard in order to locate and identify of visual objects on touch screen [24]. Sadly, current haptic technology has a lot of difficulties to achieve this goal with a single actuator. Another trend is to create haptic feedbacks that users can perceive as certain meanings of a haptic language, similarly like the meanings of red/yellow/green traffic lights to us [25, 26].

Lately, wearable devices are bringing new challenges into haptic research, like Google glasses, Apple watch. The challenges are that wearable devices not only need to be light, comfortable to wear, but also provide intelligent and real-time feedback with large-data processing and interpretation. As well as that, evaluation of effectiveness and efficiency of a wearable system is important to ascertain user acceptance. The energy supply of wearable devices is also a huge challenge [27]. Besides, current wearable devices are required of evaluation for older people.

2.1.2 Haptics in robotics

Robot devices have been shown to be rather effective as assistive devices for older or motion impaired people [28, 29], or as augmentation devices to increase force performance [30] or as a rehabilitation system for the patients with lost gait and manipulation capabilities [31]. As well as that, “physical human-robot haptic interaction” poses research in studying the interactions and communications between human and robot involved man-in-the-loop issues [32, 33]. The development of haptic force/contact interface poses the research in investigating a variety of electromechanical or mechanical actuators to generate force sensation [34]. In this area, one of the challenges is to create haptic interface through electromechanical actuators or connectors at a small scale that matches high spatial resolutions of the fingertip. Pan et al. [35] developed a new approach using nanowires that are a LED-based sensor array to offer a spatial resolution of 2.7μm enabling the development of highly intelligent human-machine interfaces. Hence, fully understanding human ability to perceive haptic interface with the fingertip, which is discussed in section 2.5, may expand haptic research into new applications.

2.1.3 Haptics in neuroscience

Haptic devices have tried to contribute into neuroscience for years but not influenced each other directly. Neuroscience has taken existing haptic devices to utilize in therapy. Researchers aim to stimulate the central nervous system by haptics, which could be utilized in cortical implants, peripheral nerve stimulators, traditional mechanical force production in muscles, or force transduction in tactile and kinesthetic mechanoreceptors [36, 37]. Neurorehabilitation is one of the main significant applications. It utilizes haptic devices to deliver the intensive and repetitive therapy for neural impairments [38]. This kind of haptic applications can benefit for the improvement of the rehabilitation and adoption of the advanced orthotic devices.

2.1.4 Outcomes for planned study

The research shows that haptics technology is related to many subjects especially in computer science, robotics and neuroscience. The applications of haptics include force feedback for flight, driving and surgical stimulation and training; vibration feedback on touch screen devices; force transduction in tactile and kinesthetic mechanoreceptors for neurorehabilitation. Thus, this thesis focuses on vibration feedback on touch screen devices for the development of haptic language.

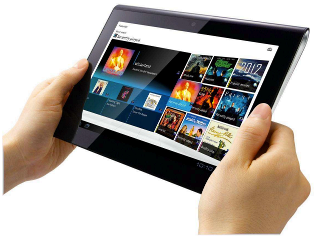
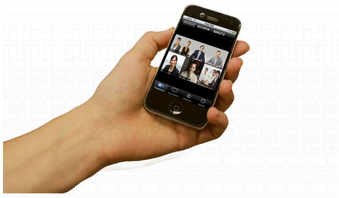
2.2 Touch screen devices

Touch screen devices became popular as modern devices with their intuitive design and ease of interaction, such as smartphones, tablets, or ATM cash machine everywhere. There is a trend that touch screens are replacing mechanical keypads due to their intuitive operation, software flexibility, and saving space [39].

2.2.1 Touch screen size

Touch screen devices can be categorized into three main groups, shown in Table 2.1. Current haptic technology, like vibrations, is wide spread on small-size devices but hardly being used on larger devices like ATM machine. The difficulties are that larger devices have limited controls on the machine compared to the expanding features and a variety of functions. They have become less constructive and more complex to manipulate, especially for motor and visually impaired users [40].

Table 2.1 - Different examples of touch screen devices

Category	Touch screen Devices	Screen Size	Display
Large-size	Kiosk, ATM, HDTV	Larger than 13 inches	
Medium-size	Tablets	7-10 inches	
Small-size	Smartphones	2.5-6.3 inches	

There is still an opportunity to start developing a haptic language on small devices and touch screens with the potential to expand to the larger devices once it has been fully established.

2.2.2 Virtual keyboard on screen

Since 1980, many studies have investigated the usable touch button size on a virtual keyboard. Button size is one of the most important design features, as well as the spacing between buttons and location on the screen. Optimizing these parameters enables users to perform task in shorter time with higher accuracy and better satisfaction. Colle and Hiszem [41] evaluated four virtual button sizes (the side length of square is 10, 15, 20, 25 mm) combined with two button spacing sizes (1, 3 mm) on index finger. The results showed that the side length of button size at 20 mm was sufficiently large for text entry on a kiosk but spacing sizes have no significant effects on text input. Parhi et al. [42] studied one-handed thumb interactions with five button sizes (the side length of square is 3.8, 5.8, 7.7, 9.6, 11.5 mm) at nine locations (3×3 grid) on a 3.5 inch PDA. They recommended that the side length should be larger than 9.2 mm for a single input. Besides, they evaluated another five sizes (the side length of square is 5.8, 7.7, 9.6, 11.5, 13.4 mm) at four locations (2×2 grid) and found out that the side length should be larger than 9.6 mm for serial inputs. Park and Han [43] continued to study the design of button sizes (the side length of square is 4, 7, 10 mm) at 25 locations (5×5 grid) on a 3.5 inch screen and made the similar conclusions that the side length of touch button size at 10 mm should be the best to improve user performance.

Taking account of ageing issue, Jin et al. [44] investigated nine levels of button sizes (the side length of square is 6.35, 8.89, 11.43, 13.97, 16.51, 19.05, 21.59, 24.13, 26.67 mm) with five spacing sizes (0, 3.17, 6.35, 12.37, 19.05 mm) on a 17 inch touch device for older adults. They found out that the length of 16.51 mm and 19.05 mm are preferable by older people when the spacing size was 6.35 mm. Kobayashi et al. [45] suggested that the target size on small or medium touch screen should be larger than 8mm as well as the same distance of spacing size for older people.

In short, these studies show that button size has a significant influence on design of touch screen devices. The side length around 10mm has better usability on small-size screen, whereas on larger screen (>6 inch), it should be larger than 16 mm for older people.

2.2.3 Outcomes for planned study

Touch screen devices commonly have three sizes in current market: small, medium and large. Current haptic feedback, like vibration, is widespread on small-size devices but hardly being used on larger devices. Virtual keyboard design is a key topic in touch screen research. Most studies show that the button size (the side length of square) with 10 mm is appropriate for small-size touch screen whereas the screen size larger than 6 inches, the side length should be larger than 16 mm. Hence, haptic feedbacks developed in this study are in the range of 10-20 mm (the side length of square) on small-size touch screen devices.

2.3 Touch screen devices design for ageing

Hawthron [46] reviewed the research work in older people's ability of vision, speech and hearing, psychomotor, attention, memory and learning, intelligence. He proposed the considerable scope for human-computer interaction (HCI) design for the older population, that future research should look at the evaluation of specific design for older users; how problems due to ageing are distributed (not only for 65 years plus group); the predicted ability of older people deteriorated; the interface style design for the motivation of older people; the bias that most current research experimental subjects is towards younger and highly educated students or colleagues, etc. These may be caused that modern devices have more barriers for older people to use and learn. Therefore, it is essential to investigate how to reduce the barriers for current older people, in an attempt to ascertain the potential usage of touch screen devices for people who reaching their retirement.

2.3.1 Barriers for older people

In general, older people are willing to use modern devices but do not feel that devices are designed with ageing in mind and have difficulties to interact with. Czaja and Lee [47] found that the designers of information technology (IT) do not consider age-related changes due to the fact that the older group are assumed as not active. Most designers have less understanding of how to accommodate older people's needs. Similar research has been carried out on mobile devices for designers and developers [48].

Other barriers are that older people are isolated because of age-related diseases, and require more care-giving responsibilities. The benefits of portable, handheld, and touch screen devices would greatly improve their quality of lives and increase social activities. However, Kurniawan [49] found out that older people are passive users of mobile phones because they often have a greater resistance to unfamiliar technology. Most new devices are perceived as a "gimmick" or a "toy" rather than a practical tool for older people. It is reported that older adults consider mobile phones as an assistive device of emergencies, whereas younger people take mobile phones for most social activities [50].

2.3.2 Design for older people

Becker and Webbe [51] proposed a comprehensive framework of designing handheld technology for older adult users in four aspects:

a. *Older user ability*: the decline of vision, hearing, motor skills, cognition, literacy-age, and technology skills [2, 52].

b. *Environmental factors*: the integration of hardware, software and usage environment on devices.

c. *Usability quality*: the evaluation of time to learn, speed performance, error rate, retention over time and subjective satisfaction [53].

d. *Technology objectives*: the benefits of information dissemination, health management, scheduling appointments and social interaction.

Dickinson et al. [54] raised the awareness that, to study the HCI research for older people, researchers should consider the different performance between the younger and older as well as the diversity of older people. They summarized some methodologies that can help to design experimental testing for older people. For instance, the researcher can carry out cognitive testing before the experiment begins. Older subjects could be asked to describe what they are doing to check if they understand the procedure. It is efficient to recruit older people from local charities (e.g. church groups) and media (e.g. newspaper). Further research can be found in [55-59] about designing, implementing, and evaluating mobile devices for older adults.

Recent research has been carried out on touch screen devices to evaluate the usability for older people. Siek et al. [60] demonstrated that older subjects can physically interact with personal digital assistant (PDA) at the same level as younger subjects. Hourcade and Berkel [61] found that 65-84 year olds have a lower performance than younger people when tapping on PDA, but in the same accuracy of gestures, for instance touching, straight-steering or circular-steering on targets. Bradley et al. [62] has evaluated tablets for older people. The results revealed that most devices are lacking in the clarity of label meanings, icons are too small to interact on the screen, and devices are too sensitive or not sensitive enough, and also unexpected displays (e.g. pop-up windows). Stößel and Blessing [63] found out that gestures designed with younger people in mind may not be suitable for older people. They suggested that gesture-based interaction patterns should suit to older people’s needs and abilities. Kobayashi et al. [45] further evaluated the basic gestures such as tapping, dragging and pinching on touch screen devices within 20 older subjects. They reported that older people performed well except for tapping on small targets.

Dragging and pinching were easier and more comfortable than tapping for older people.

2.3.3 Outcomes for planned study

The research shows that older people have difficulties of using modern devices due to their declining ability of vision, hearing, motor skills, cognition, and literacy skills. They feel that modern devices are not designed for them as the lack of evaluation by older generation. However, older people can perform well on touch screen devices at the same level of younger people. Therefore, this thesis evaluates the older groups of haptic feedback for the development of haptic language.

2.4 Human computer interactions

Human computer interaction (HCI) research is concerned with multimodal perception, cognitive and intuitive mental process, and motor actions in relation with human activities. Multimodal perception is a combination sense of visual, hearing and touch, etc.

2.4.1 Multimodality feedback on touch screen devices

Multimodal feedback can improve the usability of touch screen devices. Visual and auditory cues are known to provide highly precise spatial and temporal information, respectively [64]. Haptic feedbacks, such as vibrations, use a person's sense of touch to enhance the user-device interaction. Yantani et al. [65] found that visual feedback with the assistance of haptic feedback can offer better spatial coordination support in mobile navigation devices, and they can complement each other to reduce the overload of spatial information. Audio-haptic aids that combining auditory with haptic feedback are another applications on touch screen devices. Chang and

O'Sullivan [66] used multifunction transducer technology (MFT), a speaker that can generate audible and vibration from an audio signal, for the evaluation of audio-haptic feedback on mobile phones. They found that 83% of subjects felt audio-haptic phones better compared to non-haptic phone and the quality of audio perception was significant correlated with phones including haptic feedback. Wilson et al. [67] investigated the relationship between audio-haptic modalities and varying frequency. The results showed that best detection performance was found when the frequency of auditory and haptic modalities was equal or close. Hoggan et al. [68] found that audio-haptic feedback could improve the quality of perceiving visual buttons on touch screen devices, yet there was no positive correlation to show that further improvement in performance can be achieved by combining visual and audio-haptic together. Pathak and Kumazawa [69] further evaluated the pleasantness of multimodal feedbacks on touch mobile devices and proved that audio feedback can improve the performance significantly when adding to haptic feedback.

For older people, Jacko et al. [70] studied how multimodal feedback could assist older people when performing drag-and-drop tasks on computers. They found that older people with impaired vision or normal vision performed significantly better when an auditory component was added to visual and haptic feedback. Lee et al. [71] further investigated multimodal feedback on touch screen devices for the benefits to older people and confirmed the similar results that auditory stimulation plays an important role to the visual and haptic modalities.

Hence, haptic feedback can improve the usability of touch screen devices for younger and older people when adding to visual and audio aids.

2.4.2 Haptic feedback on touch screen devices

Haptic feedback is more complicated than visual and auditory interactions. Wüschman and Fourney [6] explained the reasons being that firstly the system of haptic perception is not dependent on two organs, but distributed all over the whole body. Secondly, the transfer of thermal or mechanical energy into human body has to be investigated not only in one dimension (e.g. force in case of touch, pressure in case of hearing), but in a multi-dimension function (e.g. force, pressure, spatial, velocity, acceleration, strain, etc.). Finally, there is no available writing system, like phoneme-grapheme based system that a letter represents a sound, to describe the haptic patterns. Thus, these could be the challenges to develop a haptic language system in the future.

Haptic feedback in vibration, also called vibrotactile feedback, was first introduced in PDAs by Fukumoto and Sugimura [72]. They attached motor actuators to the body of a PDA and assessed the vibrotactile feedback under four different environments. Their study demonstrated that vibrotactile feedback could improve the usability of touch panels, especially in noisy environments. Similar research is presented by Brewster et al. [73] and Nashel and Razzaque [74]. Poupyrev et al. [75] went on to demonstrate that vibrotactile feedback using piezoelectric actuators can improve the task completion time by 22%, when browsing the 2D map on a PDA. Kaaresoja and Linjama [76], who studied vibration generated by motor actuators in a regular mobile phone, found that the duration of vibration pluses should be between 50 and 200ms otherwise vibrotactile feedback would become obscure for human perception.

Hoggan et al. [77] compared the effects of vibrotactile feedback between physical keyboard and virtual button on mobile devices. The results showed that tactile feedback could benefit the performance of text entry of virtual buttons in comparison with a physical keyboard phone. More research [78, 79] have investigated different parameters (e.g. amplitude, frequency, number of cycles, waveform and actuator) affect vibrotactile feedback design on touch screen devices. It is proved that one trend of vibrotactile design on mobile devices is to develop identifiable key-click sensations feeling like interacting with a physical keyboard.

Other haptic sensations have also been studied. Takasaki et al. [80] conducted the experiments of roughness or texture sensation, using surface acoustic wave technique. It is proved that human can recognize the difference of roughness. Further study can be found by Barnes et al. [81]. They concluded that subjects have desirable feelings while a surface is less rough than a fingertip when subject sliding fingertip over rough glass surfaces. Thermal sensation has been carried out in a static and mobile device [82]. It revealed that the palm is more sensitive to temperature changing than other body parts and cold stimuli are more perceivable and comfortable than warm. However, thermal technology is still in the laboratory stage since it is sensitive to environmental changes. Little is known on how to design thermal feedback for touch screen devices.

2.4.3 Human gestures interacting with touch screen devices

From the perspective of human beings, tapping, dragging and pinching are the three main gestures used when humans interact with touch screen devices. The *tapping* gesture is to press the screen with thumb or index fingers; *dragging* is the action of moving displayed text or graphics up or down by touched fingers; *pinching* is the movement of two fingers coming closer or further apart to zoom in/out displays. Users commonly manipulate those gestures with one-handed thumb, two-handed thumb/index finger, two-handed two thumbs which were shown in Figure 2.3.

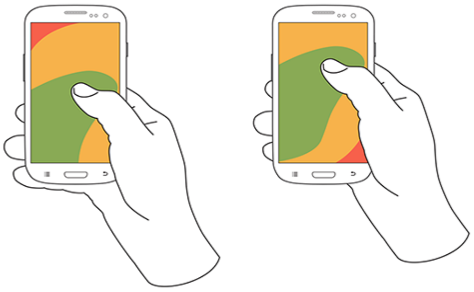
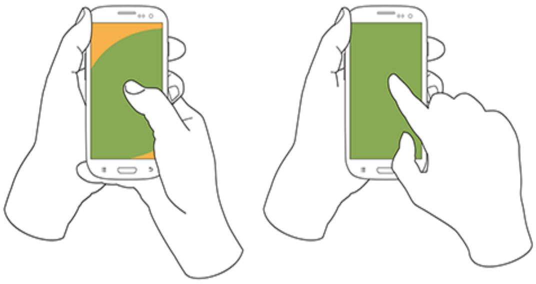
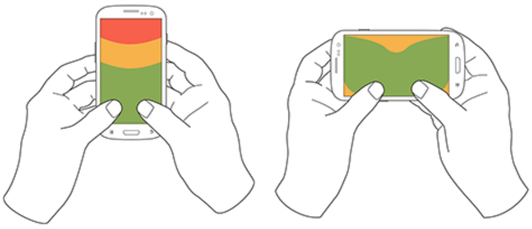
Gestures	Example
One-handed thumb (tapping, dragging)	
Two-handed thumb/index finger (tapping, dragging)	
Two-handed two thumbs (tapping, dragging, pinching)	

Figure 2.3 – Gestures interacting with touch screen devices

Olwal et al. [83] developed a way to combine tapping and pinching gestures into a single direct-manipulation action called ‘rubbing’ with a single hand or tapping with two hands. They suggest that the rubbing technique worked better on smooth and small screen, while the tapping technique was suitable on large one. Similar research is found in [21, 22, 45, 63].

2.4.4 Outcomes for planned study

The research shows that haptic feedback benefits the audio and visual aids as a multimodal feedback for human-computer interaction. Most research proved that vibrotactile feedback could improve the usability of touch screen devices. Thermal and texture sensations are also studied yet still in the laboratory stage. Recent research has been carried out on the evaluation of tapping, dragging, pinching gestures on touch screen devices. Hence, this thesis focuses on the development of vibrotactile feedback with the tapping gesture on touch screen devices to put more effort on the design of haptic language.

2.5 Haptic perception

The human somatosensory system includes the sense of pressure, stretch, stroking, vibration, warm, cold, burning/freezing pain, muscle contraction, etc. It can be divided into three main classes: exteroception, proprioception and interoception [84]. *Exteroception* is the sense of direct interaction with external world such as mechanoreception (e.g. touch), thermoreception (e.g. temperature) and nociception (e.g. pain). *Proprioception* is the sense of posture and movement of our own body (e.g. joint angle), and *Interoception* is the sense of the function of major organs and its internal state (e.g. blood gases and pH).

Haptic perception includes two kinds of sensory system known as cutaneous and kinesthetic. Cutaneous system refers to receptors embedded in skin that can sense stimuli, whereas the kinesthetic refers to receptors in muscles, joints and tendons [85]. From the perspective of somatosensory system, the cutaneous system is limited to exteroception, and cutaneous receptors are most prevalent in the hands, lips and genitals [86]. Furthermore, mechanoreception is related to touch sensation, and mechanoreceptors in the hand can be categorized into four function units:

(a) Merkel cells or slowly adapting Type I nerve fibers (SA I)

(b) Meissner’s corpuscles or fast adapting Type I nerve fibers (FA I)

(c) Ruffini endings or as slowly adapting Type II nerve fibers (SA II)

(d) Pacinian corpuscles or fast adapting Type II nerve fibers (FA II)

2.5.1 Mechanoreceptors

Haptic sensations in the human hand can be understood as the combined result of four kinds of mechanoreceptors shown in Figure 2.4. Each mechanoreceptor responds in a distinctive way depending on its structural features, nerve firing pattern, and depth in the skin [84].

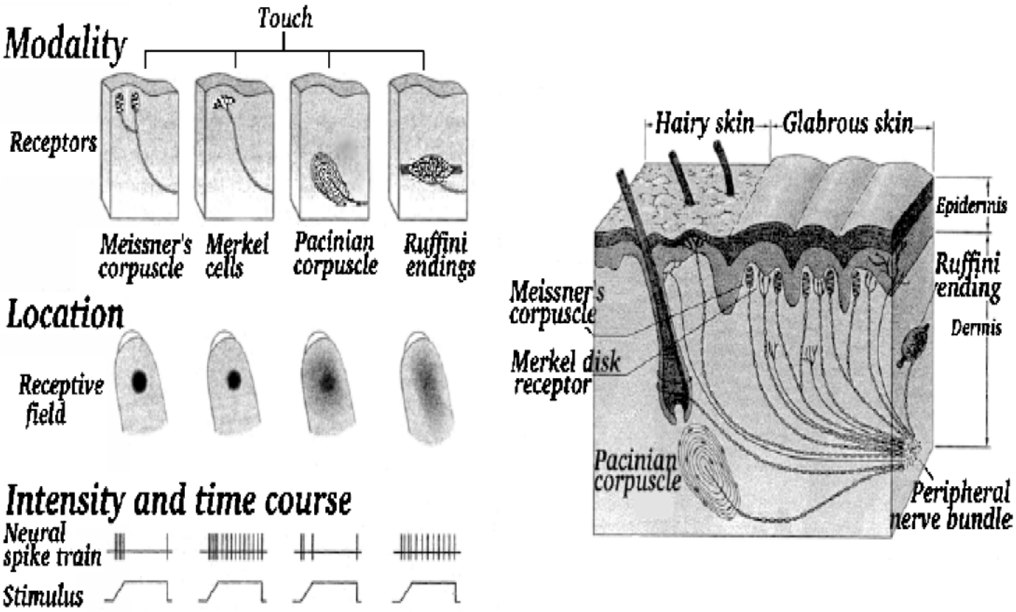


Figure 2.4 - Structure of human skin with mechanoreceptors [84]

The merkel cells and meissner's corpuscles (Type I nerve fibers) are embedded in the superficial layers of the skin at the margin between the dermis and epidermis, 0.5 to 1.0 mm below the skin surface, whereas ruffini endings and pacinian corpuscles (Type II nerve fibers) are embedded in the deeper layers of dermis (2 to 3 mm thick) or in the subcutaneous tissue [84]. The density of FA II fibers are 21 per cm^2, as well as SA II fibers are 49 per cm^2, which are much fewer than FA I (140 per cm^2) and SA I (70 per cm^2) [87]. The receptive field refers to the sensitive area of individual mechanoreceptor fibers in the skin. The receptive field for SA I on fingertips are 2-100 mm^2 and 1-100 mm^2 for FA I fibers, compared to the broader area of 10-500 mm^2 for SA II and 10-1000 mm^2 for FA II fibers [88]. For best stimulation, FA nerve fibers respond to the perception of motion and vibration, whereas SA units respond to the perception of position and skin stretch [89]. Each type of mechanosensory fiber respond to a specific range of frequencies [90]. SA I and FA I fibers can detect low-frequency vibration below 50Hz and more sensitive to coarse texture perception, whereas FA II fibers can detect high-frequency vibration between 40 to 400Hz and more sensitive to fine texture perception [85]. Interestingly, hydration in the skin affected human ability of texture perception but no influence in detecting vibration [91]. The more details of characteristics of mechanoreceptors are listed in Table 2.2.

Table 2.2 - Characteristics of mechanoreceptors

	Type I		**Type II**	
	SA I	**FA I**	**SA II**	**FA II**
Receptor	Merkel cell	Meissner's corpuscle	Ruffini ending	Pacinian corpuscle
Location in the skin	Superficial layers between dermis and epidermis		Deeper layers of dermis or subcutaneous tissue	
Density (per cm^2)	70	140	49	21
Receptive field (mm^2)	2-100 (averaging 11)	1-100 (averaging 25)	10-500 (averaging 60)	10-1000 (averaging 100)
Best stimulus	Edges, points	Lateral motion	Skin stretch	Vibration
Frequency range (Hz)	0.4-5	5-40	Low dynamic sensitivity	40-400

From the Table 2.2, it can be seen that FA II fibers are the most sensitive to vibration. They are responsible for high-frequency vibratory stimuli and can detect vibration of 250Hz in the nanometer range [84].

2.5.2 Pacinian corpuscle

Pacinian corpuscles (Figure 2.5) are large onion-like structures that are separated by fluid-filled lamellae of connective tissue [92]. The fluid-filled lamellae enclose the ending of nerve fiber (myelin sheath and ranvier). This kind of structure is uniquely suited to detect vibration.

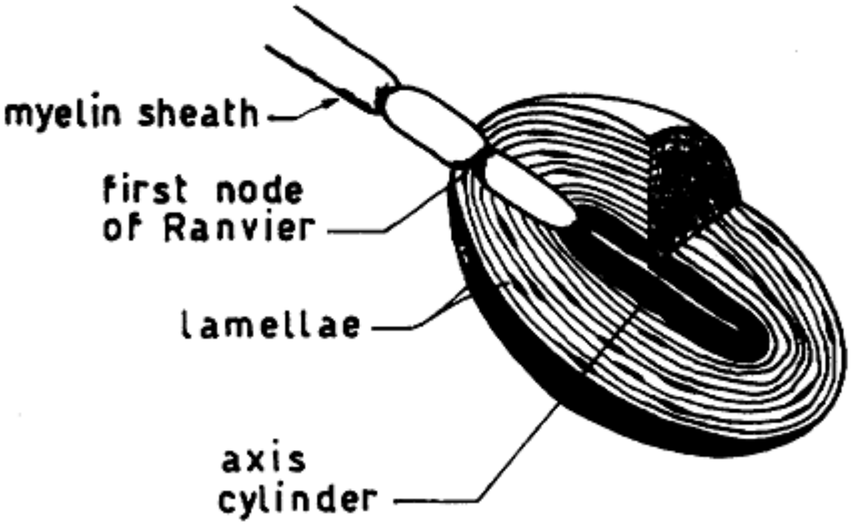


Figure 2.5 - Structure of pacinian corpuscle [92]

In response to a steady pressure, the lamellae layers in pacinian corpuscles are responsible for the mechanical compression and fibers generate an electrical signal at the beginning and end of stimulation, but stop when the pressure is constant. In contrast, a sinusoidal stimulation makes fibers work at regular intervals at the same frequency of stimulation [92]. Therefore, human can perceive the vibration when touching an object.

An experiment by Verrillo in 1971 [93] illustrated the relationship between the sensitivity to vibration and the frequency of the vibratory stimuli. Verrillo [94] continued to study the threshold of the index finger to vibration with respect to frequency. The results showed that the pacinian corpuscle, that covers the frequency range between 40 to 400Hz shown in Table 2.2, plays a big role in haptic perception.

The sensitivity of pacinian corpuscle has a U-shape trend at high frequencies (60-700 Hz) and remain stable in low frequencies (20 and 40 Hz) because the number of pacinian corpuscles reduces with age or their structural changes. Gescheider et al. [95] summarized the similar findings about pacinian corpuscle and other three receptors. Specifically, the pacinian corpuscles are more sensitive in high frequencies. The midrange of frequencies between 2 and 40 Hz, are determined by meissner's corpuscle and merkel cells are responsible for low frequencies between 0.4 and 2 Hz. Another finding is that the rate of loss sensitivity to vibration in pacinian corpuscle was greater than other three receptors [96].

2.5.3 Haptic perception in relation to age

For older generation, haptic perception was the most rapidly affected by ageing compared to muscle strength, balance, etc. [97]. The sensitivity to very low frequency vibration has no change in all populations and gradually decreases with 0.2-0.3dB per year in mid-frequency (e.g. 80 Hz). However, in high-frequency, the sensitivity has been dramatically decreased above 50 years old [94] but this decline becomes smaller after 65 years old [96]. Older people are significantly less sensitive to vibration than young individuals but no huge difference between younger and older people perceive thermal stimuli [98]. This may be caused by the number of pacinian corpuscles in the hand being dramatically decreased to 300 for older people compared to 2,400 in younger people [84]. Decorps et al. [99] reviewed most recent work and explained the process of tactile decline among the ageing population not only because the reduced number of mechanoreceptors but also the deficit of nerve system.

2.5.4 Outcomes for planned study

The research shows that mechanoreceptors in the skin are responsible for haptic perception. Four types of mechanoreceptors (SA I, FA I, SA II, and FA II) are sensitive to different stimulations, particularly, pacinian corpuscles (FA II) respond to vibration. Its sensitivity shows a U-shape curve at high frequencies (60-700 Hz) but remains the same level over low frequency range (e.g. 25 and 40 Hz). The sensitivity decreases dramatically over 50 years old yet the decline becomes smaller over 65 years old. Therefore, this thesis focuses on the pacinian corpuscle that are sensitive to vibration.

2.6 Psychophysical methods

Psychophysical methods are often used to study the relationship between physical characteristics of a stimulus (e.g. vibration) and the attributes of the sensory experience (e.g. finger sensitivity). Weber [100] first found that the sensitivity of a sensory system to differences in stimulus intensity depends on the absolute strength of the stimuli in 1834. The relationship is expressed in the equation known as *Weber's law*:

$$\Delta\theta = k\theta \tag{2.1}$$

where $\Delta\theta$ is the minimal difference in strength between a reference stimulus θ and a second stimulus that can be discriminated, and κ is a constant.

Fechner [101] extended a general formula from Weber's law in 1860, which has become well known as *Fechner's law*:

$$\psi = \kappa \log \theta / \theta_0 \tag{2.2}$$

In the equation 2.2, ψ is the intensity of the sensation experienced by a subject, θ_0 is the threshold amplitude of the stimulus, and κ is a constant, the value of which depends on the particular sensory dimension and modality.

Stevens [102] argued Fechner's Law that the intensity of auditory sensation is not an equal increment in differences of a just noticeable sensation. Then he [103] proposed a new equation in 1956, which is known as *Stevens' Power Law*:

$$\psi = \kappa(\theta - \theta_0)^n \qquad 2.3$$

where n is an exponent characteristic.

Based on Fechner's law, three classical methods, that are *the methods of constant stimuli, limits, and adjustment*, have been developed to measure the sensitivity of a sensation.

2.6.1 The classical methods

Three classical methods can be used to measure both absolute threshold and difference threshold of a sensation. The *absolute threshold* (θ_0) is defined as the smallest amount of stimulus energy necessary to produce a sensation, whereas the *difference threshold* ($\Delta\theta$) is defined as the amount of change in a stimulus required to produce a just noticeable increase in the sensation [104].

The method of constant stimuli is to detect the threshold by repeatedly using the same set of stimuli with different amplitudes (e.g. 5-9 different values) throughout the experiment. Then, each stimulus is presented to a subject repeatedly over 100 times in a random order. The percentage of times the subject reported to detect the stimuli is a function of stimulus amplitude, called *psychometric function*. If enough measurements are acquired, the psychometric function looks like an "S" shape called an *ogive* (Figure 2.6). Thus, threshold is taken as the stimulus amplitude detected in half of the trials. Brown [105] used this method to find the discrimination of lifted weights. The significant drawback of this method is that it is time consuming.

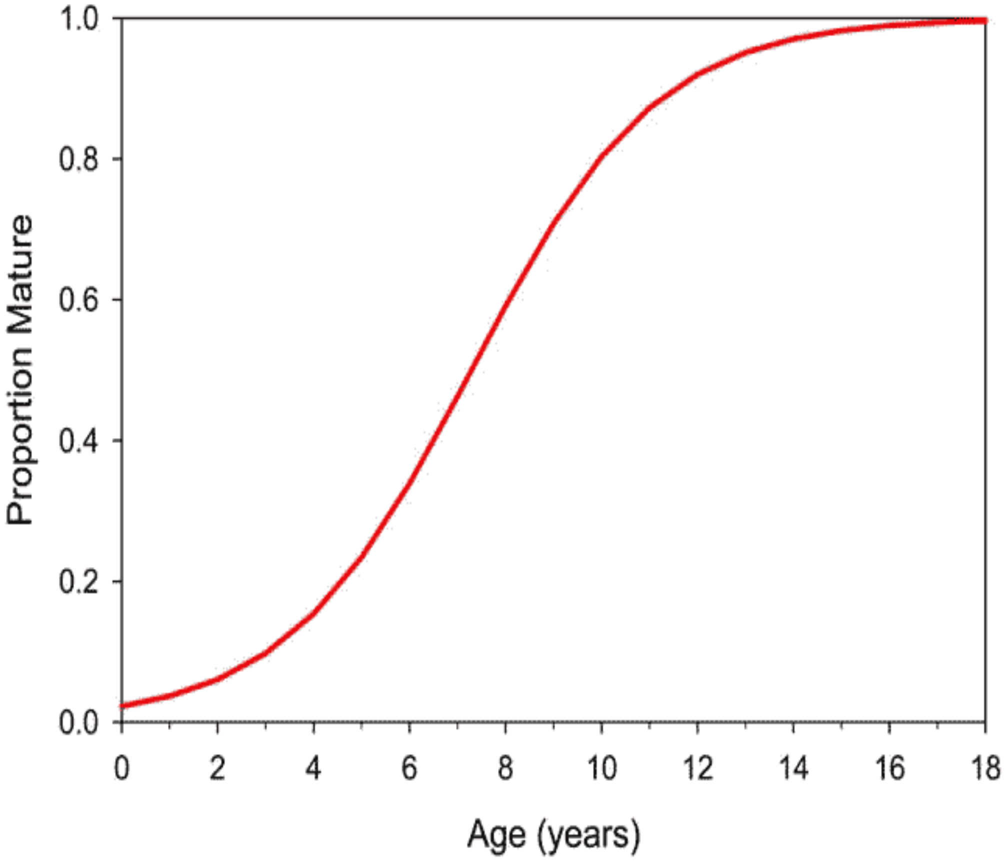


Figure 2.6 – Example of ogive curve

The method of limits starts by presenting a reference stimulus above or below threshold and then changes the amplitude of stimulus by a small amount until the sensation is detected or lost. The stimuli should be developed in either an ascending or descending sequences. For instance the ascending sequences, the transition point is recorded between the stimuli for the last no response and the first yes response by a subject. In the contrast, transition point of descending sequences is taken between the last yes response and the first no response. This procedure is repeated and the threshold is taken as the average of the transition points in all sequences. Kiesow [106] used this method for difference threshold of the length of drawing lines. The errors of this method may be caused by subject's habitation and experimenter's expectation.

The method of adjustment starts to present the amplitude of reference stimulus either far below or far above threshold. The subject decides to increase or decrease the value of stimulus amplitude until the sensation is perceived the same with reference one. Thus, the threshold is taken as the mean of a large number of trials. This procedure, also called the method of average error, is commonly used for measuring difference threshold and reported to be sufficiently accurate to be used for sensory loss [107].

2.6.2 The adaptive methods

The adaptive procedures had been derived from classical methods to increase the efficiency and accuracy of threshold measurement and reduce response bias. The difference between the classical and adaptive methods is that the stimuli amplitude is completely fixed before the experiment in the classical ones, whereas adaptive methods adjust the value of next stimuli depending on the responses of a subject and the previous stimulus amplitude [108]. As denoted in equation 2.4, the optimal stimulus amplitude x_{n+1} on the next trial depends on the previous stimulus valuesx_n, the subject's responses z_n at trial n and preceding trials with the target probability$\emptyset$.

$$x_{n+1} = f(\emptyset, n, x_n, z_n, \dots, x_1, z_1) \qquad 2.4$$

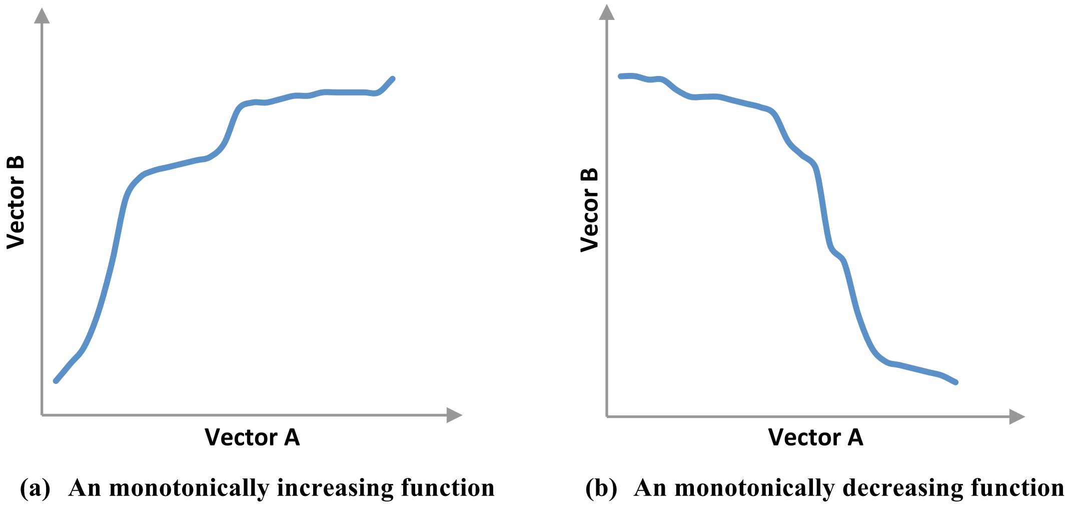
where f is a function related to an adaptive procedure.

The adaptive methods not only focus on the presenting stimulus at or near the presumed threshold but also the psychometric function, which leads to three categories:

(a) The psychometric function is known to be monotonic (Figure 2.7) but unknown shape.

(b) The psychometric function is known with estimation of threshold and slope.

(c) The psychometric function is unknown with estimation of threshold only.



(a) An monotonically increasing function **(b) An monotonically decreasing function**

Figure 2.7 - Two examples of monotonic function

In Treutwein's [109] review, the psychometric function in group (b) can be assumed to be the cumulative normal distribution (Gaussian) [110, 111], Weibull distribution [112], or the logistic distribution [113], etc. The group (c) uses either a Maximum-likelihood [114] or Bayesian estimator [115] of psychometric function. The following parts will give the details of adaptive methods.

Staircase method, also called threshold tracking method, was developed by Békésy [116] for experiments on hearing in 1947. This method starts to present a series of stimuli which gradually increase or decrease in amplitude at the same frequency. When the subject reports a change of perception, the stimulus amplitude is taken. Then the amplitude of the presenting stimuli changes from ascending to descending, or vice versa. This procedure continues until a sufficient number of reversed amplitude points have been recorded. Thus, the threshold is taken as the average of the transition points [117].

Forced-choice tracking was the first adaptive method to control for the subject's criterion by Blackwell [118] for experiments on vision, by Jones [119] for experiments on taste and smell and by Zwislocki et al. [120] for experiments on hearing. An amount of carefully specified samples are presented to the subject, one of which contains the stimulus. The subject has to choose the correct stimulus among them. Then, the stimulus amplitude is increased or decreased corresponding to responses on successive trials. For example, in a two-alternative forced-choice (2AFC) test, two stimuli are presented to the subject for each trial, and the subject would have to choose which stimulus is thought to be the correct one. Then, the stimulus amplitude is increased by one step when subject makes the wrong response and decreased one step when three correct responses are made, which results in performance level of 75% correct responses. The procedure ends when the stimulus amplitude remains within a specified range. Thus, the threshold is taken at the average stimuli value within the period of stable tracking.

Another similar method, up-down transformed response (UDTR) method by Wetherill and Levitt [121], is that each incorrect response leads to increase the stimulus amplitude, whereas a sequence of tow correct responses leads to decrease the intensity. This procedure aims to determining the threshold that results in performance level of 71% correct responses.

Parameter Estimation by Sequential Testing (PEST) method was developed by Taylor and Creelman [122] in 1967. PEST method is similar to staircase method but the step size is changed. Specifically, the step size starts out large at the beginning of each trial. When the stimulus amplitude is changed as a reversal, the step size is reduced in half from the previous step until a minimum step size is reached. On the other hand, when there is no reversal, but the procedure calls for a change in stimulus amplitude in the same direction, the step size remains the same for the first two steps but double the third steps until a reversal occurs when the maximum step size is reduced to a number of times that of minimum step size. Thus, the threshold is reached when a specified number of responses are made while the step size is within the range of the minimum size.

2.6.3 Comparison of the classical and adaptive methods

Three classical methods are easy to conduct and are still used for preliminary estimates of thresholds studies today. However, they have problems of the no control of subject's decision criterion, no theoretical justification for the procedure, no guarantee to detect the real threshold, the waste of a large number of data and time consuming [109]. Another problem is that three methods do not give the same value for difference threshold. The method of average error usually gives smaller thresholds than the method of constant stimuli [123].

Adaptive methods for measuring thresholds are efficient, accurate and can reduce response bias, which is highly recommended for experimental work in which precise measurements required.

The ability to tell two stimuli apart for the difference threshold experiment is called detection paradigm that if one of the stimuli is the null stimulus. Yes-no choice paradigm is often used in classical methods, where the subject has to decide whether the two stimuli are the same (no response) or different (yes response). Adaptive methods often use force-choice paradigm such as 2AFC. Overall, the comparison of classical and adaptive methods is listed in Table 2.3.

Table 2.3 - Comparison of psychophysical methods

Psychophysical methods	**Stimulus**	**Relationship**	**Sensation**	
	Intensity level	**Psychometric Function**	**Subject responses**	
Classical				
Constant Stimuli	θ = constant or $\Delta\theta$ = constant	ogive (Transition points)	Yes-no choice paradigm	n/a
Limits	$\Delta\theta / \theta$ = constant			
Adjustment	$\Delta\theta / \theta$ = constant			
Adaptive				
Staircase	$x_{n+1} = f(\emptyset, n, x_n, z_n, \dots, x_1, z_1)$	Monotonic	Yes-no choice paradigm	Forced-choice paradigm
Forced-choice tracking			n/a	Forced-choice paradigm
Parameter Estimation by Sequential Testing (PEST)				
Maximum-likehood		ML estimation		
Bayesian		Bayesian estimation		

2.6.4 Outcomes for planned study

The research shows that both classical and adaptive psychometric methods can be used to study the relationship between physical characteristics of a stimulus and the attributes of the sensory experience. Three classical methods are easy to implement and are still utilized for preliminary estimates of thresholds studies, whereas adaptive methods for measuring thresholds are efficient, accurate and can reduce response bias and used for the requirements of precise measurements. This study applies the classical method (method of limits) and adaptive method (staircase methods) to investigate the sensitivity of haptic perception.

2.7 Summary

This chapter has introduced the overview of haptics research in multidisciplinary field and also reviewed recent studies related to the development of haptic technology from the perspective of touch screen design, ageing effects to the products design, interactions between humans and touch screen devices. It then outlines the mechanism of the haptic perception, especially vibration, and compares the classic and adaptive psychometric methods.

The previous research provides the following directions to this study:

- To design virtual keyboard on touch screen devices, the button size (the side length of square) is appropriate in the range of 10-20 mm for both younger and older people.
- Older generations have difficulties of using modern devices due to their ability of vision, hearing, motor skills, cognition, and literacy skills decline and older people feel that modern devices are not well designed such as the lack of evaluation by older group. However, they can perform well on touch screen devices at the same level of younger people.
- Haptic technology is one of the key topics in human computer interaction (HCI) research field. The haptics can improve the usability of touch screen devices together with visual and audio cues. Little research has been carried out on the development of haptic language.
- Four types of mechanoreceptors (SA I, FA I, SA II, and FA II) in the skin are responsible for haptic perception. Pacinian corpuscle (FA II) has the best perception to vibration. Its sensitivity shows a U-shape curve at high frequencies (60-800 Hz) but remains stable in the range of low frequency

(e.g. 25 and 40 Hz). The sensitivity decreases dramatically over 50 years old but becomes slower over 65 years old.

- Classical methods are easy to implement and can be used for preliminary estimates of thresholds studies, whereas adaptive methods are efficient, accurate and reduce response bias, and can be used for the requirements of precise measurements.

3 Assessing the Vibrotactile Feedback on Current Smartphones

Vibrotactile feedback is related to vibration that provides the sensation of touch for human interaction with computers. Vibration is a process that involves the transfer of energy between potential and kinetic forms. All objects such as bridges, airplane wings that include mass and elasticity are capable of vibration [124]. It is vital to understand the vibration features on current smartphones for the help with vibrotactile patterns design as a haptic language. Therefore this chapter aims to investigate the mechanical behavior of the vibrotactile feedback available on current smartphones.

3.1 Experimental design

This experiment starts with a standard testing of natural frequencies of smartphones in order to find the estimate of the frequencies of the vibration available on smartphones. Then the study has accessed the vibrotactile feedback available on current smartphones in order to understand the behavior of vibrotactile feedback for the help with haptic language development.

3.1.1 Natural frequency testing

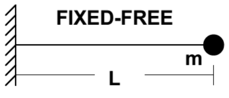
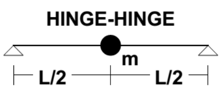
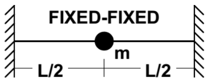
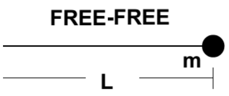
The purpose of this testing is to analyze the natural frequencies of current smartphones in different boundary conditions because the natural frequencies could affect the performance of vibrotactile feedback due to the different structure design. It is well known that if two objects are mounted together having a similar or the same natural frequency, they are getting into ‘resonance’. A smartphone assembled by different parts, such as touch screen, battery and hard cover, has multiple natural frequencies due to its geometry. If the excited frequency is at the natural frequencies, the vibration on smartphones will be amplified. This could cause the phone to fail over time. Thus this situation should be avoided. If the excited frequency is near the natural frequencies, the vibration will be enhanced so that the energy to drive the vibration from the phone could be reduced with the same vibrotactile feedback. Therefore, the first step is to find the natural frequencies of smartphones as this can help to have an estimate of the frequencies of the vibration available on smartphones.

In theory, if an object is a beam with uniform structure, the natural frequency ω_n is defined in the equation 3.1.

$$\omega_n = A\sqrt{\frac{EI}{\mu L^4}} \tag{3.1}$$

where E is the Young's modulus, I is the area moment of inertia, L is the length of the beam and μ is the mass per unit length of beam. A is given in Table 3.1.

Table 3.1 – Parameter A in different modes and boundary conditions [125]

Boundary condition	**Mode 1**	**Mode 2**	**Mode 3**	**Diagram** ***(m*** **is the mass of load)**
Fixed-Free (Cantilever)	3.52	22.0	61.7	
Hinged-Hinged (Simple)	9.87	39.5	88.9	
Fixed-Fixed (Builtin)	22.4	61.7	121.0	
Free-Free	22.4	61.7	121.0	

In equation 3.1 the natural frequency is determined by boundary conditions. Other parameters are constant as they are the mechanical properties of an object itself. The value of A in fixed-fixed condition is the same with free-free condition in all modes. The fixed-free condition has the smallest A, followed by the condition of hinged-hinged. However, the mechanical properties of smartphones such as E, Young's modulus are unknown and the phones may not be assumed as the uniform beam due to its complex structure design. Hence a natural frequency testing was implemented instead. The above boundary conditions can guide to design the natural frequency testing.

Furthermore, two of the most commonly techniques are the shaker modal testing and impact hammer testing to measure the natural frequency. The shaker modal testing is that a shaker is utilized to generate an impact on the object surface. The random frequency and sinusoid sweep are commonly used signals of the excitation.

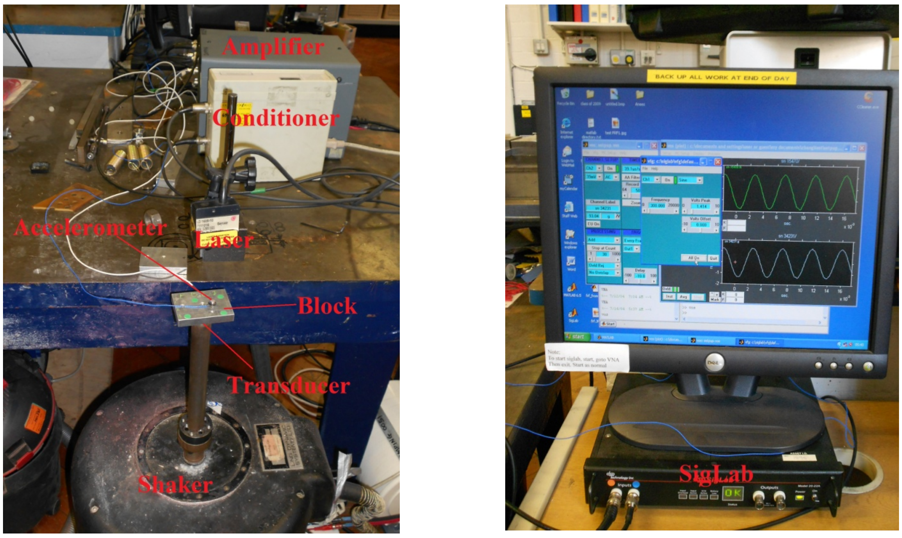


Figure 3.1 – Diagram of the system for shaker model testing

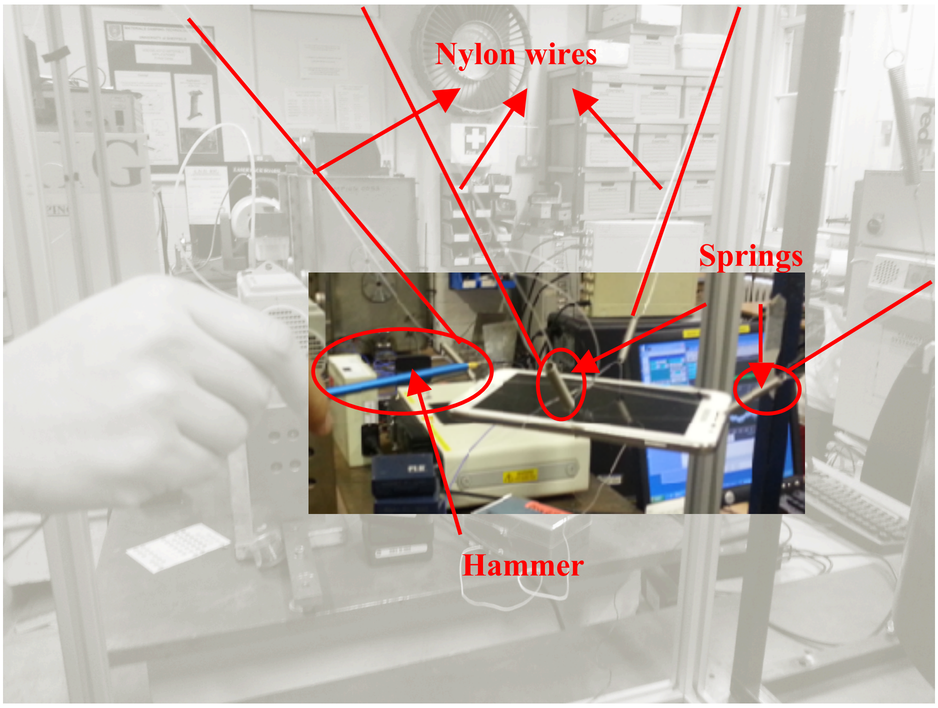
Figure 3.1 shows the diagram of the shaker model testing. The object can be attached directly to the shaker table. An accelerometer is used to measure the vibration responses of the object. Alternatively, a laser vibrometer can be used for non-contact measurement. Finally, a data acquisition system is collecting and analyzing the signals from the sensor. This method can provide more energy over a long period of time, especially suitable for a large-scale structure.

The differences of impact hammer testing from the shaker method are that the object has to be held in a free-free or fixed condition and a hammer is used to create an impulse excitation in the object surface. It is commonly used to test a small lightweight structure due to its poor signal to noise ratio for a large scale one. This method is fairly easy and effective to implement because the impact generates a small amount of force in the object and the vibration responses are over a large frequency range.

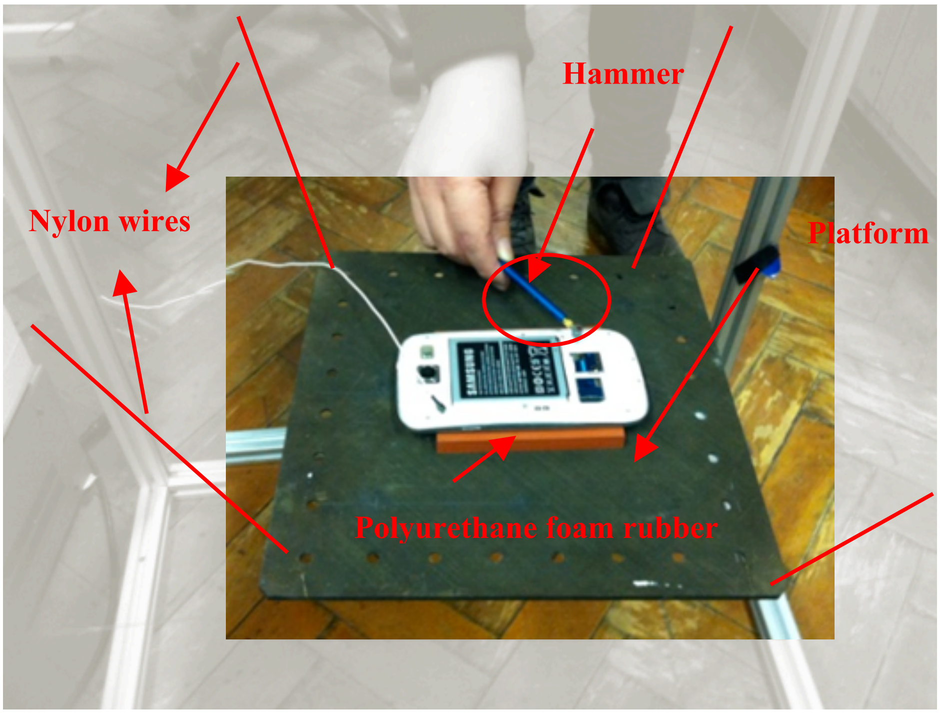
Therefore, two boundary conditions (free-free hanging and platform supporting) were selected because most people use the smartphones by holding on hands or putting on the table. The free-free hanging condition is similar to the position of hand holding whereas the platform supporting is related to the position of putting on the table. And also, due to the size of most smartphones and simplicity of operation, the impact hammer testing was carried out to calculate the natural frequency of smartphones.

In the free-free hanging condition (Figure 3.2 (a)), the smartphone (model: Samsung Galaxy S3) is connected with four springs by nylon wires at the edge and hanged freely, whereas in the platform supporting condition (Figure 3.2 (b)), the smartphone is placed on a soft polyurethane foam rubber to avoid damping effects. The rubber is supported by a metal platform, which is hanged freely by nylon wires at the edge. A tiny impulse force hammer (model: PCB Piezotronics 086D80; head diameter: 0.25 in; measurement range: 0-50 lbf) is used to impact the edge of the phone and the accelerometer (Dytran 3224A1) is attached to the phone in order to measure the vibration responses. When the hammer hits the phone, the signals from the accelerometer are sent out through a conditioner to the data acquisition system

(SigLab toolbox: DSP Technology 20-22A). The sample rate of the data is 13 kHz with 8192 data points.



(a) Free-free hanging



(b) Platform supporting

Figure 3.2 - Diagram of the impact testing in different boundary conditions

3.1.2 Vibrotactile feedback on current smartphones

Four smartphones (Apple iPhone 5, Samsung Galaxy S3, Sony Xperia Z and Nokia Lumina 800) were selected to investigate the mechanical behavior of vibrotactile feedback on smartphones. The criterions of selecting smartphones are based on the popularity in current market. Samsung and Apple are the most popular brands, following by the brand of Sony and Nokia. All the models are launched near the year of 2012 with the similar design and features. The basic features of four smartphones are shown in Table 3.2.

Table 3.2 – The features of four smartphones

Model	Launch Time	Specification	Actuator Type
Samsung S3 	05/2012	4.8 inches screen; 136.6 x 70.6 x 8.6 mm; 133g;	Linear Resonance Actuator
Apple iPhone 5 	09/2012	4.0 inches screen; 123.8 x 58.6 x 7.6 mm; 112g;	Eccentric Rotating Motor
Sony Xperia Z 	01/2013	5.0 inches screen; 139 x 71 x 7.9 mm; 146g;	Linear Resonance Actuator
Nokia Lumia 800 	10/2011	3.7 inches screen; 116.5 x 61.2 x 12.1 mm; 142g;	Linear Resonance Actuator

From the results of the natural frequency testing, a single boundary condition is chosen to avoid the vibration of vibrotactile feedback near the natural frequency for the assessment. Taking an example of iPhone 5, Figure 3.3 illustrates that the phone is placed in the platform supporting condition. The accelerometer (Dytran 3224A1) is attached to the centre of the screen to measure the vibration of vibrotactile feedback. The data acquisition system is the same with the natural frequency testing. The sample rate is set at 13 kHz with 512 points.

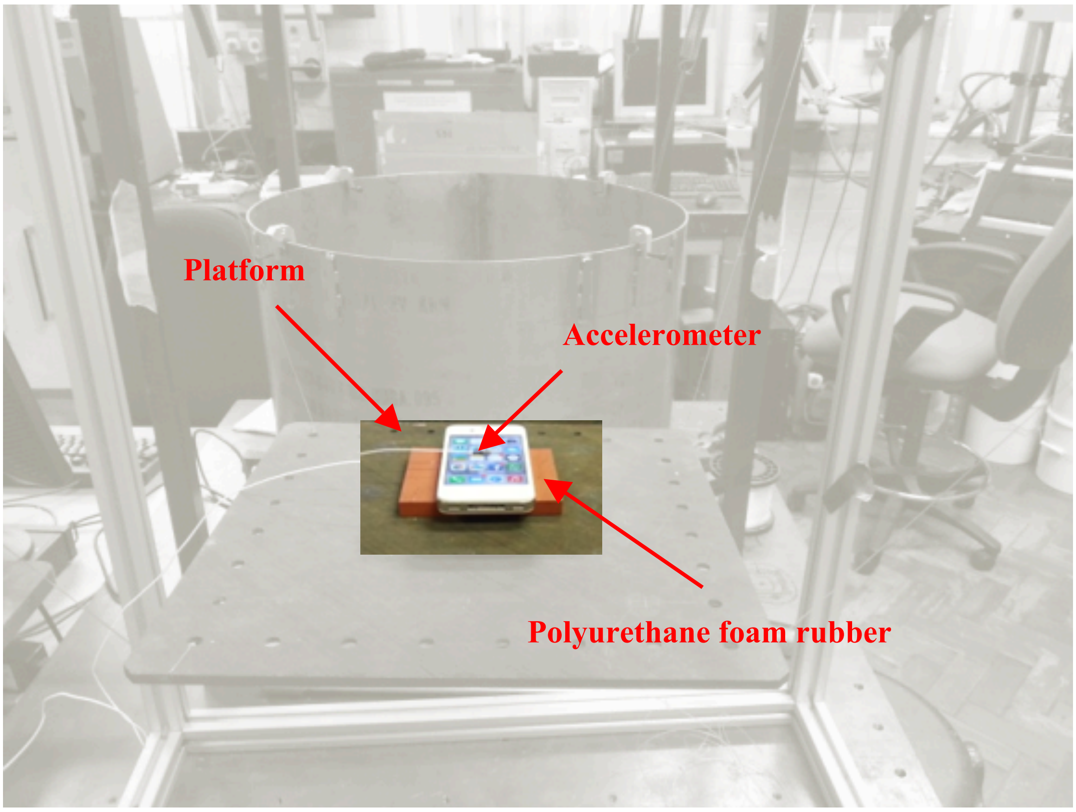


Figure 3.3 - Diagram of the vibrotactile feedback testing

The phone is set in the alarm mode. The reason is that firstly, some smartphones, for instance iPhone 5, do not provide vibrotactile feedback for text-entry. Secondly, the smartphones reach the maximum vibration responses in the alarm mode compared to other vibrotactile feedbacks, for instance small vibration when typing text. When the alarm is on, the phone starts to vibrate and the accelerometer measures the vibration responses.

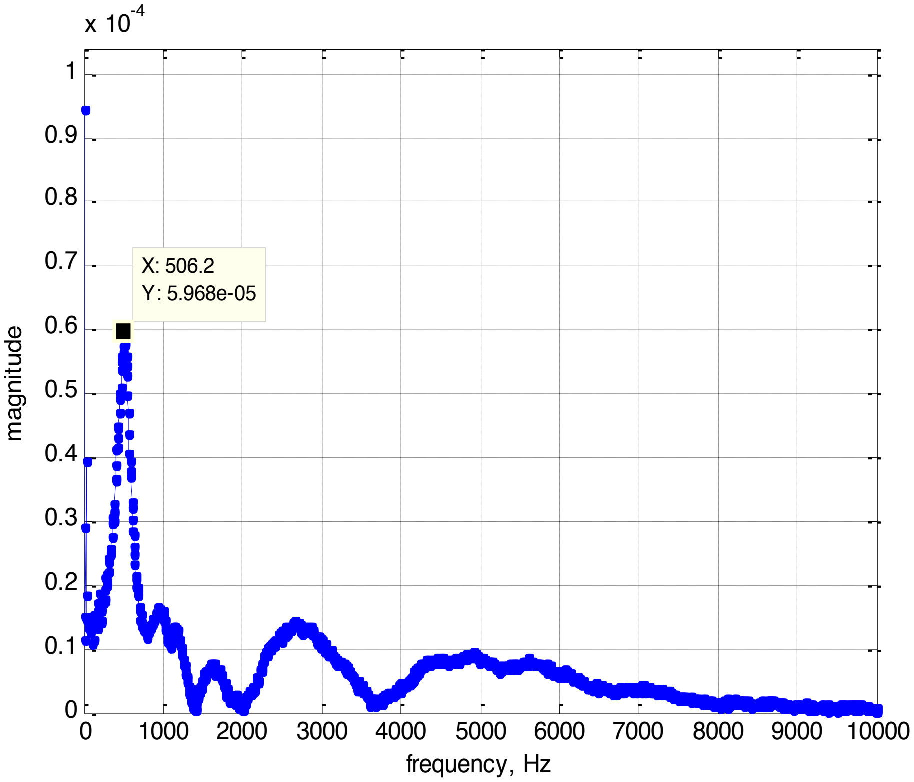
3.2 Experimental procedures

Firstly, the natural frequency testing was repeated four times in each boundary condition (free-free hanging and platform supporting) to measure the vibration responses of the smartphone (model: Samsung Galaxy S3). From the results of natural frequency testing, the vibrotactile feedback on four selected smartphones (Apple iPhone 5, Samsung Galaxy S3, Sony Xperia Z and Nokia Lumina 800) was assessed in the alarm mode in the platform supporting condition. All the collected data were processed using fast Fourier transform (FFT) methods in Matlab.

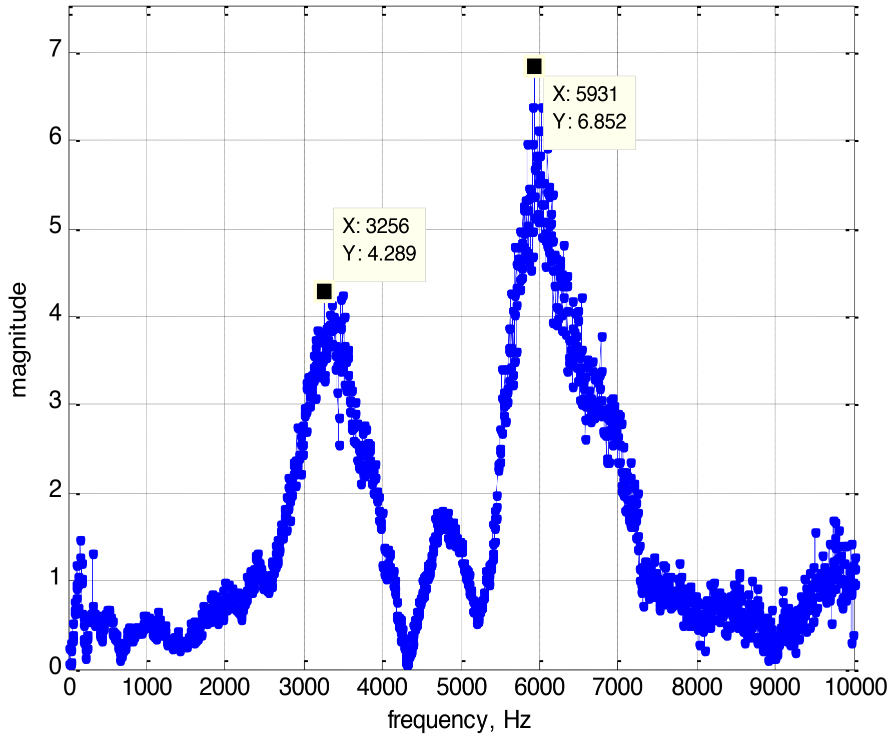
3.3 Results

3.3.1 Results from the natural frequency testing

Figure 3.4 shows the resonance frequencies of the phone in a range of 0-10K Hz in two boundary conditions. Each vertical peak represents one natural frequency. The magnitude represents the strength of the vibration. The higher value means the stronger oscillation at that frequency point. In other words, the smartphone has more sensitivity at that special frequency. Therefore, the first peak significantly higher than others was noted as the natural frequency that should be avoided. In Figure 3.4, the natural frequency of smartphone is 506.2 Hz in the free-free hanging condition and 3256.0 Hz in the platform supporting condition.



(a) The free-free hanging condition



(b) The platform supporting condition

Figure 3.4 – Resonance frequencies of smartphone (Samsung S3) in different boundary conditions

Figure 3.5 shows the average natural frequency that was 467.5 ± 40.7 Hz in the free-free hanging condition and 2861.3 ± 263.4 Hz in the platform supporting condition.

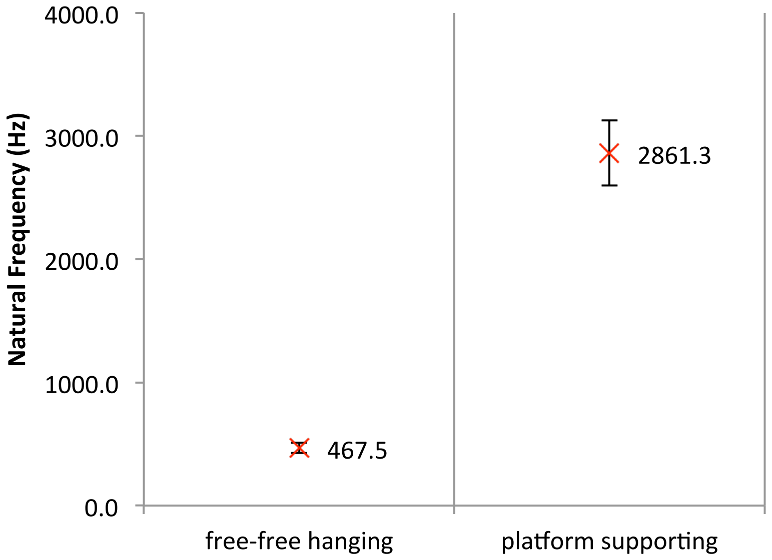
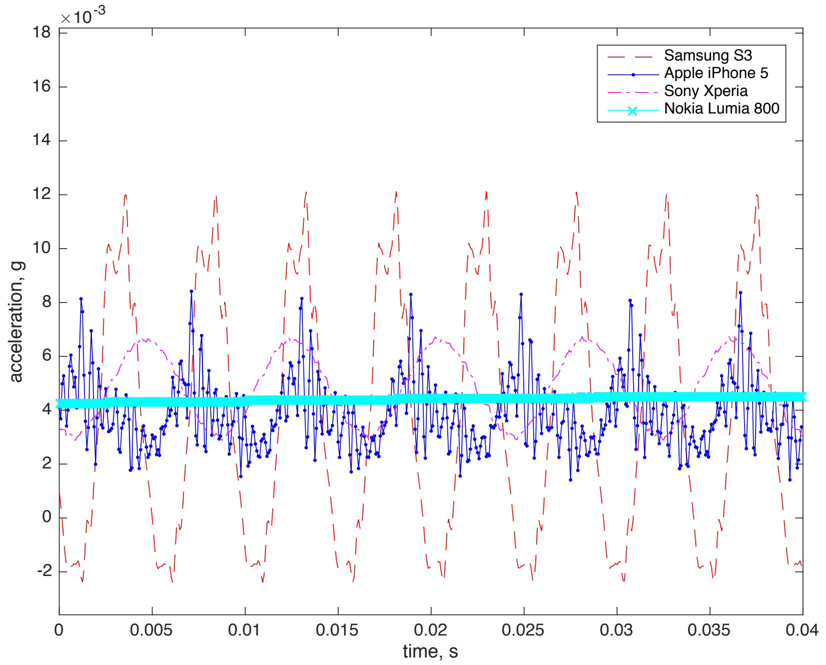


Figure 3.5 – Average natural frequencies of smartphones (Samsung S3) in different boundary conditions

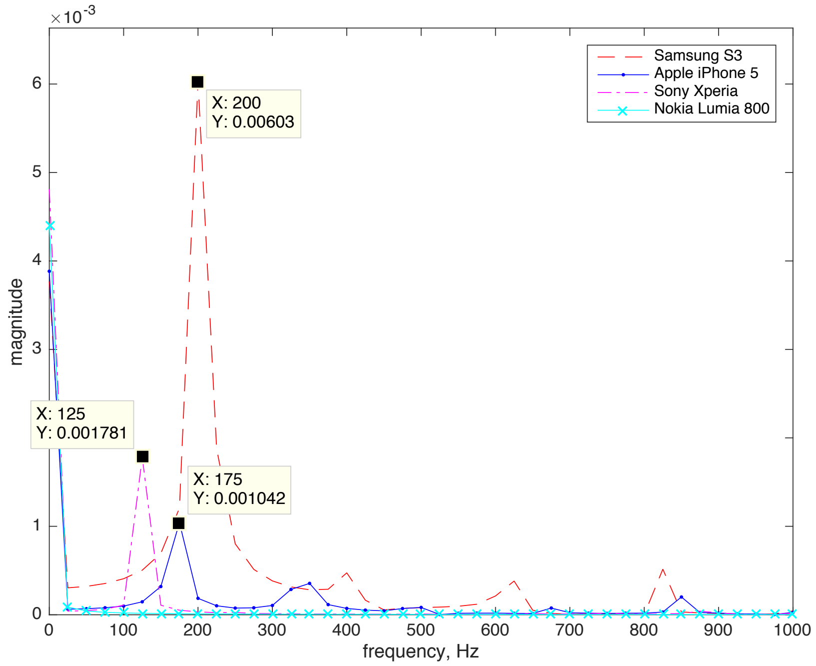
The natural frequency in the free-free hanging condition is around 400-500 Hz. If the vibrotactile feedback is produced in the range of 40-400 Hz, which is the sensitive range of the pacinian corpuscles (see Table 2.2), the vibration will be amplified and may cause resonance. It was also seen that the natural frequency in the free-free hanging condition is significantly lower than the platform supporting condition. If the vibrotactile feedback is produced in a platform condition, there is little possibility of causing a resonance between the phone and the platform. Therefore, the frequency range of 40-400 Hz is tolerable to design the vibrotactile feedback and the platform condition is appropriate to investigate the vibratactile feedback.

3.3.2 Results from the vibrotactile feedback testing

The results from the natural frequency testing proved that platform supporting is suitable for study the vibrotactile feedbacks on smartphones. The vibrations in time and frequency domain are shown in Figure 3.6.



(a) Time domain



(b) Frequency domain

Figure 3.6 - Vibrations on smartphones in time and frequency domain

It illustrates that the vibrations on smartphones had different waveforms with sinusoidal signatures. The major frequency of vibration on Samsung, Apple, and Sony were 200Hz, 175Hz and 125Hz, respectively. They align with the range of 40-

400 Hz as previous discussion. The vibrotactile feedback of Samsung S3 was significantly stronger than other phones according to the results in both time and frequency domain. However, the vibrations on Nokia were hardly acquired. The signals could be too weak to be measured by the accelerometer.

Furthermore, the results in Figure 3.6 (b) show that the phone such as Samsung also responds to the frequency at around 400, 600 and 800 Hz, which mean that the vibrotactile feedback could combine more than one sinusoidal signal. This may be caused by the noise of the system or from the structure layout of the phone itself.

3.4 Discussion

The natural frequency of the smartphone tested in the free-free hanging condition is much lower than the platform supporting. Hence, the frequency of vibrotactile feedback as an excitation should be no more than 400 Hz. It is suggested to design the vibrotactile feedback in the range of 40-400 Hz, which supports with the frequency design of vibrotactile feedback in the selected smartphones. Furthermore, it was found that different brand smartphones vibrate at different waveforms and frequencies due to the different structures and materials, and also the vibrotactile feedback on four smartphones is generated from a single actuator. The results in Figure 3.6 (a) proved that the behavior of vibrotactile feedback is like sinusoidal signals. The reason of sinusoidal waveform is mostly utilized in research study and most commercial smartphones is that it is very simple to generate and can provide comfortable sensation like smoothness. However, other waveforms such as triangle or square may cause much noise of the sound and create no sensation because the structure of pacinian corpuscles in the skin is sensitive to the sinusoidal signals.

There is no significant proof that human would perceive square or triangle waveforms better than sinusoid. Hence, sinusoidal waveform could be the optimal option for the vibrotactile feedback design.

An issue is raised that whether the driven signatures of vibrotactile feedback remains the same features when passing through the mechanoreceptors. The current technology can only measure the amplitude of the driven stimulation. Therefore, the innovation of equipment or technologies is required in order to study the mechanism of stimulation passing through the skin layer and reaching into pacinian corpuscles.

3.5 Summary

This chapter has explained the experimental procedures and results of the assessment of vibrotactile feedback on current smartphones. The results proved that the natural frequency is significantly different in different boundary conditions. The natural frequency smartphones of Samsung S3 is around 400-500 Hz in the free-free hanging condition. Therefore, the frequency range of 40-400 Hz is appropriate to design the vibrotactile feedback on smartphones. Although the signatures of vibrotactile feedback from different smartphones are different, they are all generated from a single actuator with a single frequency in the range of 100-200 Hz.

4 Vibrotactile Perception Threshold and Discrimination in Vibration

This chapter aims to validate the absolute threshold of finger sensitivity and human discrimination in vibration between younger and older people based on the knowledge of skin mechanoreceptors discussed in chapter 2. These values and limits are essential for the vibrotactile patterns designed. Therefore the absolute threshold testing was first conduced in two age groups of subjects and followed by the discrimination testing under the ethical approval of University of Sheffield (consent form can be found in Appendix 3).

4.1 Experimental design

To design a vibrotactile perception experiment, the first factor is concerned with the *stimuli* to human finger based on the parameters of waveform, frequency and amplitude. Three type of waveforms of stimuli, *pure tone, tone burst* and *gliding tone,* are suggested in the BS ISO 13091-1:2001 [126] for the vibrotactile perception thresholds (VPTs) tests. *Pure tone* is defined as an oscillatory signal whose magnitude is a sinusoidal function of time; *Tone burst* is an intermittent pure tone signal; *Gliding tone* is a pure tone in which the frequency changes continually with time. The recommended frequency of stimuli is varied for each of the receptors in the skin due to the different responses of each receptor discussed in the chapter 2.5. For instance, 4.0 Hz is responsible for the SA I mechanoreceptors, 31.5 Hz for the FA I mechanoreceptors and 125 Hz for the FA II mechanoreceptors. ISO 13901 recommends the frequencies of 100 Hz and 160 Hz for the FA II receptors as well. As the pacinian corpuscles (FA II) are the most sensitive to vibration stimulation, three threshold measurements (100Hz, 125 Hz, 160 Hz) are selected for the absolute threshold test. Other threshold measurements are adapted from the similar experiments carried out by Verrillo [94]. He tested thresholds at 25, 40, 64, 80, 100, 160, 200, 250, 320, 500, and 700 Hz in order to investigate possible relationships between sensitivity and the structure of mechanoreceptors over a wide span of ages. Finally the changes of stimuli amplitude are recommended no more than 3 dB per second when utilizing *tone burst* or *gliding tone*. Therefore, the *tone burst* is selected at twelve threshold measurements of 25, 31.5, 60, 80, 100, 125, 160, 200, 250, 320, 500, and 700 Hz for the absolute threshold test. Figure 4.1 shows two series (ascending and descending) of the *tone burst* stimuli with 'on' and 'off' duration of 1.0 second and the amplitude changes at rate of 1-2 dB per second.

Figure 4.1 - Stimuli at 25Hz threshold measurement

In addition, the *pure tone* at 125 Hz is selected as one of the frequency bases for the discrimination test. It is known that 250 Hz is the most sensitive frequency for the pacinian corpuscles [84], hence it is also selected as another frequency base for the comparison. Table 4.1 shows the 11 vibration pairs at each frequency base to find the minimum discriminating changes of frequency that younger and older people can differentiate. The discriminating changes of frequency start from 5 Hz until 125 Hz because the responses range of the FA II receptors is around 40-400 Hz as discussion in the section 2.5.

Table 4.1 - Vibration pairs for the discrimination test

	125 Hz Base (Hz) pairings		**250 Hz Base (Hz) pairings**	
	Vibration A	**Vibration B**	**Vibration A**	**Vibration B**
(1)	100	125	125	250
(2)	105	125	150	250
(3)	110	125	175	250
(4)	115	125	200	250
(5)	120	125	225	250
(6)	125	125	250	250
(7)	130	125	275	250
(8)	135	125	300	250
(9)	140	125	325	250
(10)	145	125	350	250
(11)	150	125	375	250

Another consideration is the measurement procedure for the threshold test. In ISO 13901, the up-down algorithm or von Békésy methods [116] are recommended guidelines. The former method is that of presenting two series of short-duration stimuli to a subject. The amplitude of the series of stimuli is either ascending or descending. The latter method is that the amplitude of stimuli changes continuously. In each case of the ascending or descending series subject must report the transition point between the stimuli for the last no response and the first yes response or vice versa. Finally, the threshold was recorded as the average of the transition points in all series. Three classical methods discussed in chapter 2.6 are easy to implement for preliminary estimates of threshold whereas the adaptive methods are efficient and accurate for the requirements of precise threshold measurements. As mentioned in ISO 13901, the up-down algorithm is one of the classical methods (method of limits) and the Békésy method is one of the adaptive methods (staircase). As this experiment aims to find the limits of human perception and no requirement of precise threshold, hence the up-down algorithm is selected for the absolute threshold test.

Number of subjects is a key issue for human evaluation experiment. The more subjects the more precise results are, however the longer experimental period. It varies from less than 10 [94] to more than 50 [127] for the experiments of measuring tactile sensitivity in 1980s. In general, two types of sampling procedures are probability and non-probability in order to decide the target number of subjects. The former one is used when the probability of selecting each subject is already known. The researcher selects a large group of individuals randomly that are representative of the population. The latter one is used when the probability of selecting a subject is unknown in the lack of access, time, resource or financial constraints and the researcher selects subjects who can be particularly informative about the research issues. 30 subjects are commonly selected for correlational research, 15 subjects in each group for experimental research and approximately 250 responses for survey research based on the rules of thumb [128]. Due to the time and access constrains, this experiment was utilized in the non-probability sampling procedures using the strategy of subjects' availability from the local university and charity. The total target number of subjects is around 20-40. The subjects are divided into 20-40 years old and 60-90 years old groups in order to find the changes of the ability of the finger sensation from younger age into late years. Above all, the number of subjects is 10-20 in each age group.

The number of judgments that each subject has to make during the test is another important factor for the VPTs test. If the large number of different stimuli is used, it is not feasible to present each stimulus more than once in a given session. Most subjects are able to make as many as 60 judgments in a single session, unless they come quickly one after another [129]. If too many stimuli are presented in a single session, the subject's performance near the end of such a long session would have deteriorated and the judgment could false. Therefore, the testing is limited to a maximum of 50 stimuli in a single session with pauses between the testing. As the absolute threshold test is repeated four times and the discrimination test twice to reduce human bias and error, the number of judgments is 96 for subjects for the absolute threshold test and 88 for the discrimination test.

Temperature and contact force of finger also have a big influence in the performance of haptic perception. ISO 13091 [126] guidelines suggest that the test room temperature should be between 20°C to 30°C and subjects' skin temperature need to be confirmed at 27-35°C. Therefore, the test room temperature and the subjects' finger shall be measured before the experiment in order to ascertain the values within the above range. The contact force has a major influence on the finger perception [130]. The minimum contact force of 0.15 ± 0.09 N is required when using a stimulator with a diameter of less than 4.0 mm if the vibrator contacts the fingertip without a surround. A large force could be required if the stimulating probe with a diameter of more than 4.0 mm. Hence, the contact force is determined by the diameter of the stimulator that is used in the experiment.

Finally, the sound from the actuator during the experiment may also influence the subject responses. It has to be blocked using music or narrow-band noise to cancel out. As the noise is annoying for the subjects if testing in such a long time, the music is chosen to play during the experiment.

To summarize, Table 4.2 shows the conclusions from the previous discussion for designing the absolute threshold and discrimination testing.

Table 4.2 – Factors of designing finger sensitivity experiment

Factors	**Design Range**	
	Test I **(absolute threshold)**	**Test II** **(discrimination)**
Stimuli	*Tone burst* at the frequency of 25, 31.5, 60, 80, 100, 125, 160, 200, 250, 320, 500 and 700 Hz; The changes of amplitude at 1-2 dB per second;	*Pure tone* at the frequency bases of 125Hz and 250 Hz; 11 pairs for each base with the discriminating changes from 5 Hz until 125 Hz;
Measurement procedure	Up-down algorithm	n/a
Number of subjects	10-20 in 20-40 years old group; 10-20 in 60-90 years old group;	10-20 in 20-40 years old group; 10-20 in 60-90 years old group;
Number of judgments	1 tone burst × 2 series × 12 threshold measurements × 4 times = 96	2 pure tone × 11 pairs × 2 base × 2 times = 88
Temperature	Test room: 20-30°C Finger: 27-35°C	Test room: 20-30°C Finger: 27-35°C
Contact force	Depends on the size of stimulator	Depends on the size of stimulator
Noise	Music provided	Music provided

4.2 Equipment for vibrotactile perception experiment

A wide variety of haptic devices have been utilized for vibrotactile perception experiment with the design of minimizing power consumption and size/weight while maximizing the haptic effects at the same time. The most common techniques are the electrical and vibro-mechanical haptic devices. The electrical haptic device provides the sensation of touch using tiny electrodes by passing a small electric current through the skin, whereas a vibro-mechanical haptic device provides the sense of touch by vibration.

Therefore, actuators utilized in haptic devices are varied and have specific strengths and weakness. The electrical actuator, for example TENS machine, produces voltage-based pulses by controlling signals of amplitude, frequency, duty cycle, and polarity [131].

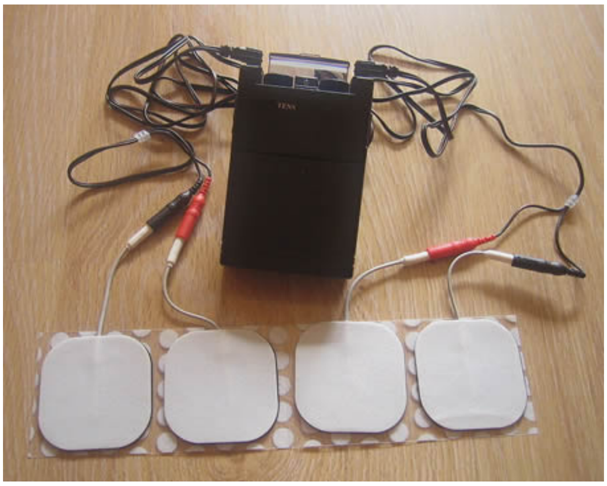


Figure 4.2 – TENS machine with electrodes

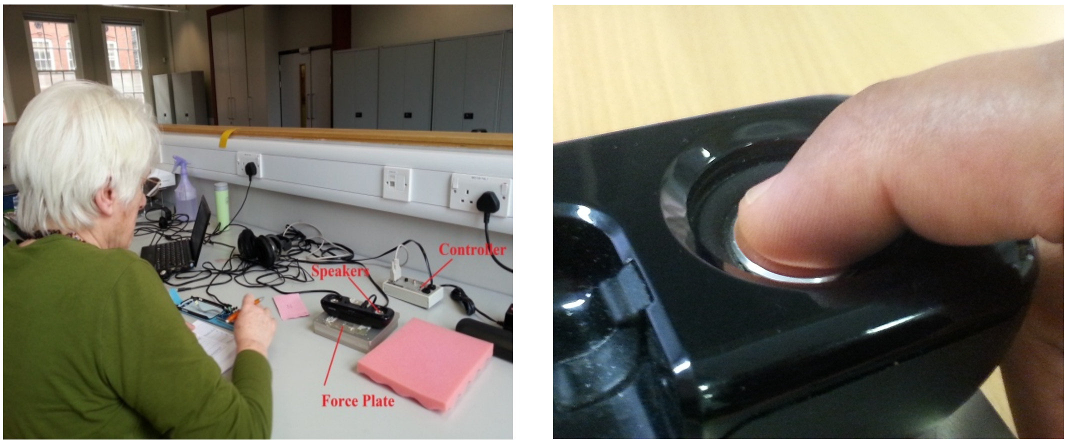
In Figure 4.2, TENS machine consists of four whites pads and a black controlled unit. The pads with electrodes can be attached to any conductive materials such as human skin. This type of actuators can provide the combination sensations of pain, pressure, tingle or vibration. The benefits of electrical actuators are that inner electrodes have smaller size and lighter weight and can be manufactured into any shape. The stimulation from the machine has ideal parameters and human sensation is localizable. However, this kind of actuator is not acceptable for the operational environment because electrodes require direct and continuous contact with the skin to maintain the same sensation. And also, the subjects could experience certain levels of pain. Therefore, it is not an option for the help with the improvement of vibrotactile feedback on smartphones.

The shaker as a vibro-mechanical device can be implemented in vibrotactile perception experiment. The advantage is that it offers a variety of stimulations such as sinusoid, square, and triangle signals, and also a large range of frequencies from 10 Hz to 10 kHz. The stimulation produced is without significant noise like a drift. However because of the lack of portability and loud sound in operating conditions it is still not suitable for use in the subject testing proposed.

As the size of shaker is not portable, a speaker becomes an alternative option. The speaker is a portable device with a great degree of control of the sounds or vibrations produced and able to be used for testing finger sensation. A speaker consists of a cone, an electromagnet (coil) and a fixed permanent magnet. The direction of the magnetic field of the coil can rapidly change if the electricity passes through. These changes make the coil attracted to and repelled from the permanent magnet. As the electromagnet is attached to a cone made of a flexible material, which amplifies the vibration, the sound or vibration is created. Therefore, the speaker in Figure 4.3 (model: Creative TravelSound ZEN Stone) was selected for vibrotactile perception experiment.

4.3 Experimental procedures

The subjects were tested under the normal laboratory environment. The test room temperature was within 24-27°C. A thermometer was used to measure the temperature of subjects' finger.



(a) a subject in the threshold test

(b) Close-up of finger in contact area within speaker during testing

Figure 4.3 – Diagram of the human perception experiment

Figure 4.3 illustrates that the subject was tested in the haptic experiment. It is very simple to drive and control a speaker. The software, Audacity version 2.0.2, is used to generate a variety of sounds or vibrations to the speaker through audio cables and integrated sound card in laptop. The laptop provides the power for the speaker. Alternatively, two A7 batteries can be a power supply for this speaker. As previous discussion, the contact force depends on the diameter of the vibrator. Thus the contact force is designed within 0.5-1.0 N as the buttons on the speaker with a diameter of 18 mm. A force plate (model: AMTI HE6X6-10) is used to monitor the force in the range of 0.5-1.0 N. A foam pad is used to support the subjects' arms and maintain the hand on the same level as the speaker. The background music is provided through an earphone during the experiment. The subjects would perceive a vibration stimulus by touching the button on the speaker.

4.3.1 Test I: absolute threshold to vibration

Before the subjects filled in the consent the form, the experimental objectives and procedures were explained to them. The subjects were then required to put their index fingers of the hands they use for writing onto the right button of the speaker. The subjects were presented first the descending series and followed the ascending series at twelve threshold measurements. The up-down algorithm method was implemented as discussed in section 4.1. The number of the series (marked with the number of 1 to 10） was noted at the transition point that subjects could not perceive the vibrations or vice versa. The subjects were invited to have a break after testing six threshold measurements because the sensitivity may be deteriorated over a period in a single session. The procedure was repeated four times and the test protocol took approximately 30 minutes to complete.

4.3.2 Test II: discrimination in vibration

After the break from the threshold testing, the discrimination testing was carried out at two frequency bases, 125Hz and 250Hz respectively. Each frequency base consists of 11 pairs of vibrations (see Table 4.1) and the exposure time of each vibration was 1.0-second with the amplitude of 54 dB.

The subjects first experienced the reference vibration (e.g. 125 Hz base) and then the comparison one with 1.0-second pause between two vibrations. Then subjects were asked if the vibration sensation was the same or different using two-forced alternative choices (2FAC) method with Yes-No paradigm as discussed in section 2.6. A flexible time was left for subjects to make judgments.

Table 4.3 - Score criteria

	Correctly identified same or different signals	Scores
Correct	2 out of 2 times	1
Moderate	1 out 2 times	0.5
False	0 out 2 times	0

The procedure was repeated twice in order to reduce human error. The results were scored according to the criterion in Table 4.3, followed the requirements in [132]. The test protocol took approximately 20 minutes to complete.

4.4 Results

For the absolute threshold testing (Test I), 11 younger adults (7 males and 4 females aged 20-40 years, and average age 27.7 ± 5.1 SD) and 16 older adults (5 males and 11 females aged 60-90 years, and average age 72.3 ± 5.6 SD) were tested. Another 6 younger adults (4 males and 2 females aged 20-40 years, and average age 28.3 ± 4.5 SD) were also invited for the discrimination testing (Test II). The subjects were all right-handed from the University of Sheffield and the University of Third Age (U3A) society.

Two younger subjects had cold hands whose temperature was beyond the designed range. They were advised to warm the hand before the test. Thus, the average of subjects' finger temperature was 29.2 ± 1.5 °C (including warmed hands) in younger group and 30.5 ± 1.6 °C in older group.

4.4.1 Results from the absolute threshold testing

Figure 4.4 shows the trend of threshold at twelve threshold measurements. Each point is the average absolute threshold for each age group. Overall, the absolute thresholds in 20-40 years group are lower than in 60-90 years, which proves that younger people have better sensitivity to vibration than older people. The haptic sensation to vibration is deteriorated due to age. Furthermore, in the 20-40 years group, the average threshold decreases rapidly from the 60Hz to 100Hz. Then, it remains at a similar level from 100 to 300Hz. In the high-frequency range (300-800 Hz), the threshold increases up again. This result agreed with a similar study undertaken by Verrillo [94]. He found that finger sensitivity to vibrations is like a U-shape curve between 60-800 Hz. However, the average threshold shows slightly different shape in 60-90 years group but the trend is the same with the younger group. The reason may be that the button size of the speaker is different from the vibrator in the study of [94].

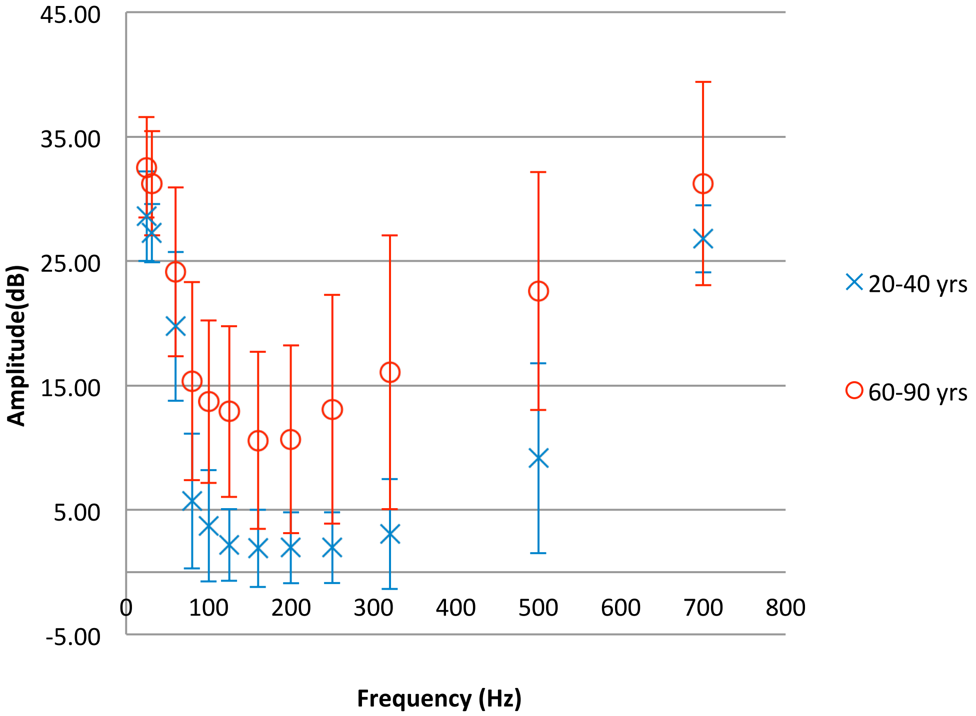
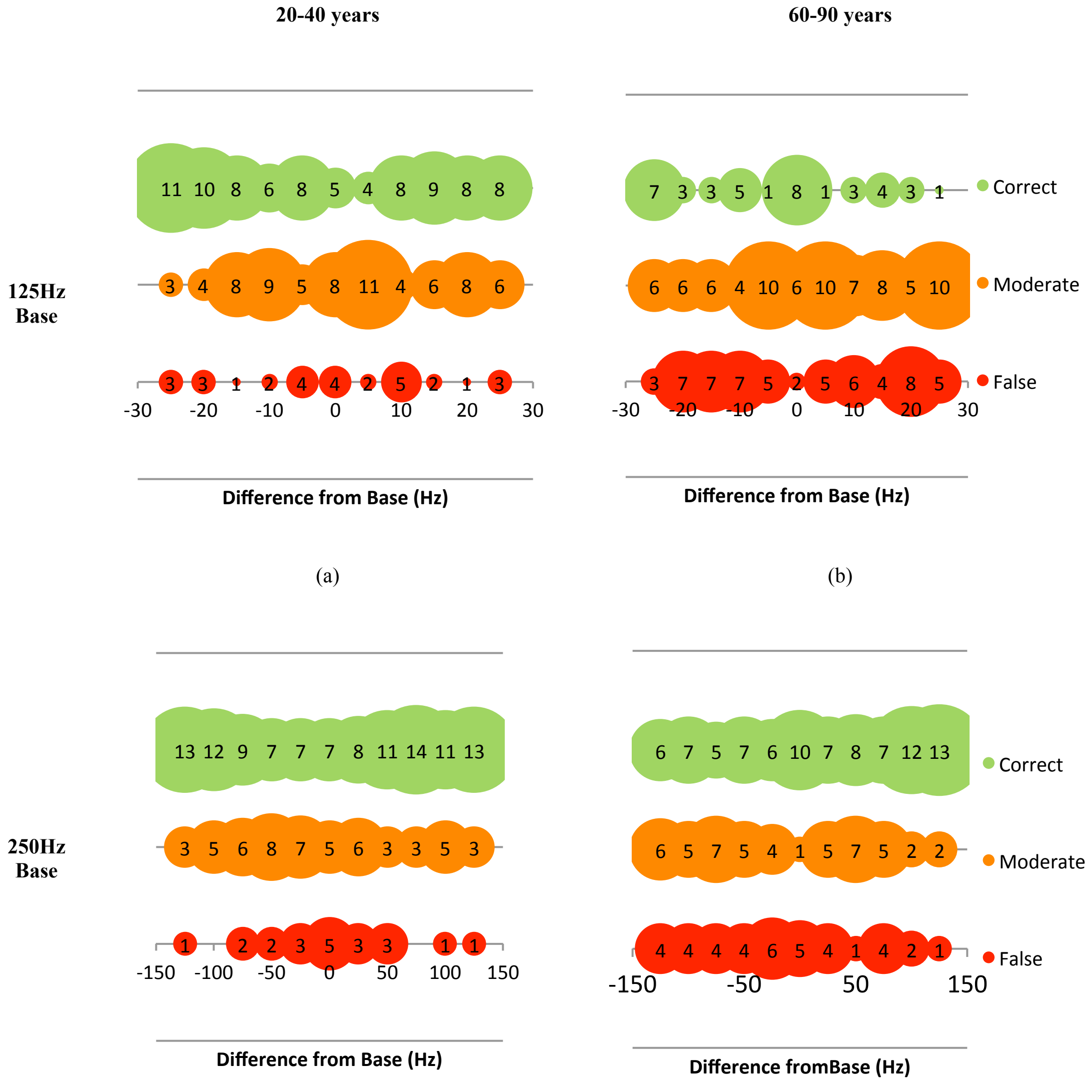


Figure 4.4 - Absolute threshold of finger sensitivity

In short, the optimal sensitivity to vibration is in the range of 100-300 Hz for both younger and older people however the ability of perceiving vibration declines due to age.

4.4.2 Results from the discrimination testing

The results of discrimination testing are shown in Figure 4.5. It illustrates that the number of correct responses increases significantly in the frequency base of 250 Hz in 60-90 years group compared to 125 Hz base. And also, the number of moderate and false responses at 250 Hz base reduces slightly. This may be caused by the discriminating changes (the minimum value is 25 Hz) at 250 Hz base are larger than the ones (the minimum value is 5 Hz) at 125 Hz. However, in 20-40 years group, there are no big changes of the number in each response.



(a) (b)

(c) (d)

Figure 4.5 – Discrimination testing for the vibrotactile perception experiment

Furthermore, Figure 4.6 shows that, at 125Hz base, the younger group outperforms the older people according to the percentage of correct responses, whereas at 250 Hz the older group has no significant difference from younger group. The best discrimination is in the pair of ‘100Hz - 125 Hz’ at 125 Hz base for both age groups, whereas the pair of ‘375Hz - 250 Hz’ at 250 Hz base. Overall, 60% of subjects can differentiate the vibrations between 125 Hz and 100 Hz, whereas at 250 Hz base with the discriminating changes of 50 Hz, 100 Hz and 125 Hz.

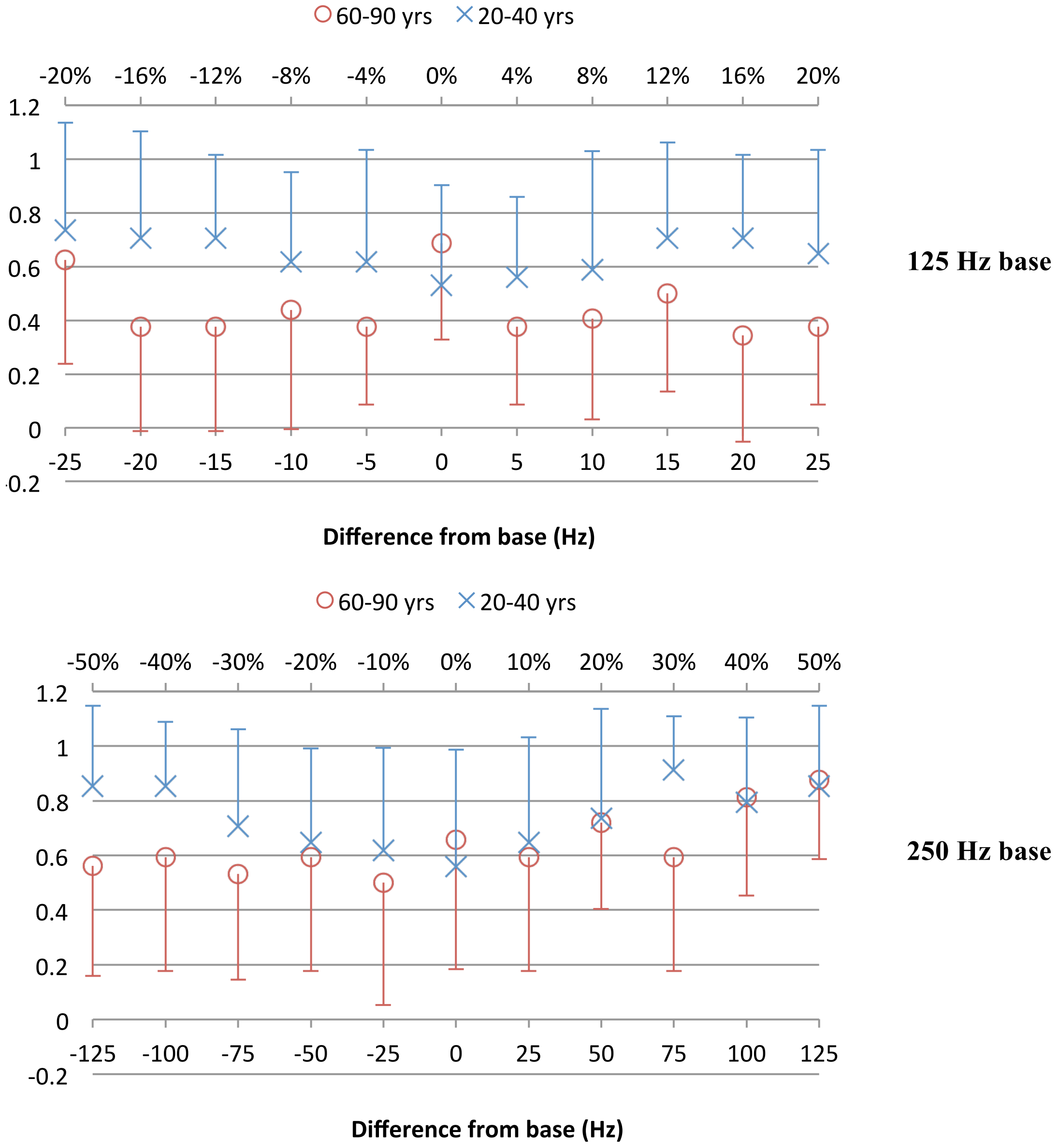


Figure 4.6 - The percentage of correct responses at each frequency base.

In short, the ability to discriminate the vibration at 250 Hz base is better than 125 Hz base. The best discrimination is the pair of '100Hz - 125 Hz' and '375Hz - 250 Hz' for all ages. 60% of younger and older subjects can differentiate the vibrations of 125 Hz base from 100 Hz, whereas at 250 Hz, the subjects can tell the differences of 250 Hz from 300 Hz, 350 Hz and 375 Hz.

4.5 Discussion

The following sections discuss the results of the finger sensitivity to vibration.

4.5.1 Absolute threshold to vibration testing

The results show that the absolute threshold of finger sensitivity to vibration has the trend of U-shape in the range of 20-800 Hz in 20-40 years group. The threshold shows a slightly different curve in 60-90 years group but the trend is the same with younger group. However, this finding is different from the conclusions by Verrillo [94], who found out that the finger sensitivity (e.g. 20-40 Hz) remained stable at lower frequencies for all ages except the 10 years group shown in Figure 4.7.

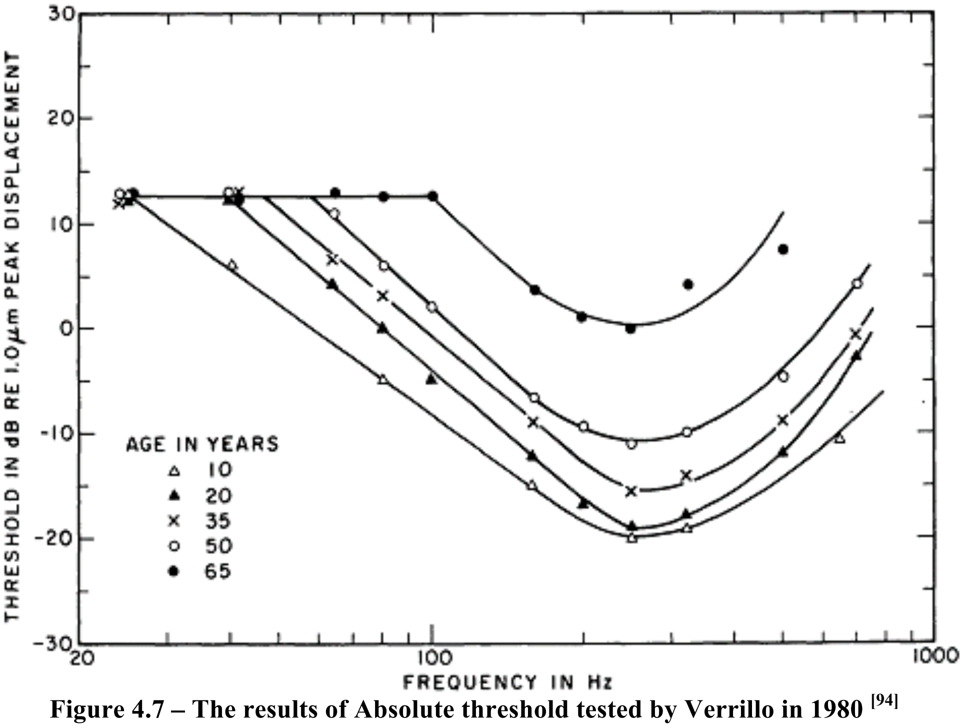


Figure 4.7 – The results of Absolute threshold tested by Verrillo in 1980 [94]

The explanation could be that the meissner's corpuscles (FA I) are responsible for the lower frequencies in the range of 5-40 Hz. The ability of FA I receptors remains at the same level whereas the number of the pacinian corpuscles (FA II) changes due to age. However, the experimental set-up in this testing is designed to measure the sensitivity of pacinian corpuscles to vibration and may not be appropriate to measure the threshold of meissner's corpuscles. The differences could be also caused by the author or subjects biases.

In addition, the statistical analysis using T-Test was carried out in order to find a relationship between age groups at each average threshold. The dependent variables are the average of absolute thresholds of each subject at each threshold measurement. The results are shown in Table 4.4. Take an example of 25 Hz, there is a statistically significant effect of age between groups (F (2,27) = 3.79, p = .035). Overall, the age factor is significant at all threshold measurements except the frequency of 60 Hz.

Table 4.4 – p-Value of the T-Test at each threshold measurement

No.	**Frequency (Hz)**	**F**	***p***
(1)	25	3.794	**0.035**
(2)	31.5	4.020	**0.030**
(3)	60	1.818	**0.182**
(4)	80	6.189	**0.006**
(5)	100	10.799	**0.000**
(6)	125	12.555	**0.000**
(7)	160	8.058	**0.002**
(8)	200	6.974	**0.004**
(9)	250	7.720	**0.002**
(10)	320	7.252	**0.003**
(11)	500	7.948	**0.002**
(12)	700	2.082	**0.144**

Above all, it is found that the range of 100-300 Hz is the optimal limit for both younger and older people to perceive the vibration and age factor has a significant influence in finger sensitivity except the frequency of 60 Hz.

4.5.2 Discrimination of vibration testing

Due to the collected data does not meet the criterion of the ANOVA method because the dependent variables (score of responses) are designed in the ordinal level (false, moderate, correct). Thus, the Chi-Square test was carried out to determine whether there is a relationship between two age groups of the discrimination in vibration.

Table 4.5 – p-Value of the Chi-Square test at different frequency bases

	No.	Vibration A	Vibration B	Chi-Square Test *p*
	(1)	100	125	**0.394**
	(2)	105	125	**0.027**
	(3)	110	125	**0.030**
	(4)	115	125	**0.092**
	(5)	120	125	**0.027**
125 Hz Base	(6)	125	125	**0.446**
	(7)	130	125	**0.212**
	(8)	135	125	**0.207**
	(9)	140	125	**0.241**
	(10)	145	125	**0.015**
	(11)	150	125	**0.031**
	(1)	125	250	**0.069**
	(2)	150	250	**0.071**
	(3)	175	250	**0.395**
	(4)	200	250	**0.514**
	(5)	225	250	**0.393**
250 Hz Base	(6)	250	250	**0.205**
	(7)	275	250	**0.874**
	(8)	300	250	**0.218**
	(9)	325	250	**0.033**
	(10)	350	250	**0.442**
	(11)	375	250	**0.919**

Table 4.5 shows that *p* value of most discrimination pairs are greater than 0.05, except for the pairs of ‘110 Hz - 125 Hz’, ‘120 Hz - 125 Hz’, ‘145 Hz - 125 Hz’, ‘150 Hz - 125 Hz’ at 125 Hz frequency base, and ‘325 Hz - 250 Hz’ at 250 Hz frequency base. Due to the limited number of subjects, it cannot statistically prove whether the age has a significant influence in the discrimination of vibration. A large sample size is required in the future experiment for each discrimination pair in order to find the limits of people discriminating frequency changes.

Above all, the performance of discriminating vibration is better at 250 Hz base compared to 125 Hz base, and 60% of subjects can differentiate vibrations at 125 Hz base with the discriminating changes of -25 Hz and at 250 Hz base with the discriminating changes of +50 Hz, +100 Hz and +25 Hz.

4.6 Summary

This chapter has explained the details of the experiment of vibrotactile perception. The results validated that the absolute threshold shows the U-shape curve in the range of 20-800 Hz in the younger group. The optimal sensation to vibration for both younger and older people is in the range of 100-300 Hz. However, the ability to detect vibration decreases gradually with age. In addition, the ability to discriminate vibration at 250 Hz base is better than 125 Hz base.

5 Descriptions of Vibrotactile Effects

This chapter assesses the vibrotactile effects available on smartphones using the semantic differential descriptions with the purpose of investigating the relationship between the descriptions and the vibrotactile effects.

5.1 Experimental design

In this experiment, the target number of subjects is the same as the vibrotactile perception experiment, which is 10-20 in each age group with the maximum number of judgments being 50 in a single session. The test room temperature and subjects' finger were measured as discussed in Chapter 4.

The most important part of the experimental design was to determine the adjective ratings to be used to describe the haptic sensations to the vibrotactile effects. Inwook and Seungmoon [133] tried to sort out the semantic differential adjective pairs through testing nine Korean subjects. The study concluded that 13 pairs of expressions that well matched the feelings of vibration and then translated the expressions into English. Furthermore, they invited another ten Korean subjects to rate those 13 adjectives and the conclusions are shown in Table 5.1. It can be seen that *'dull-clear'* were the most appropriate expressions to describe the feelings of vibration in the range of 40-250 Hz. In addition to this, *'slow-fast'* and *'vague-distinct'* were the best pairs for the lower frequency vibration and *'heavy-light'* for the higher vibration in the range of 40-250 Hz.

Table 5.1- Conclusions from 13 adjective ratings [133]

Group	Adjective pairs	Vibration Frequency	Appropriate pairs
1	Dull-Clear; Dark-Bright;	40-250 Hz	Dull-Clear
2	Slow-Fast; Vague-Distinct; Sparse-Dense; Bumpy-Smooth; Jagged-Aligned	40-100 Hz	Slow-Fast; Vague-Distinct;
3	Light-Heavy; Thick-Thin; Deep-Shallow; Soft-Hard;	100-250 Hz	Light-Heavy
4	Blunt-Sharp; Gentle-Brisk;	N/A	No significant agreement

According to Inwook and Seungmoon’s work, Park et al. [78] tested seven pairs of semantic adjective pairs as shown in Table 5.2, in order to evaluate the vibrotactile sensation for virtual buttons on mobile phones. It was found that the subjects had a preference of ‘clear’ or ‘smooth’ sensation of vibrotactile feedback over ‘dull’ or ‘bumpy’ and ‘vague-distinct’ or ‘soft-hard’ are likely to describe the realism of the virtual buttons compared to the physical buttons.

Table 5.2- List of adjective descriptions for the vibrotactile effects

Pair No.	Evaluation Criteria	Adjective 1	Adjective 2
1	Speed	Slow	Fast
2	Dissimilarity	Vague	Distinct
3	Regularity	Bumpy	Smooth
4	Density	Light	Heavy
5	Strength	Weak	Strong
6	Solidity	Soft	Hard
7	Clarity	Dull	Clear

Therefore, this experiment replicated the above adjective ratings in order to ascertain the most appropriate adjectives to represent the meaning of vibration as a language. Hence, seven adjective pairs of descriptions in Table 5.2 are determined for the assessment and evaluation in vibrotactile effects.

5.2 Equipment for the description of vibrotactile effects experiment

For the purpose of haptic language development, this study focuses on classical vibro-mechanical actuators to generate vibrotactile effects because they are currently available technology on smartphones. In the future, the vibrotactile effects could be produced with new technology. For instance, new materials could bring new solutions into actuator design, such as electro-active polymers (EAP) materials that can contract, expand or bend to a limited extent when an electric current or voltage is applied to them [134]. Holographic interaction introduces a new research field into haptic feedback design for projections [135, 136].

From Table 3.2 it is noticed that four smartphones use either eccentric rotating mass motors (ERM) or linear resonance actuators (LRA) to provide vibrotactile feedback. ERM actuators are widely established in current mobile phones. The reasons are that they are small size, lightweight and cheap. However they have limited control of the stimulation parameter, with frequency and amplitude linked together. LRA actuators are also commonly used in smartphones because it is more robust than ERM and has a greater degree of controlling stimulation, with frequency and amplitude being independent parameters.

Table 5.3 - Characteristics of different vibro-mechanical actuators[137]

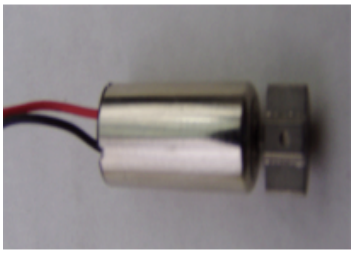
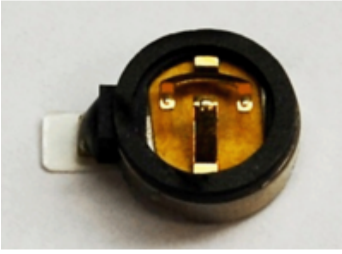
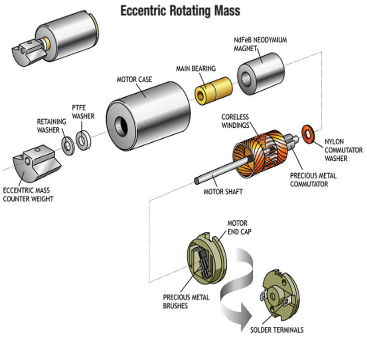
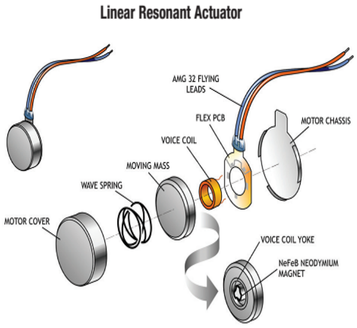
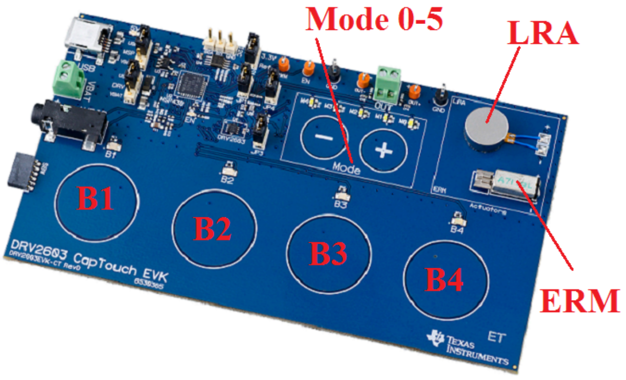
Actuator	**ERM**	**LRA**
Example		
Diagram		
Size	15.5 mm long with diameter 4.7 mm	contact surface 20 -30 mm square with thickness 8 - 10 mm
Weight	5 - 10g	5 - 20g
Displacement	dependent for actuator	up to 10 mm peak
Frequency	up to 160 Hz	20-500 Hz
Drive waveform	direct current (DC)	any waveform, sine wave typical
Power	0.05 – 0.2 W	0.2 - 1.0 W

Table 5.3 lists the characteristics of LRA and ERM actuators. LRA actuators vibrate like a specialized "speaker". It is a coin based actuator so instead of a cone generating sound waves, there is a moving mass in a closed housing vibrating when the electrical signal is applied, whereas ERM actuators are known as *pager motors*,

which consist of a housing incorporating a motor with an eccentric mass. When the eccentric mass rotates, the centripetal force of the mass is asymmetric, resulting in a net centrifugal force, which drives the motor constantly being displaced and moved. Hence, the regular movements are perceived as a vibration. In order to drive the above actuators, LRA actuators need an AC voltage, typically a sinusoidal waveform, in the range of 20-500Hz. However, ERM actuators require a DC voltage in the range of 1.5-2 V. The intensity and frequency of the motor is dependent in a limited range up to 160 Hz [137].

Table 5.4 – Vibrotactile effects of Mode 0 on the haptic evaluation kit [138]

Mode	LED	Button	Vibrotactile Effects	Actuator Mode
Mode 0	off	B1	Ramp-up and click	LRA (auto-resonance on)
		B2	Click and Ramp-down	
		B3	Ramp-up and click	ERM
		B4	Click and Ramp-down	
				

Therefore, the haptic evaluation kit in Table 5.4 (model: DRV2603 from Texas Instruments) was selected for this experiment because it can offer a great solution to drive both LRA and ERM actuators in a single board as well as provide multimodal effects on four capacitive touch buttons (B1-B4) and LEDs. Six modes can generate totally 21 haptic effects such as ramp-up/down, click, and alert. The details of each mode (Mode 0-5) can be found at Appendix 2. Mode 0 was selected because the vibrotactile effects are designed with the vibration ramping up/down and generated on both LRA and ERM actuators without any visual cues from the LEDs. Thus, when the kit is powered on through a USB cable and port on computer, a demo application automatically starts. The vibrotactile effects are produced every time by pressing the button.

5.3 Experimental procedures

Seven semantic differential adjective pairs was used to evaluate the vibrotactile effects, which are *'slow-fast', 'vague-distinct', 'bumpy-smooth', 'light-heavy', 'weak-strong', 'soft-hard'* and *'dull-clear'* (see Table 5.2), in order to provide the descriptions of the sensations to vibration for the subjects.

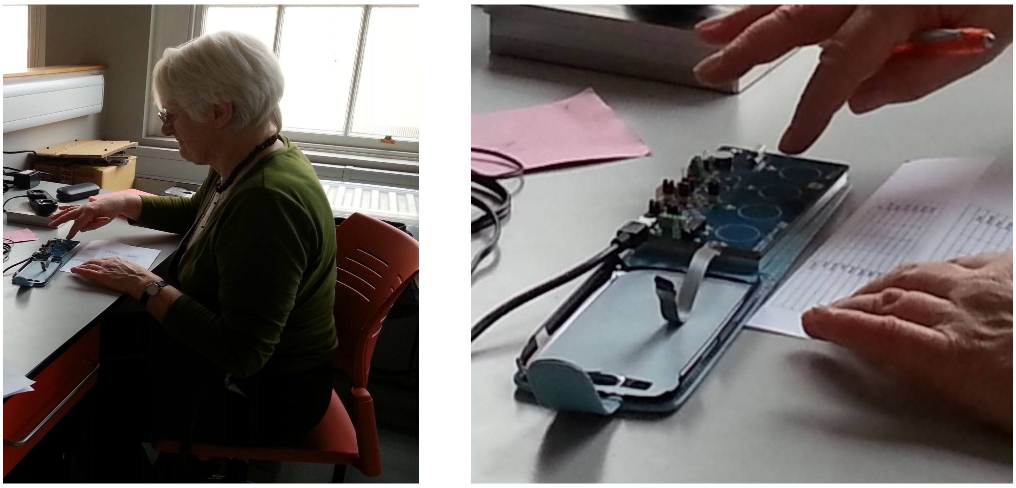


Figure 5.1 – Subject experienced vibrotactile effects on the haptic evaluation kit

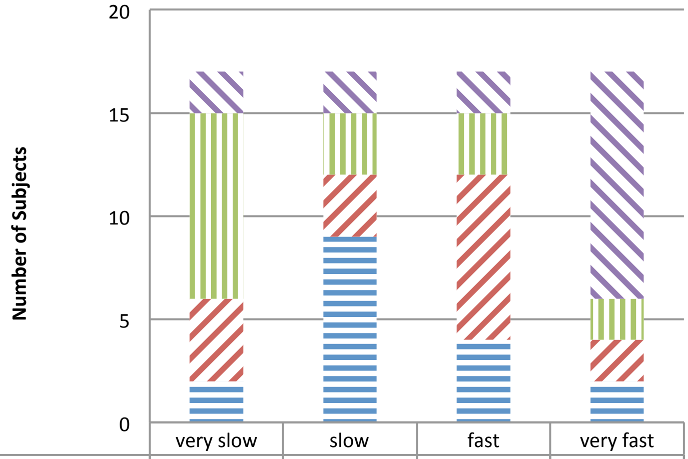
Figure 5.1 illustrates that the subject was pressing the button to experience the vibrotactile effects. The subjects sat casually under normal laboratory condition. The haptic evaluation kit was put in a phone case and placed in the table. They were allowed to interact with the vibrotactile effects freely and were required to rank four selected vibrotactile effects (see Table 5.4) according to each adjective pair, for instance, *'very slow'*, *'slow'*, *'fast'* and *' very fast'*. The subjects would perceive the vibration when pressing the button and the vibration stops when releasing it. Finally, they were asked to choose one out of four effects they would prefer to experience as vibrotactile feedback on the smartphones. The test protocol took around 10 minutes to complete.

5.4 Results

The same subjects from the discrimination testing were invited in this experiment. 17 younger subjects (11 males and 6 females aged 20-40, and average age 28.0 ± 5.0) and 16 older subjects (5 males and 11 females aged 60-90, and average age 72.3 ± 5.6) were tested. All the subjects were right-handed.

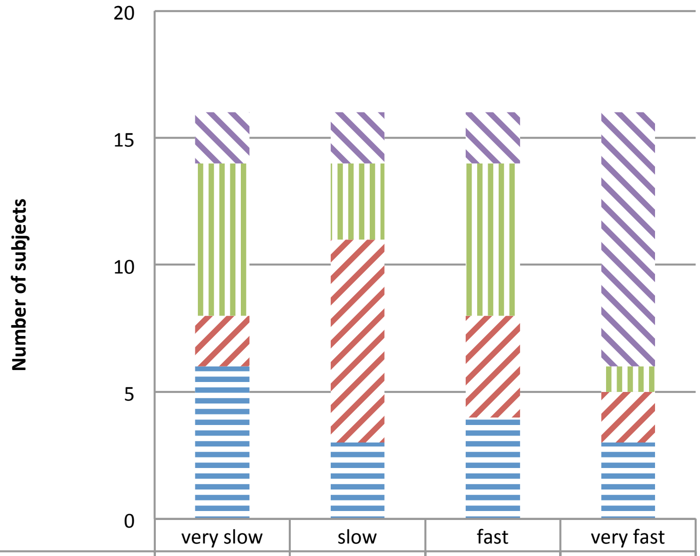
Figure 5.2 shows that 11 out of 17 younger subjects ranked the vibration from B4 as *'very fast'*, and 9 out of 17 younger subjects chose the vibration from B3 as *'very slow'* and B1 as *'slow'*. Furthermore, 8 out of 17 younger subjects ranked B2 as *'fast'*. Thus, the speed of four vibrotactile effects is agreed with B3<B1<B2<B4 from slow to fast in younger group. However, there is no clear order in older group yet 10 out of 16 older subjects ranked the vibration from B4 as *'very fast'*.

20-40 years



	very slow	slow	fast	very fast
B4 Click and Ramp-down (ERM)	2	2	2	11
B3 Ramp-up and Click (ERM)	9	3	3	2
B2 Click and Ramp-down (LRA)	4	3	8	2
B1 Ramp-up and Click (LRA)	2	9	4	2

60-90 years

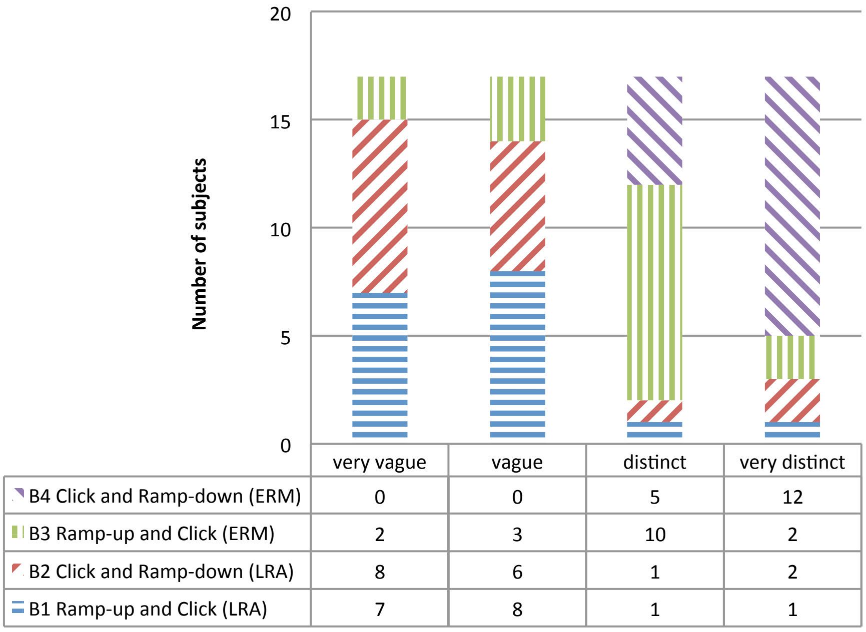


	very slow	slow	fast	very fast
B4 Click and Ramp-down (ERM)	2	2	2	10
B3 Ramp-up and Click (ERM)	6	3	6	1
B2 Click and Ramp-down (LRA)	2	8	4	2
B1 Ramp-up and Click (LRA)	6	3	4	3

Figure 5.2 - Agreement level of vibrotactile effects according to vibration speed between younger people and older people

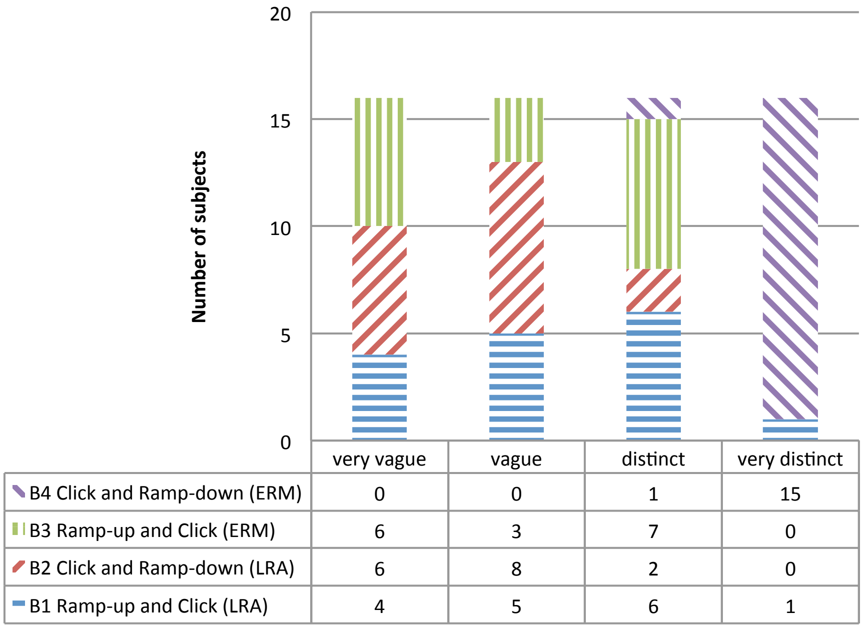
In Figure 5.3, there is a clear agreement that 12 out of 17 younger subjects and 15 out of 16 older subjects selected B4 as the most distinct vibration. However, there is no clear order according to the criterion of *'very vague'*, *'vague'* and *'distinct'* in both age groups. Hence, the adjective pair of *'vague-distinct'* is not clear to describe the perception to vibrotactile effects in both younger and older group.

20-40 years



	very vague	vague	distinct	very distinct
B4 Click and Ramp-down (ERM)	0	0	5	12
B3 Ramp-up and Click (ERM)	2	3	10	2
B2 Click and Ramp-down (LRA)	8	6	1	2
B1 Ramp-up and Click (LRA)	7	8	1	1

60-90 years

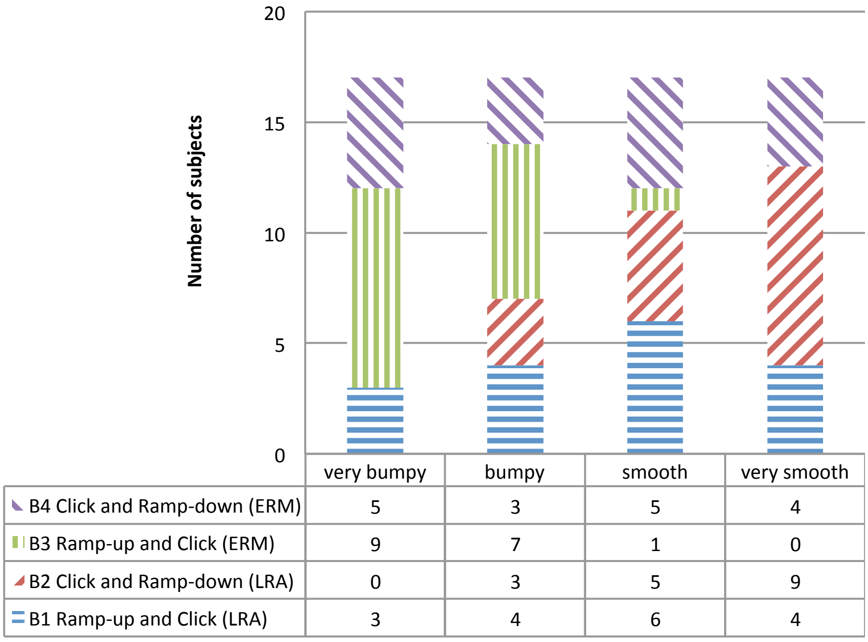


	very vague	vague	distinct	very distinct
B4 Click and Ramp-down (ERM)	0	0	1	15
B3 Ramp-up and Click (ERM)	6	3	7	0
B2 Click and Ramp-down (LRA)	6	8	2	0
B1 Ramp-up and Click (LRA)	4	5	6	1

Figure 5.3 - Agreement level of vibrotactile effects according to vibration dissimilarity between younger and older people

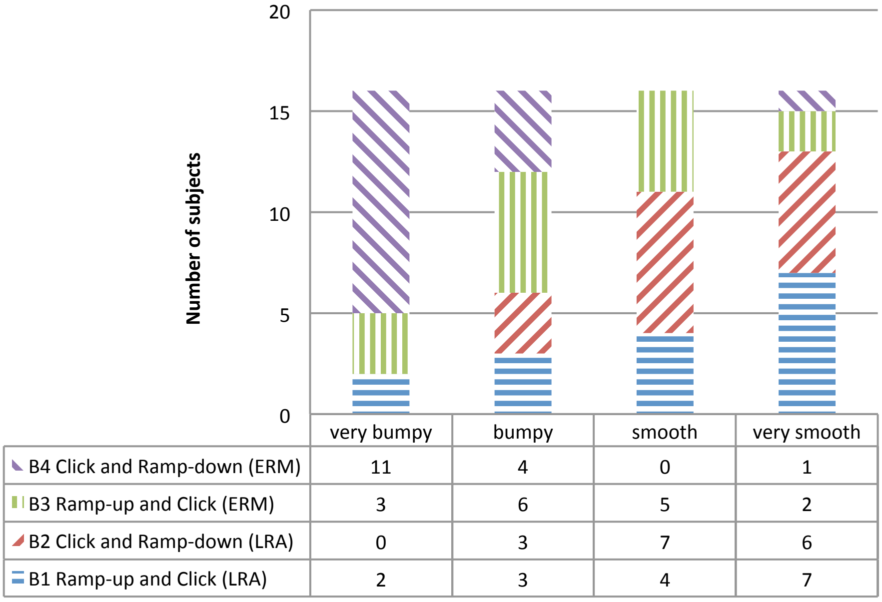
Figure 5.4 illustrates there is no clear order according to the criterion of *'very bump'*, *'bumpy'*, *'smooth'* and '*very smooth'* in both age groups but 11 out of 16 older subjects selected B4 as the bumpiest vibration. Thus, the adjective pair of *'bumpy-smooth'* is not clear to describe the perception to vibrotactile effects in both younger and older group.

20-40 years



	very bumpy	bumpy	smooth	very smooth
▧ B4 Click and Ramp-down (ERM)	5	3	5	4
▥ B3 Ramp-up and Click (ERM)	9	7	1	0
▨ B2 Click and Ramp-down (LRA)	0	3	5	9
▤ B1 Ramp-up and Click (LRA)	3	4	6	4

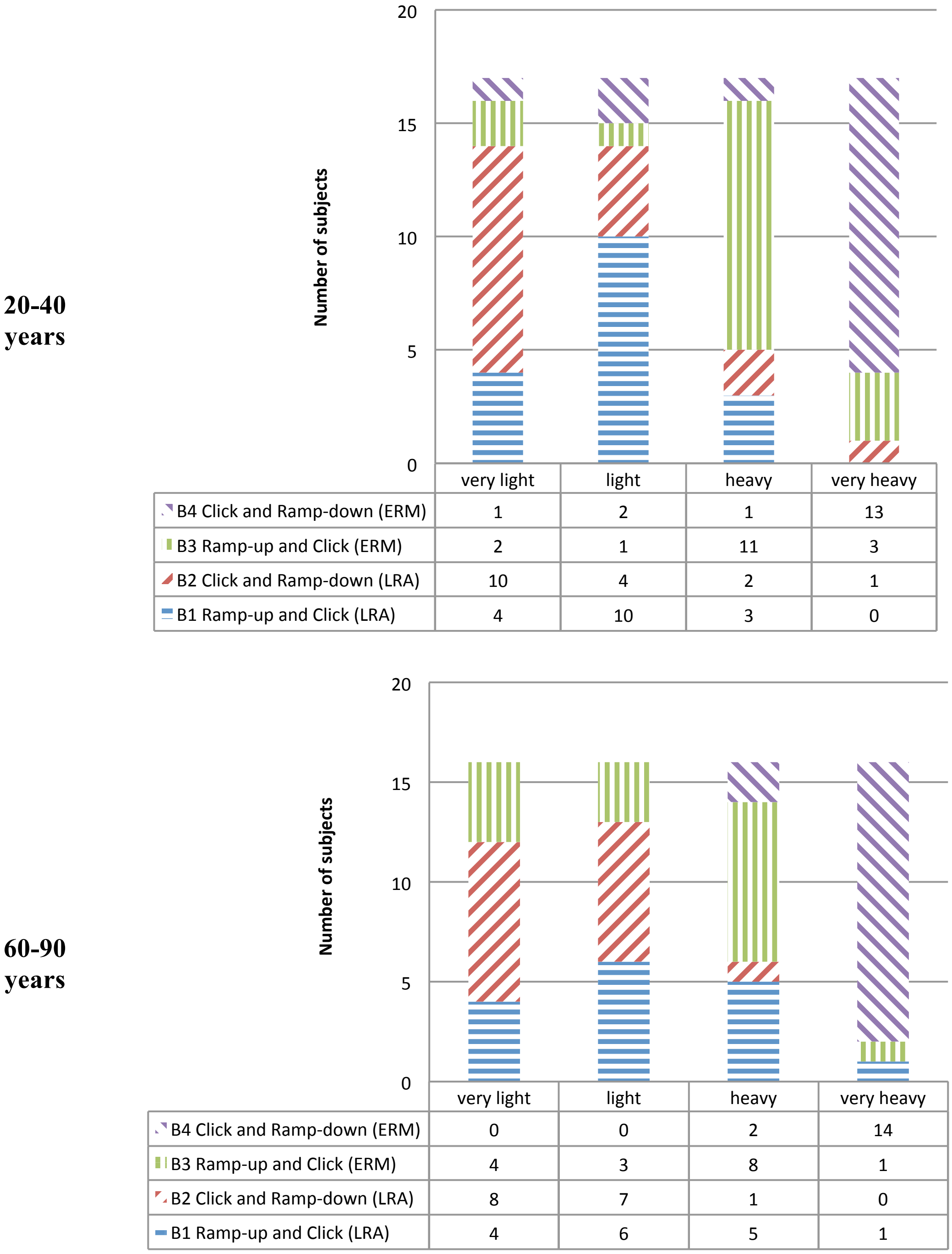
60-90 years



	very bumpy	bumpy	smooth	very smooth
▧ B4 Click and Ramp-down (ERM)	11	4	0	1
▥ B3 Ramp-up and Click (ERM)	3	6	5	2
▨ B2 Click and Ramp-down (LRA)	0	3	7	6
▤ B1 Ramp-up and Click (LRA)	2	3	4	7

Figure 5.4 - Agreement level of vibrotactile effects according to vibration regularity between younger and older people

In Figure 5.5 there is a clear agreement that 13 out of 17 younger subjects and 14 out of 16 older subjects chose B4 as the heaviest vibration. In younger group, the density of four vibrotactile effects is agreed with B2<B1<B3<B4 from light to heavy. However, there is no clear agreement in older group.



20-40 years

	very light	light	heavy	very heavy
B4 Click and Ramp-down (ERM)	1	2	1	13
B3 Ramp-up and Click (ERM)	2	1	11	3
B2 Click and Ramp-down (LRA)	10	4	2	1
B1 Ramp-up and Click (LRA)	4	10	3	0

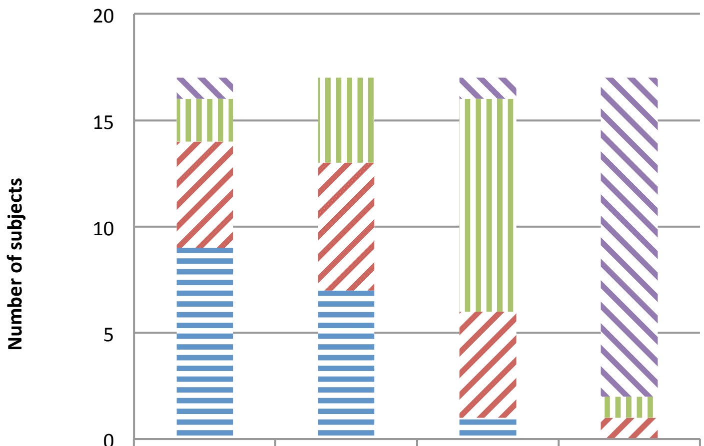
60-90 years

	very light	light	heavy	very heavy
B4 Click and Ramp-down (ERM)	0	0	2	14
B3 Ramp-up and Click (ERM)	4	3	8	1
B2 Click and Ramp-down (LRA)	8	7	1	0
B1 Ramp-up and Click (LRA)	4	6	5	1

Figure 5.5 - Agreement level of vibrotactile effects according to vibration density between younger and older people

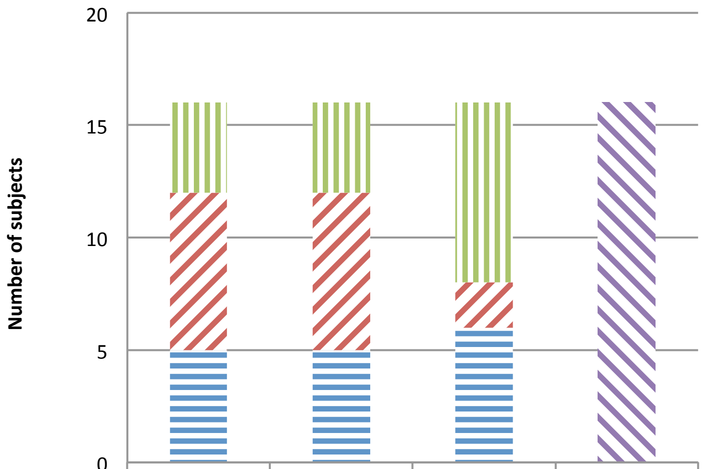
Figure 5.6 shows that 15 out of 17 younger subjects and 16 out of 16 older subjects ranked B4 as the strongest vibration. However, there is no clear order according to the criterion of *'very weak'*, *'weak'* and *'strong'* in both age groups. Hence, the adjective pair of *'weak-strong'* is not clear to describe the perception to vibrotactile effects in both younger and older group.

20-40 years



	very weak	weak	strong	very strong
▧ B4 Click and Ramp-down (ERM)	1	0	1	15
▥ B3 Ramp-up and Click (ERM)	2	4	10	1
▨ B2 Click and Ramp-down (LRA)	5	6	5	1
▤ B1 Ramp-up and Click (LRA)	9	7	1	0

60-90 years

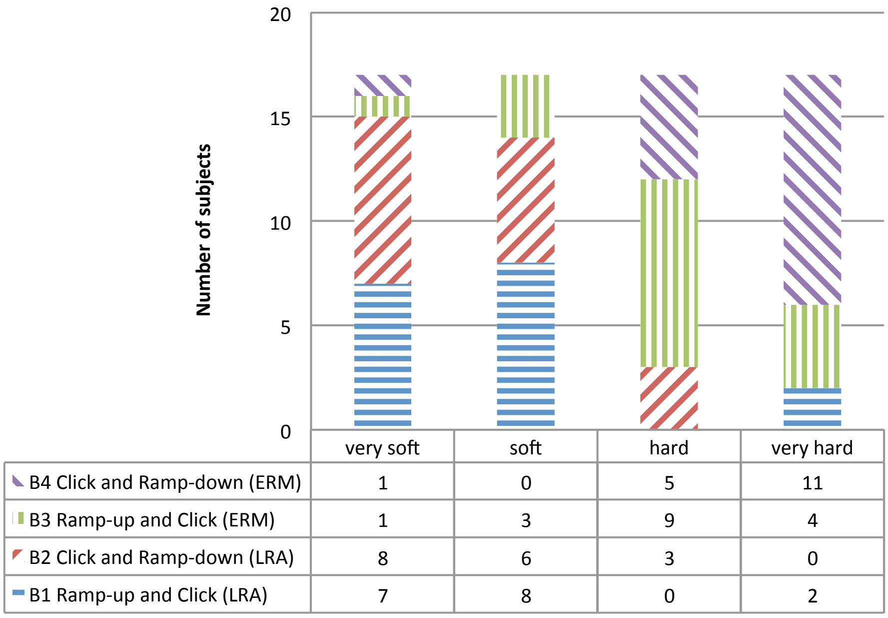


	very weak	weak	strong	very strong
▧ B4 Click and Ramp-down (ERM)	0	0	0	16
▥ B3 Ramp-up and Click (ERM)	4	4	8	0
▨ B2 Click and Ramp-down (LRA)	7	7	2	0
▤ B1 Ramp-up and Click (LRA)	5	5	6	0

Figure 5.6 - Agreement level of vibrotactile effects according to vibration strength between younger and older people

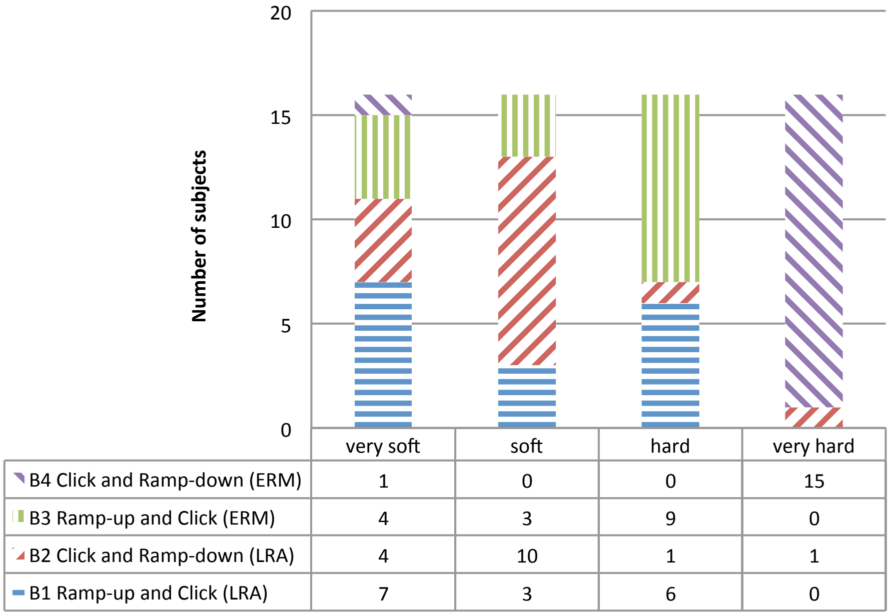
In Figure 5.7, 11 out of 17 younger subjects and 15 out of 16 older subjects ranked B4 as the hardest vibration. However, there is no clear order according to the criterion of *'very soft'*, *'soft'* and *'hard'* in both age groups. Hence, the adjective pair of *'soft-hard'* is not clear to describe the perception to vibrotactile effects in both younger and older group

20-40 years



	very soft	soft	hard	very hard
B4 Click and Ramp-down (ERM)	1	0	5	11
B3 Ramp-up and Click (ERM)	1	3	9	4
B2 Click and Ramp-down (LRA)	8	6	3	0
B1 Ramp-up and Click (LRA)	7	8	0	2

60-90 years

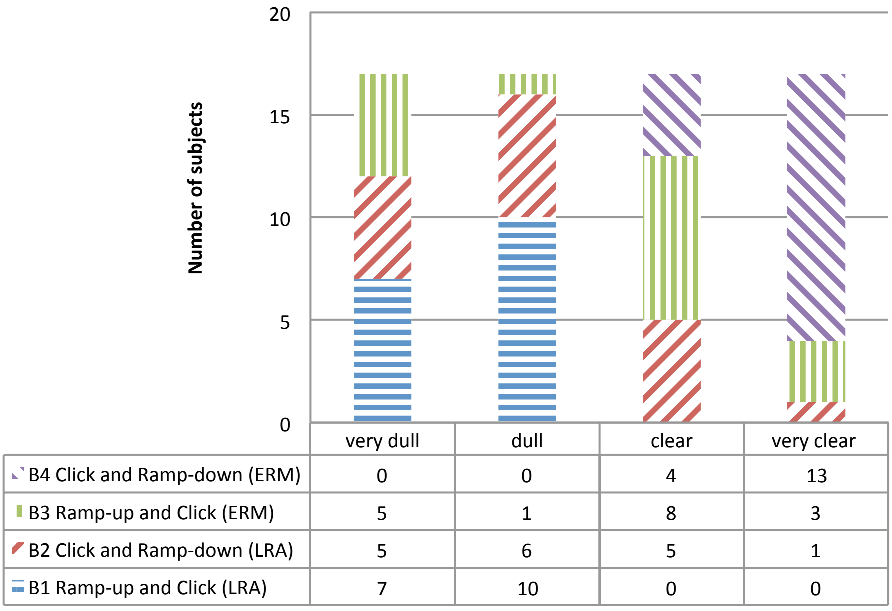


	very soft	soft	hard	very hard
B4 Click and Ramp-down (ERM)	1	0	0	15
B3 Ramp-up and Click (ERM)	4	3	9	0
B2 Click and Ramp-down (LRA)	4	10	1	1
B1 Ramp-up and Click (LRA)	7	3	6	0

Figure 5.7 - Agreement level of vibrotactile effects according to vibration solidity between younger and older people

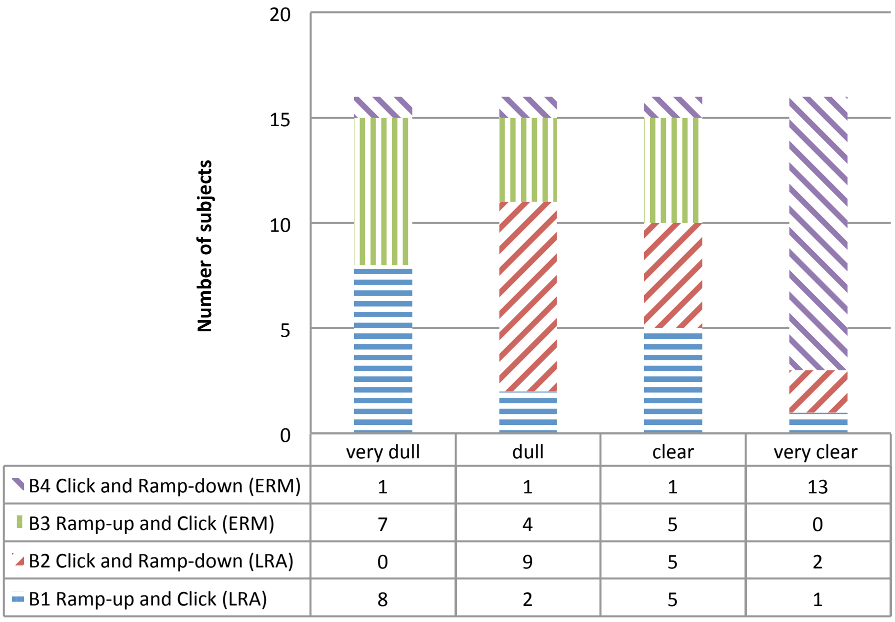
Figure 5.8 shows that there is a clear agreement that 13 out of 17 younger subjects and 13 out of 16 older subjects selected B4 as the clearest vibration. However, there is no clear order according to the criterion of *'very dull'*, *'dull'* and *'clear'* in both age groups. Hence, the adjective pair of *'dull-clear'* is not clear to describe the perception to vibrotactile effects in both younger and older group.

20-40 years



	very dull	dull	clear	very clear
B4 Click and Ramp-down (ERM)	0	0	4	13
B3 Ramp-up and Click (ERM)	5	1	8	3
B2 Click and Ramp-down (LRA)	5	6	5	1
B1 Ramp-up and Click (LRA)	7	10	0	0

60-90 years



	very dull	dull	clear	very clear
B4 Click and Ramp-down (ERM)	1	1	1	13
B3 Ramp-up and Click (ERM)	7	4	5	0
B2 Click and Ramp-down (LRA)	0	9	5	2
B1 Ramp-up and Click (LRA)	8	2	5	1

Figure 5.8 - Agreement level of vibrotactile effects according to vibration clarity between younger and older people

Overall, the conclusions of each pair are summarized in Table 5.5. The criterion of *‘slow-fast’* and *‘light-heavy’* are suitable to describe the feelings of vibrotactile effects for younger people. The vibrotactile effect of *‘click and ramp-down’* generated by the ERM actuator is the fastest, most distinct, heaviest, strongest, hardest and clearest vibration for both younger and older people but it is the bumpiest sensation to older people.

Table 5.5 – Conclusion of each pair in the descriptive preferences experiment

Pair No.	Evaluation Criterion	Adjective 1	Adjective 2	Ranking Order
1	Speed	Slow	Fast	B3<B1<B2<B4 in younger group; No agreement in older group;
2	Dissimilarity	Vague	Distinct	No agreement in both age groups
3	Regularity	Bumpy	Smooth	No agreement in both age groups
4	Density	Light	Heavy	B2<B1<B3<B4 in younger group; No agreement in older group;
5	Strength	Weak	Strong	No agreement in both age groups
6	Solidity	Soft	Hard	No agreement in both age groups
7	Clarity	Dull	Clear	No agreement in both age groups

Finally, 47% of younger subjects preferred the vibration on B2 as an alert effect as well as B4 is selected by 35% of younger people shown in Figure 5.9. However, 38% of older people chose B4 as an alert message compared to 6% of older subjects prefer B2. Hence, the effect of *'click and ramp-down'* could be seen as an alerting message for both younger and older people.

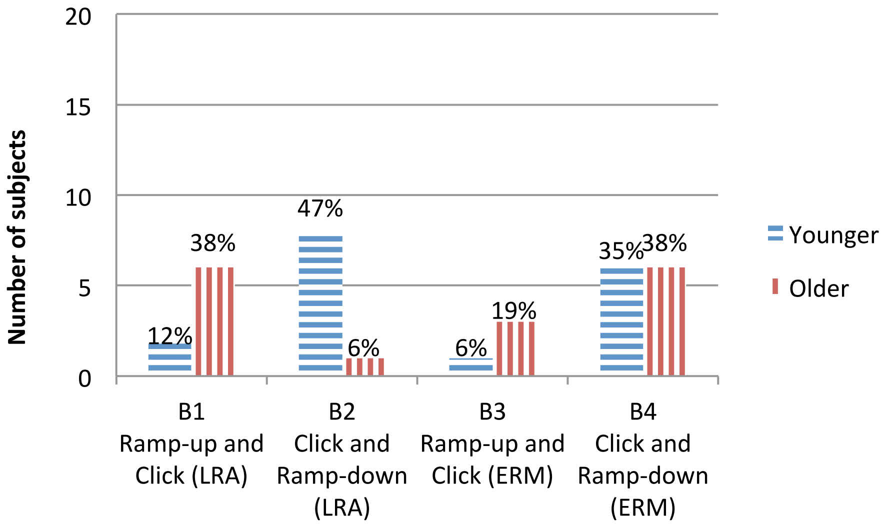


Figure 5.9 - Preference for different vibrotactile effects

In short, '*slow-fast'* and *'light-heavy'* are the best pair to describe the feelings of vibrotactile effects for younger people. The effect of *'click and ram-down'* produced by the ERM actuator is the fastest, most distinct, heaviest, strongest, hardest and clearest vibration for all ages and was chosen among four effects as the alert message for both younger and older people.

5.5 Discussion

The results conclude that *'slow-fast'* and *'light-heavy'* are the appropriate rating to describe the feelings of vibration by younger people but not for older people. The similar conclusions in [133] found that *'slow-fast'* was suitable to describe the sensation at lower frequency vibration in the range of 40-100 Hz and *'heavy-light'* for the higher vibration in the range of 100-250 Hz. Hence, the above two pairs could be the opposite meanings to guide the development of haptic language. The following sections discuss the influences of different factors on experimental results.

5.5.1 Age factor

The Chi-Square test was carried out to determine whether there is a significant difference between age groups for adjective ratings as the collected data (the number of responses) are designed in the ordinal level (seven adjective pairs).

Table 5.6 - *p*-Value of Chi-Square test for adjective descriptions

Criterion	*p*-Value			
	B1 Ramp-up and Click (LRA)	B2 Click and Ramp-down (LRA)	B3 Ramp-up and Click (ERM)	B4 Click and Ramp-down (ERM)
Slow-Fast	0.159	0.236	0.592	0.999
Bumpy-Smooth	0.675	0.636	0.052	0.027
Soft-Hard	0.017	0.230	0.123	0.061
Weak-Strong	0.081	0.446	0.602	0.367
Vague-Distinct	0.168	0.411	0.212	0.085
Light-Heavy	0.480	0.504	0.375	0.342
Dull-Clear	0.010	0.116	0.122	0.287

Table 5.6 shows that *p*-value of each pair of description are greater than 0.05, which means that younger and older people have no significant difference of the adjective ratings to the vibrotactile effects. However, the adjective ratings to describe the effect of B4 (*'click and ramp-down'* on ERM actuator) in younger and older groups have a significant difference according to the pair of *'bumpy-smooth'* ($\chi(3) = 9.171$, $p = .0027$), as well as *'soft-hard'* and *'dull-clear'* to describe B1 (effects of ramp-up and click on LRA actuator).

5.5.2 Ramping effects and actuators

The same results were also categorized into different actuators according to two effects of *'ramp-up and click'* and *'click and ramp-down'*. Figure 5.10 shows that the effect of '*click and ramp-down'* on the ERM actuator is the faster vibration than on the LRA actuator in the 20-40 years group. However, the effect of *'ramp-up and click'* on the ERA actuator is the slower vibration than LRA actuator. The reason is that younger people can quickly respond to the vibration of decreasing amplitude rather than increasing no matter what type of actuator. In the 60-90 years group, there is no clear agreement of the effect of *'ramp-up and click'* yet the sensation to the effect of *'click and ramp-down'* on the ERM actuator feels faster than on LRA actuator.

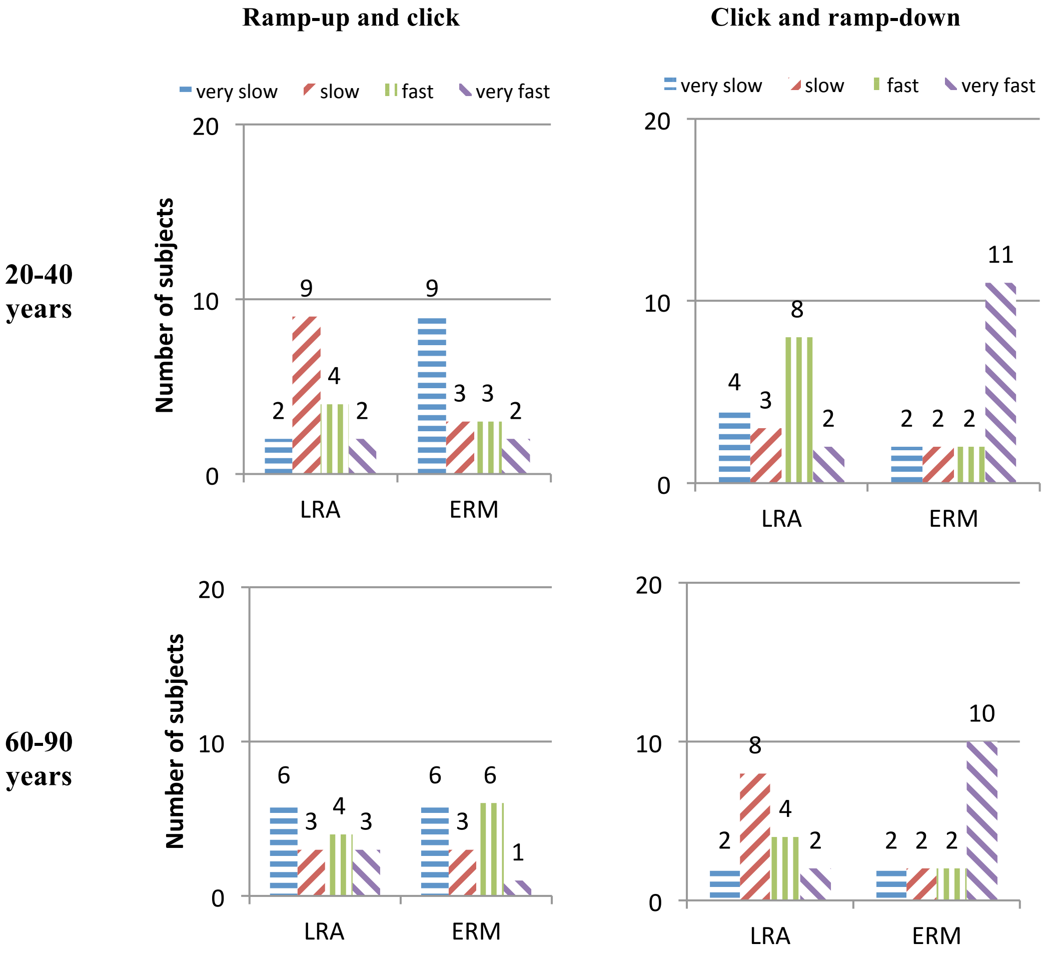


Figure 5.10 – Vibrotactile effects generated by LRA and ERM actuators from slow to fast

Therefore, the vibrotactile effect of *'click and ramp-down'* on the ERM actuator is faster than LRA actuator for both younger and older subjects. However, there is no agreement of the vibrotactile effect of *'ramp-up and click'*.

Furthermore, Figure 5.11 – 5.16 shows the number of responses sorted by LRA and ERM actuators for other adjective pairs. The results illustrates that the vibration on ERM actuator is more distinct, heavier, stronger, harder and clearer than on LRA actuator for both younger and older group except the comparison of the effect of *'ramp-up and click'*. However, the vibration on LRA actuator is smoother than on ERM actuator.

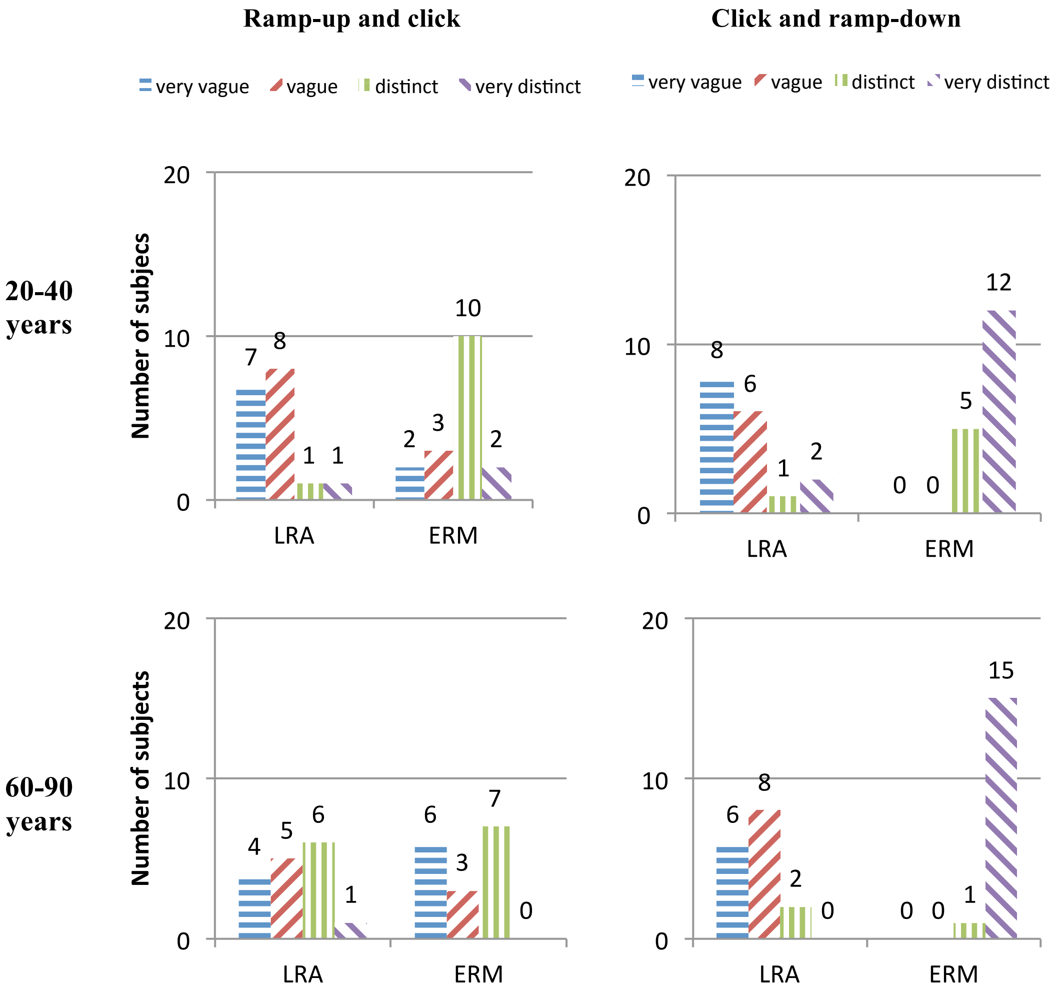


Figure 5.11 – Vibrotactile effects generated by LRA and ERM actuators from vague to distinct

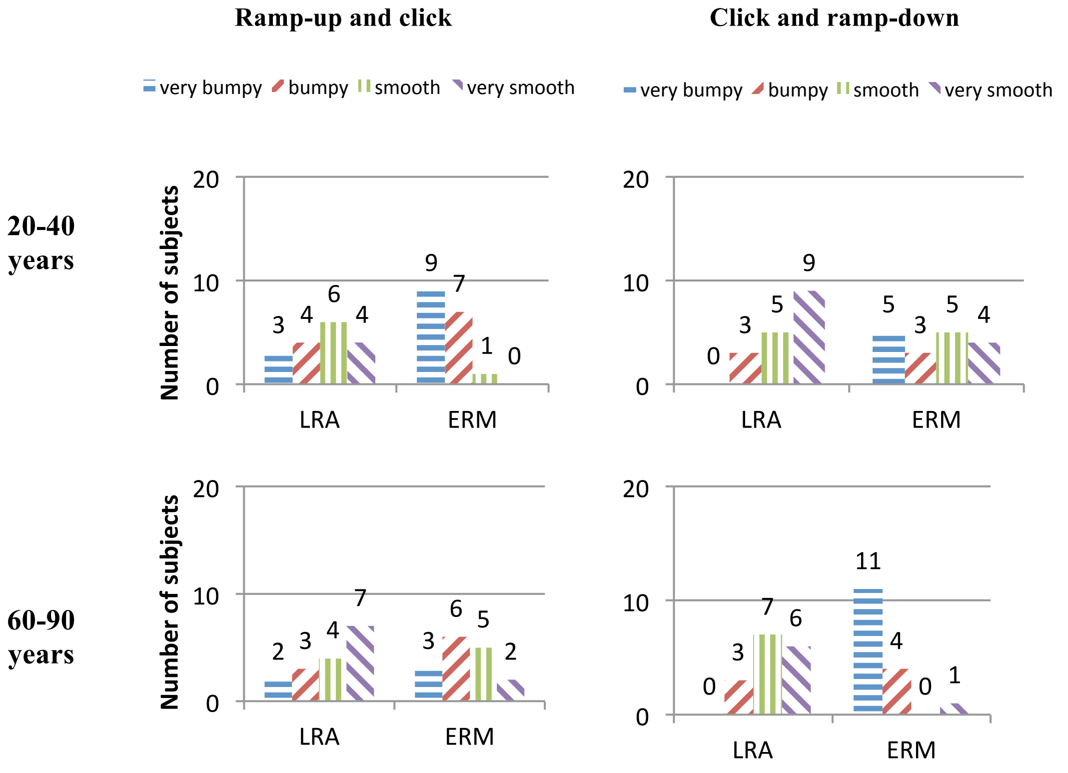


Figure 5.12 – Vibrotactile effects generated by LRA and ERM actuators from bumpy to smooth

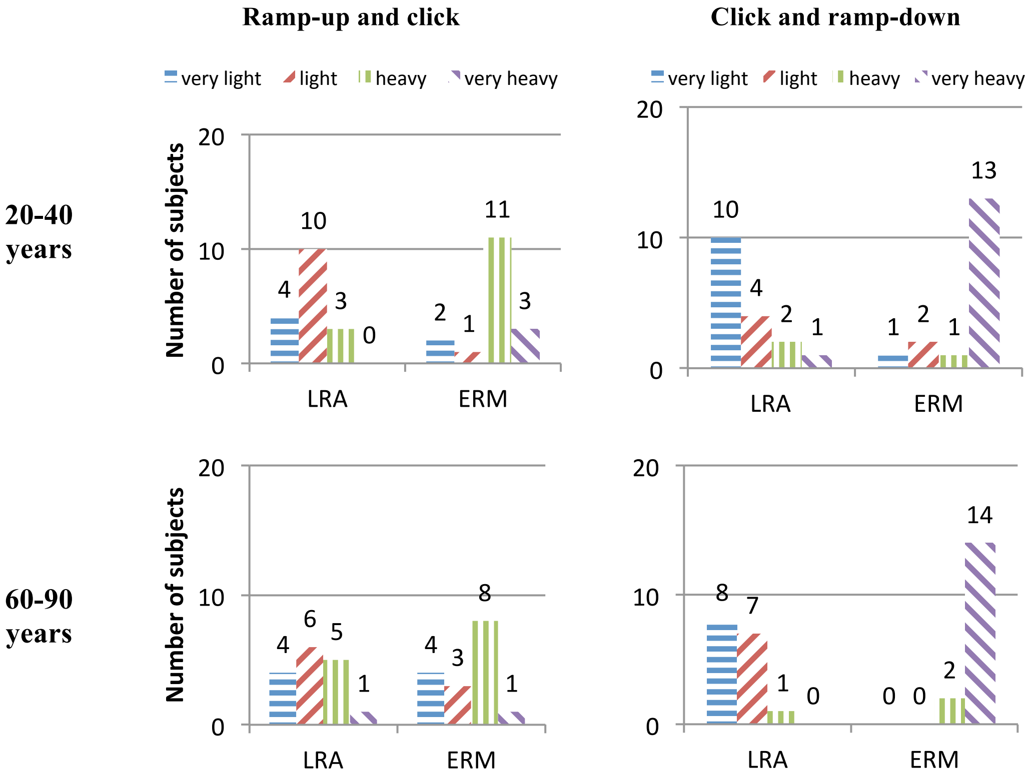


Figure 5.13 – Vibrotactile effects generated by LRA and ERM actuators from light to heavy

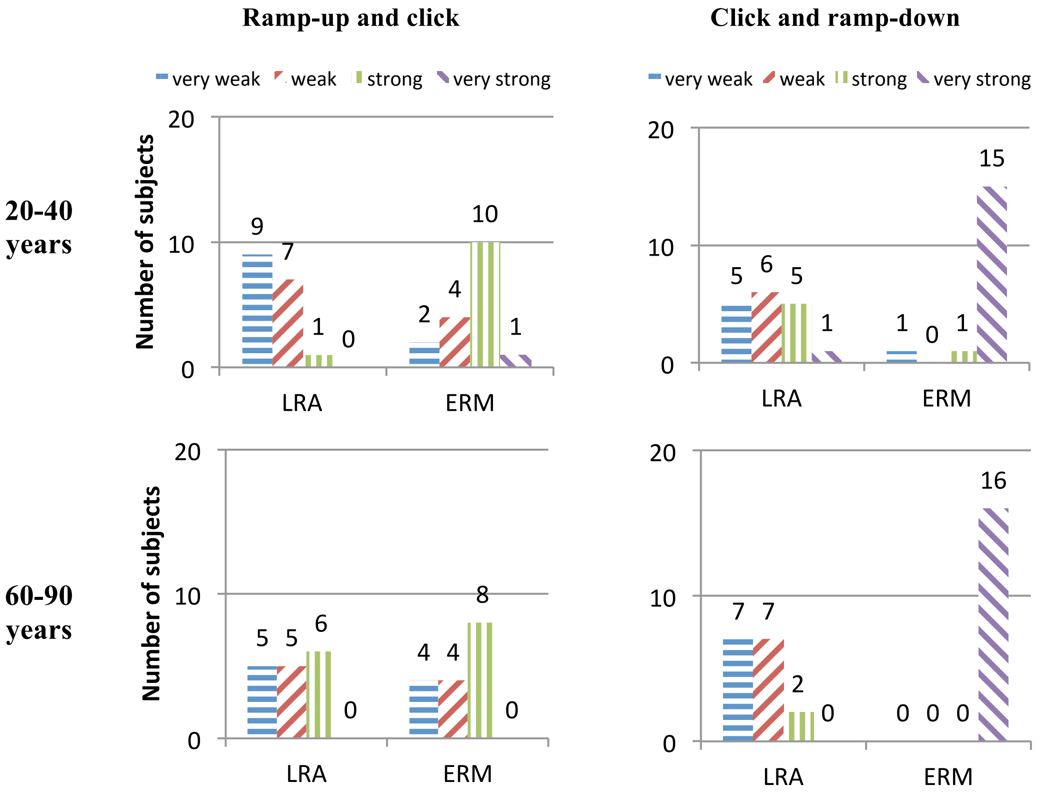


Figure 5.14 – Vibrotactile effects generated by LRA and ERM actuators from weak to strong

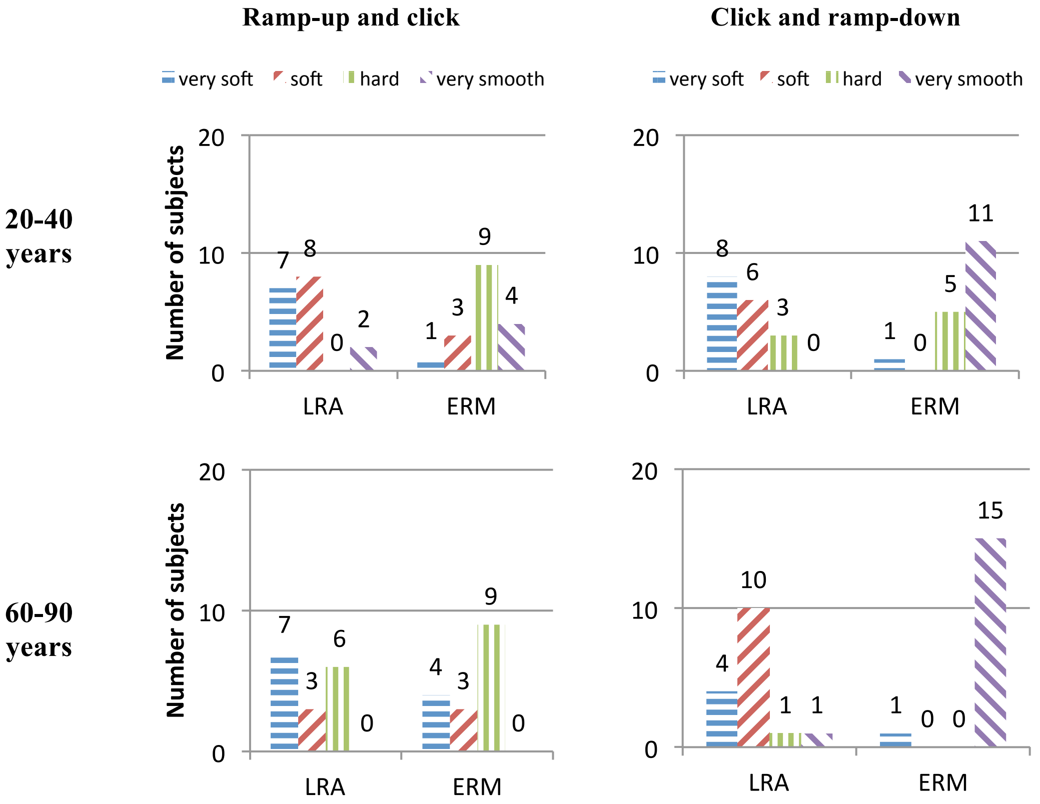


Figure 5.15 – Vibrotactile effects generated by LRA and ERM actuators from soft to hard

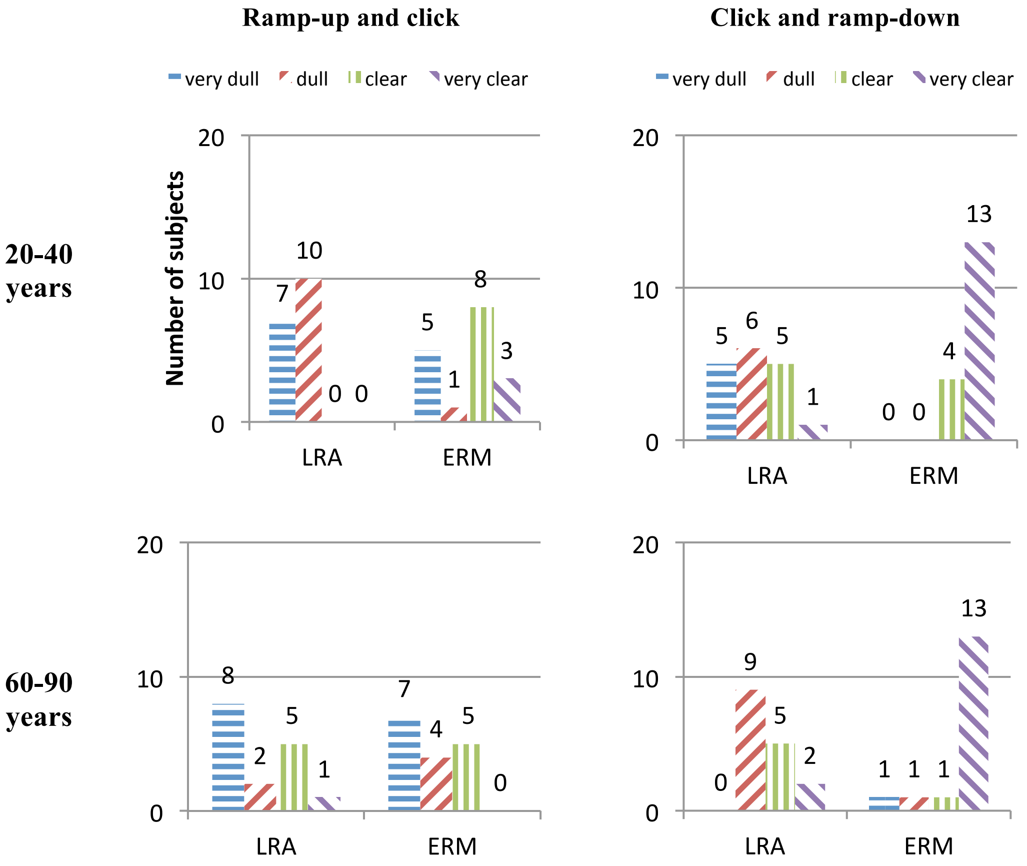


Figure 5.16 – Vibrotactile effects generated by LRA and ERM actuators from dull to clear

In short, the vibration of *'click and ramp-down'* produced by the ERM actuator is faster, more distinct, heavier, stronger, harder and clearer than by the LRA actuator, but bumpier, for both younger and older people.

5.6 Summary

This experiment has evaluated the sensation to vibrotactile effects according to seven adjective descriptions. The *'slow-fast'* and *'light-heavy'* could be the best pairs to describe the feelings of vibration for younger people. However, older people show no agreement on any descriptions. They preferred the effect of *'click and ramp-down'* generated on the ERM actuator because of the sensation with the fastest, most distinct, heaviest, strongest, hardest and clearest features.

In addition, the vibration generated by the ERM actuator provided the faster, more distinct, heavier, stronger, harder and clearer sensation, but bumpier, than by the LRA actuator for both younger and older people. Over 30% of younger and older subjects would like the vibrotactile effect of *'click and ramp-down'* produced by the ERM actuator as an alert vibration.

Finally, due to the limited number of subjects used in this experiment no significant relationship was found between the seven pairs of adjective descriptions and the sensation of vibrations. Therefore it is recommended that for future experiments each adjective pair should be provided such as 'Slow – not Slow' instead of 'Slow – Fast' for human evaluation of vibrotactile effects. The magnitude estimation technique [139] is also suggested to measure judgments of the vibrotactile stimuli by assuming numerical values proportional to the vibration magnitude human can perceive. This technique is robust enough to yield statistically significant results, compared to the 5- or 7- likewise scale. The reason is that magnitude estimation provides data on an interval scale so that the parametric statistics can be applied for evaluation.

6 Development of Vibrotactile Patterns

From the results of the description of vibrotactile effects experiment, a new experiment was carried out in order to find the identifiable vibrotactile patterns that could represent the common notifications of smartphones.

6.1 Experimental design

The requirements of the target number of subjects, the number of judgments and the temperature of test room and subjects' finger are the same as discussed in section 4.1.1.

The key factor is to develop the vibrotactile patterns based on three parameters (amplitude, frequency, rhythm) of sinusoidal signals. From the results of the vibrotactile perception experiment, a frequency range of finger sensitivity to vibration can be used to guide the patterns design. Table 6.1 shows the parameters of the vibrotactile patterns that are defined by three amplitudes, five frequencies and two types of rhythms.

Table 6.1 - Parameters designed for vibrotactile patterns

Parameters	Criteria
Amplitude (V)	Low intensity
	Medium intensity
	High intensity
Frequency (Hz)	Very slow frequency
	Low frequency
	Medium frequency
	High frequency
	Very high frequency
Rhythm	Amplitude ramp up or down
	Frequency ramp up or down

The amplitude is designed to represent low, medium and high intensity of vibrotactile patterns and the frequency is determined at five scale of very low, low, medium, high and very high from the results of finger sensitivity experiment. Rhythm parameter is defined as the amplitude or frequency of vibrations ramp up or ramp down continuously.

6.2 Equipment for the vibrotactile pattern experiment

LRA and ERM actuators are mature technology for creating vibrotactile feedback on smartphones since 2000 but they have certain limitations of controlling the vibrations. The frequency and amplitude of ERM motors are co-dependent and the input voltage is limited to a small range, typically 90-200 Hz within 0-3V, whereas the amplitude of LRA actuators is independent from the frequency yet the vibration on LRA actuators is fixed at its resonance frequency. Therefore, piezoelectric actuators was selected to replace LRA and ERM actuators to generate the vibrotactile patterns because it offers a great solution to generate a variety of vibrations as the amplitude and frequency of the actuators are independent and the frequency range in operation is up to kHz.

Piezoelectric actuators transfer an electrical signal into a precisely controlled physical displacement (accuracy is 0.01 μm in the range of 0.05mm). When the displacement is prevented, a useable force (blocking force) will develop. Then the actuator vibrates back and forth. Two types of design are the most popular, the multilayer (stack) and bimorph (stripe). The former one consists of around 100 thin piezoelectric ceramic sheets stacked together. Whereas, the bimorph is made up of multiple piezoelectric and elastic plates bonded together. The multilayer actuator has the advantages of low driving voltage, quick responses, high generative force and high electromechanical coupling but its displacement is minor in the order of 10 μm. However, the bimorph actuators generate a greater bending displacement of several hundred μm.

Two examples, that are the multilayer actuator (model: PL055 from Physik Intrumente (PI) Company) and bimorph actuator (model: PI P-878), were tested as a trial in order to determine the optimal type to generate vibration that can be perceived. The multilayer actuator vibrates in the direction of Z-axis whereas the displacement of the bimorph one occurs in the X-axis direction. Both were glued on to the same size of rig. The results showed that any vibration was hardly perceived from the rig with the multilayer actuator, whereas the rig with the bimorph actuator successfully produced sensations to vibration. The reason could be the displacement of the multilayer actuator is too small for human perception. Therefore, the bimorph actuator was chosen to generate a variety of vibration for the subject perception testing proposed.

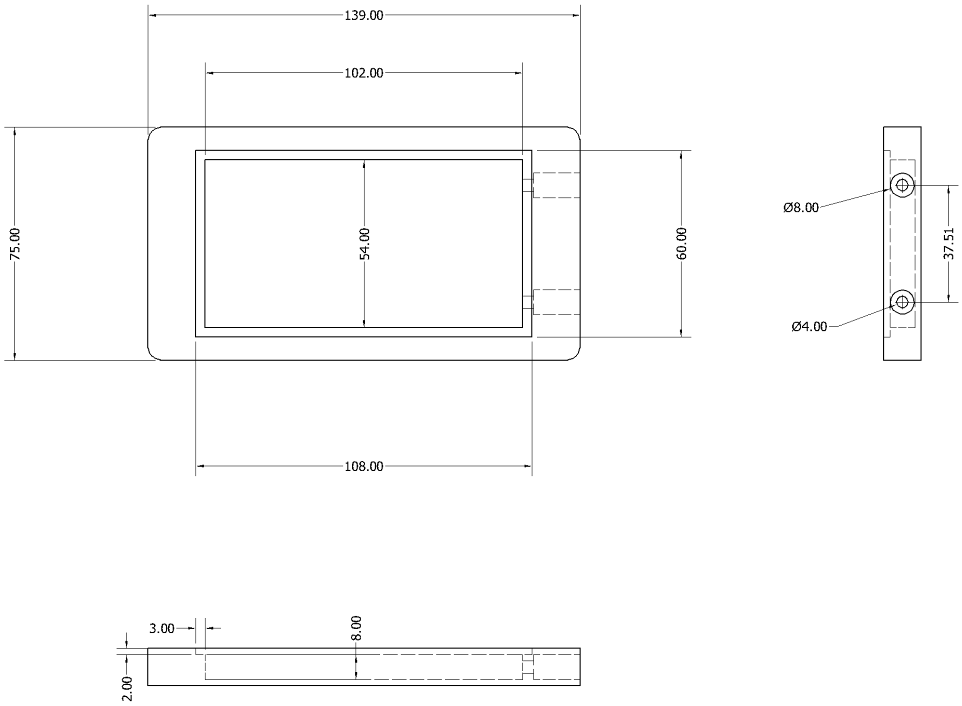


Figure 6.1- The size of hard cover of the rig

A new rig has been developed that consists of a hard cover and a piece of glass using the bimorph actuator (model: PI P-878) for the vibrotactile patterns experiment. Figure 6.1 shows the size of the hard cover. It is made of acrylic with the dimension of 139×75×12 mm. The glass size is 108×60×2 mm in order to emulate a screen size of 4.8 inches smartphone of Samsung Galaxy S3.

Figure 6.2 shows the operating system to provide vibrotactile patterns that consists of the haptic rig, a driver (model: PI E835) and a waveform generator (model: 3390 from Keithley). The piezoelectric actuator is glued to the centre of the glass and the waveform generator is used to create the signatures of vibrotactile patterns. When the signals are sent out through the driver, subjects can experience vibration on the haptic rig.

(a) the haptic rig **(b) the diagram of the control system**

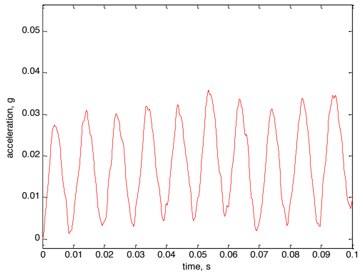
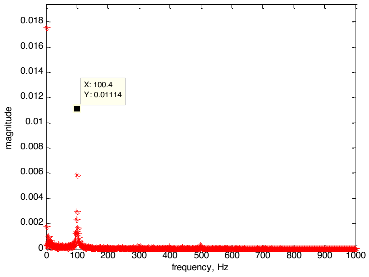
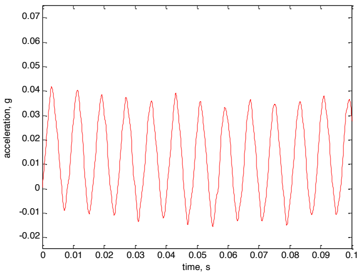
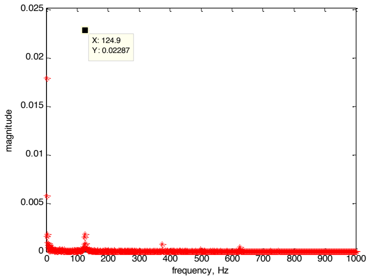
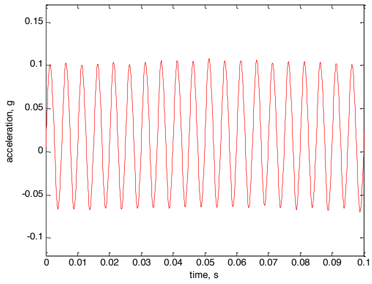
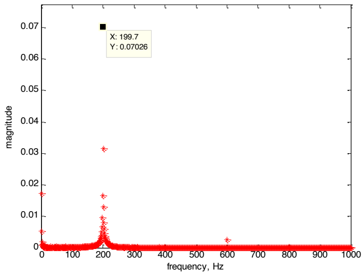
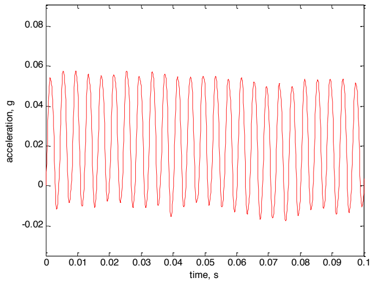
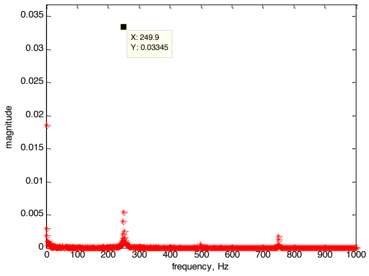
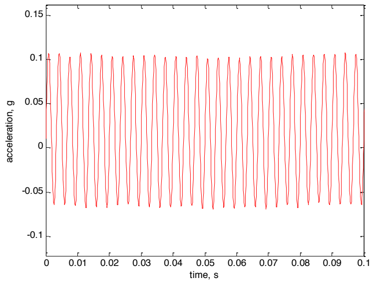
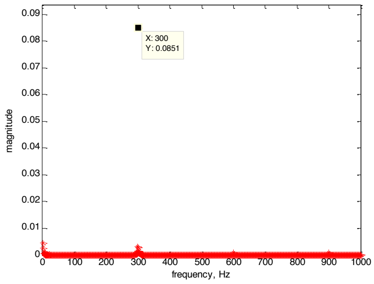
Figure 6.2 - The diagram of the haptic rig control system

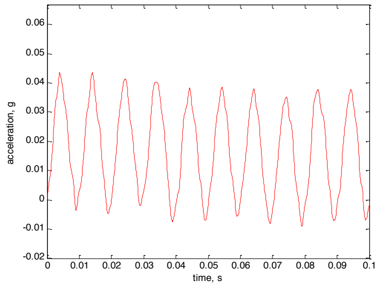
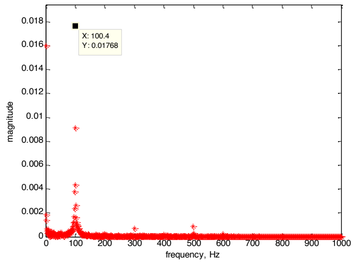
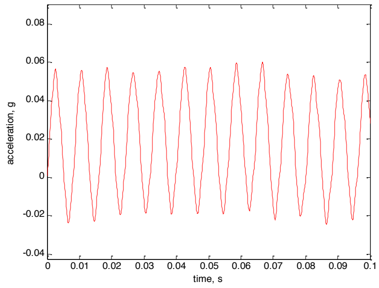
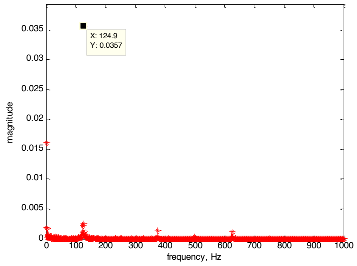
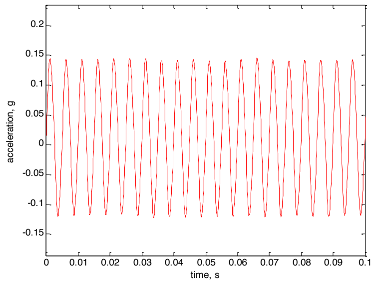
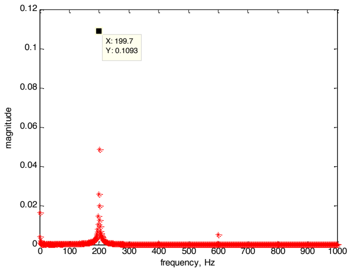
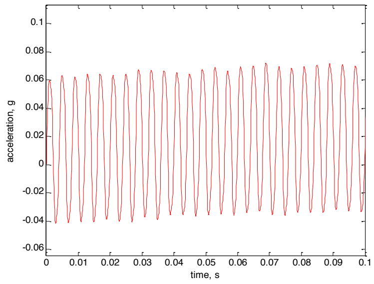
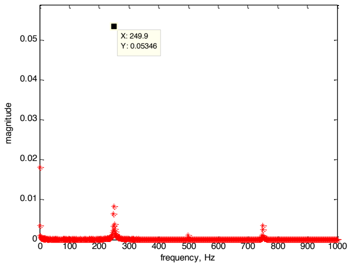
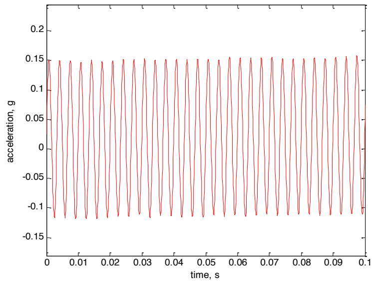
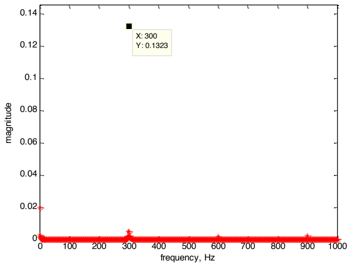
From the Table 6.2, the amplitude is set in the range of 1-2 V and the output of the haptic rig in the range of 25-50V as the piezoelectric actuator requires a high voltage (-100-250 V) to drive and the input to the driver is limited to -4-10 V. The greater amplitude could not be safe for human testing. The frequency is set at 100 Hz, 125 Hz, 200 Hz, 250 Hz and 300 Hz according to the development of the vibrotactile perception experiment. There are two types of rhythms designed as the amplitude changing between 1 V to 2 V and the frequency changing between 100 Hz to 300 Hz. The values of each parameter are shown in Table 6.2 and the signatures of each pattern can be found at Appendix 4. Table 6.3 shows the vibration responses to vibrotactile patterns from the haptic rig.

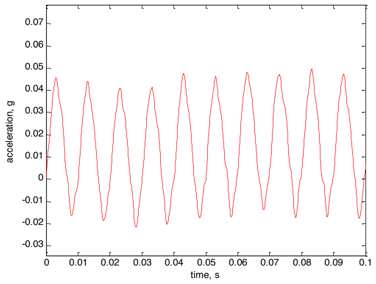
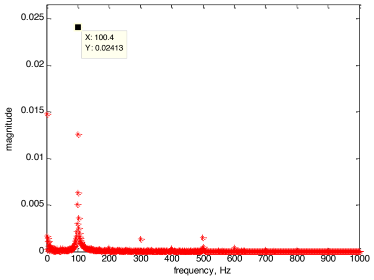
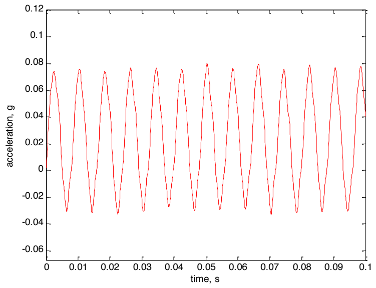
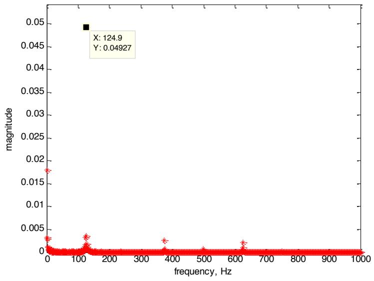
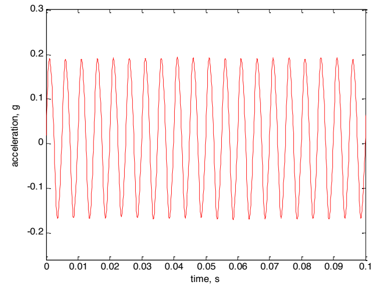
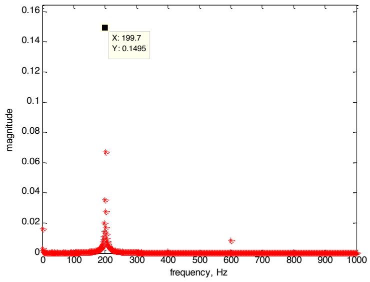
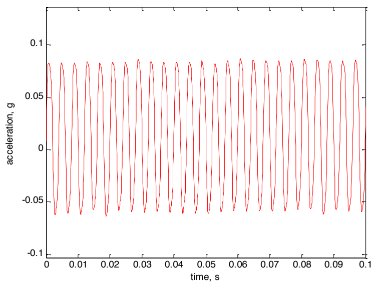
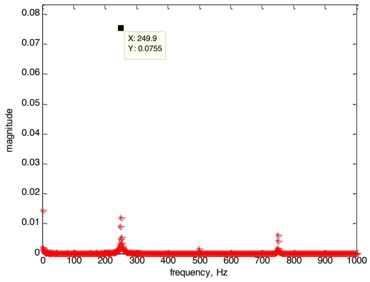
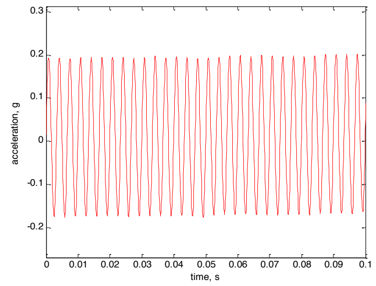
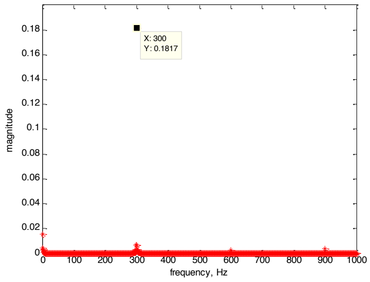
Table 6.2 - Vibrotactile patterns for developmental design of haptic language

No	Pattern	Amplitude (V)	Frequency (Hz)	Rhythm	Group
1	(1.0v, 100hz)	1	100	n/a	**A [Low amplitude, Different frequencies, No rhythm]**
2	(1.0v, 125hz)		125		
3	(1.0v, 200hz)		200		
4	(1.0v, 250hz)		250		
5	(1.0v, 300hz)		300		
6	(1.5v, 100hz)	1.5	100	n/a	**B [Medium amplitude, Different Frequencies, No rhythm]**
7	(1.5v, 125hz)		125		
8	(1.5v, 200hz)		200		
9	(1.5v, 250hz)		250		
10	(1.5v, 300hz)		300		
11	(2.0v, 100hz)	2	100	n/a	**C [High amplitude, Different frequencies, No rhythm]**
12	(2.0v, 125hz)		125		
13	(2.0v, 200hz)		200		
14	(2.0v, 250hz)		250		
15	(2.0v, 300hz)		300		
16	(1-2v, 100hz)	n/a	100	Amplitude ramp up from 1 to 2 V	**D [Amplitude ramping, Different frequencies]**
17	(1-2v, 125hz)		125		
18	(1-2v, 200hz)		200		
19	(1-2v, 250hz)		250		
20	(1-2v, 300hz)		300		
21	(1v, 100-300hz)	1	n/a	Frequency ramp up from 100 to 300 Hz	**E [Different amplitudes, Frequency ramping,]**
22	(1v, 300-100hz)			Frequency ramp down from 300 to 100 Hz	
23	(1.5v, 100-300hz)	1.5		Frequency ramp up from 100 to 300 Hz	
24	(1.5v, 300-100hz)			Frequency ramp down from 300 to 100 Hz	
25	(2v, 100-300hz)	2		Frequency ramp up from 100 to 300 Hz	
26	(2v, 300-100hz)			Frequency ramp down from 300 to 100 Hz	
27	(1v, 100hz+200hz)	1	100+200	n/a	**F [Low amplitude, Combined frequencies]**
28	(1v, 125hz+250hz)		125+250		
29	(1v, 250hz+500hz)		250+500		
30	(1v, 300hz+600hz)		300+600		
31	(1v, 200hz+400hz)		200+400		

Table 6.3 – Vibration Responses of the haptic rig

No.	Pattern	Vibration Response	
		Time Domain	**Frequency Domain**
1	(1.0v, 100hz)		
2	(1.0v, 125hz)		
3	(1.0v, 200hz)		
4	(1.0v, 250hz)		
5	(1.0v, 300hz)		

No.	Pattern	Vibration Response	
		Time Domain	Frequency Domain
6	(1.5v, 100hz)		
7	(1.5v, 125hz)		
8	(1.5v, 200hz)		
9	(1.5v, 250hz)		
10	(1.5v, 300hz)		

No.	Pattern	Vibration Response	
		Time Domain	Frequency Domain
11	(2.0v, 100hz)		
12	(2.0v, 125hz)		
13	(2.0v, 200hz)		
14	(2.0v, 250hz)		
15	(2.0v, 300hz)		

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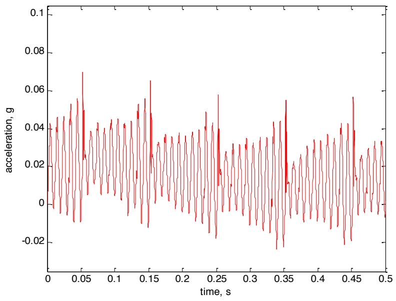
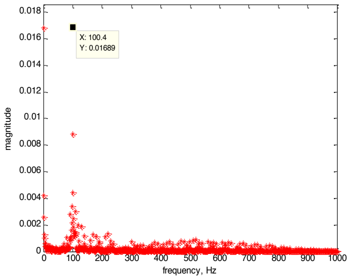
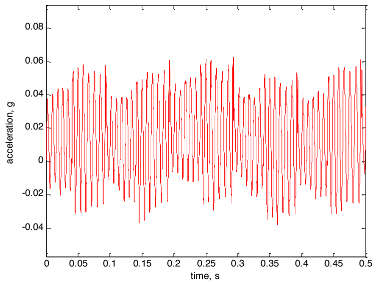
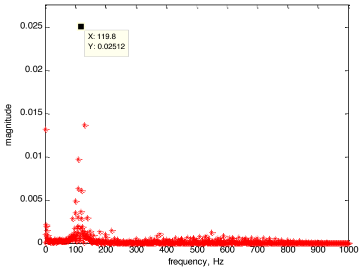
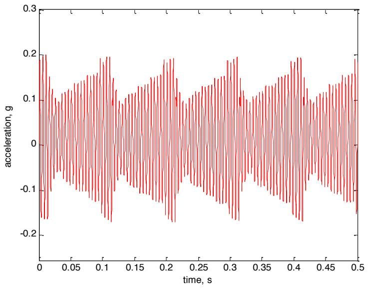
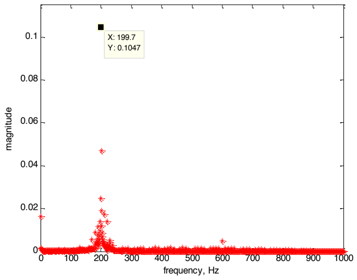
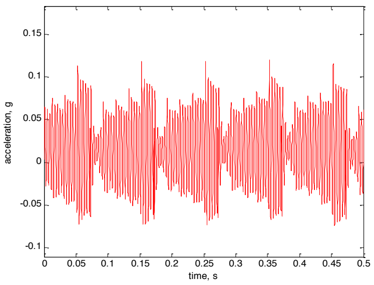
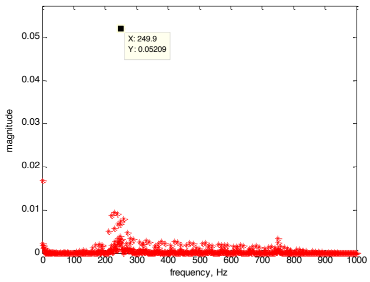
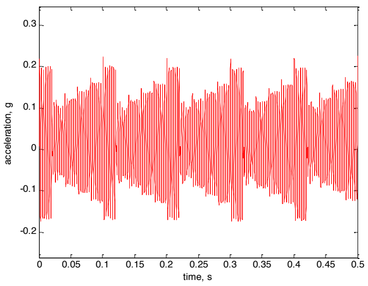
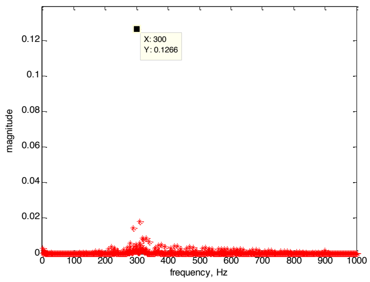
<tr><td>16</td><td>(1-2v, 100hz)</td><td> </td><td> </td></tr>
<tr><td>17</td><td>(1-2v, 125hz)</td><td> </td><td> </td></tr>
<tr><td>18</td><td>(1-2v, 200hz)</td><td> </td><td> </td></tr>
<tr><td>19</td><td>(1-2v, 250hz)</td><td> </td><td> </td></tr>
<tr><td>20</td><td>(1-2v, 300hz)</td><td> </td><td> </td></tr>
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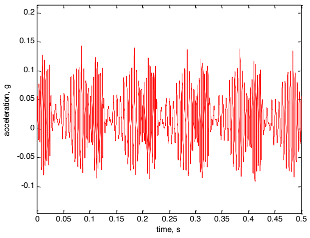
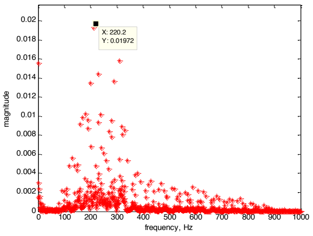
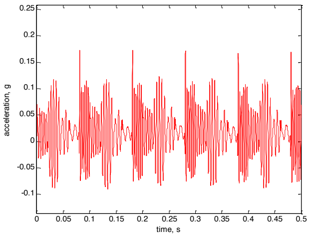
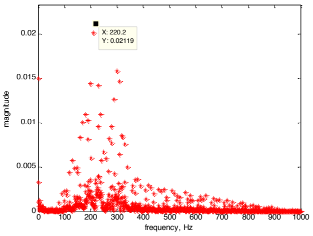
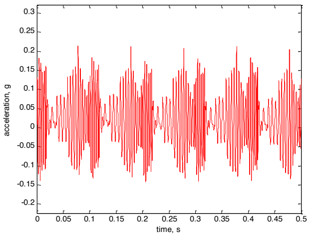
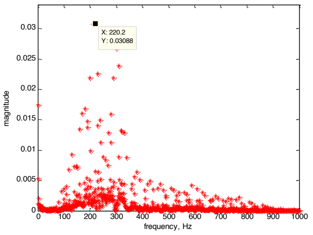
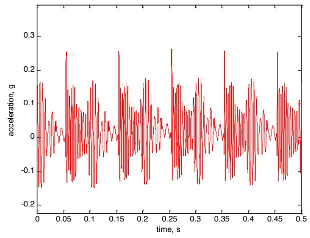
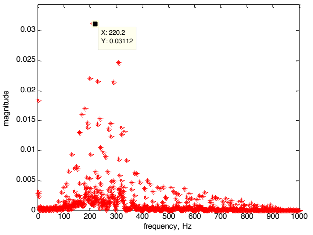
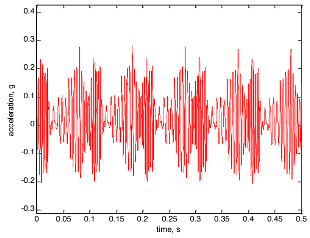
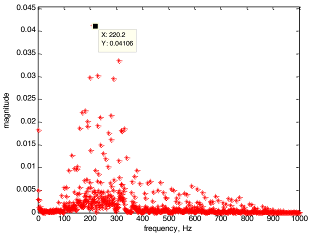
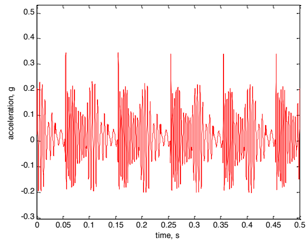
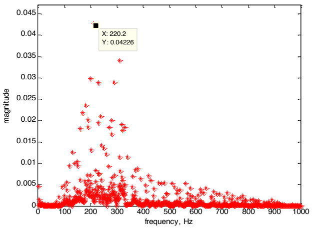
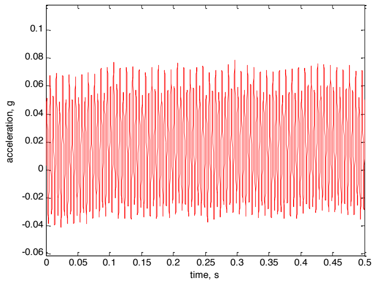
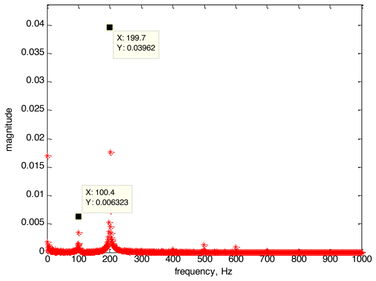
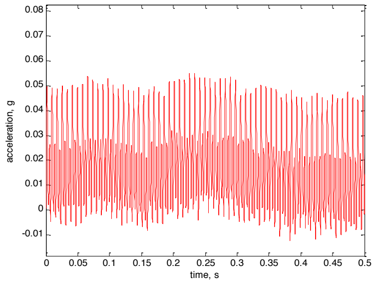
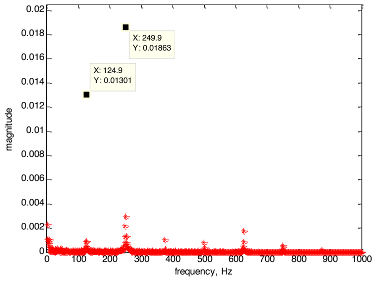
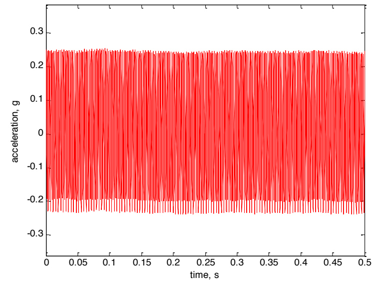
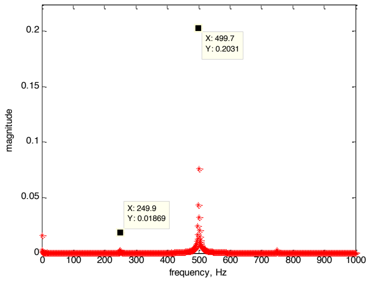
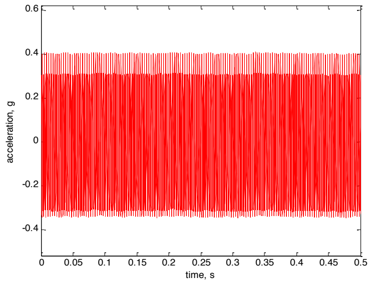
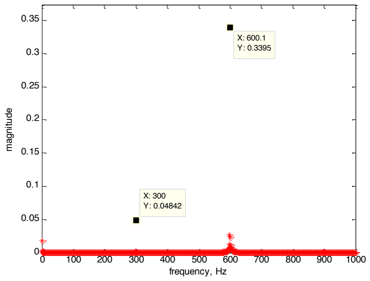
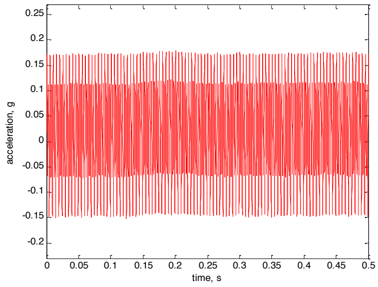
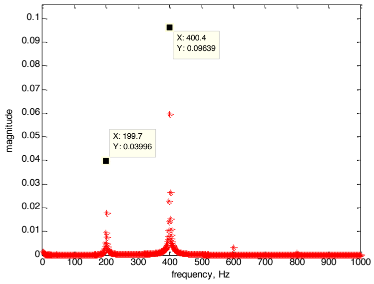
No.	**Pattern**	**Vibration Response**	
		Time Domain	**Frequency Domain**
21	(1v, 100-300hz)		
22	(1v, 300-100hz)		
23	(1.5v, 100-300hz)		
24	(1.5v, 300-100hz)		
25	(2v, 100-300hz)		
26	(2v, 300-100hz)		

No.	**Pattern**	**Vibration Response**	
		Time Domain	**Frequency Domain**
27	(1v, 100hz+200hz)		
28	(1v, 125hz+250hz)		
29	(1v, 250hz+500hz)		
30	(1v, 300hz+600hz)		
31	(1v, 200hz+400hz)		

In addition, the same method conducted in the assessment in the vibrotactile feedback experiment was used to evaluate the vibrotactile patterns on the haptic rig in order to ascertain the consistency of the vibration on the haptic rig.

6.3 Experimental procedures

The experiment was conducted under the normal laboratory condition. The haptic rig was evaluated once a week over the testing period using the method of assessing the vibrotactile feedback discussed in section 3.2.2, in order to ascertain the consistency of the performance of the vibrotactile patterns on the rig.

6.3.1 Preliminary testing

Before carrying out the evaluation of the vibrotactile patterns, three preliminary tests were carried out in order to study the capability of subjects to perceive the patterns as well as providing the trainings for the subjects to get familiar with the vibrotactile patterns. A soft foam pad was provided to support the arm in order to keep the hand and haptic rig at the same level. The subjects were required to place the hand they used when writing on the pad and put the index finger on the top of the haptic rig.

Table 6.4 - Vibrotactile patterns produced the weakest and strongest sensations

No.	Pattern	Perception
4	(1 V, 250 Hz)	Very Weak
2	(1 V, 125 Hz)	Weak
15	(2 V, 200 Hz)	Strong
14	(2 V, 300 Hz)	Very Strong

The first testing was assessed if the subjects could sense the strongest and weakest patterns. Four patterns were selected shown in Table 6.4. Four patterns were presented individually in a random order and the subjects were required to rank the sensations of the following patterns from the weakest to the strongest.

Secondly, the next test was implemented to study the ability for discriminating of the frequency ramping and the amplitude ramping. Another four patterns were chosen shown in Table 6.5. Vibration A was first presented to subjects and then followed the vibration B. The subjects were required to answer if the feelings of vibration were the same or different.

Table 6.5 - Vibrotactile patterns for discrimination testing

Pair	**Vibration (A)**		**Vibration (B)**	
	Value	Effect	Value	Effect
1	(2 V, 100-300 Hz)	Frequency ramp up	(1-2 V, 200 Hz)	Amplitude ramp up
2	(2 V, 100-300 Hz)	Frequency ramp down	(2-1 V, 200 Hz)	Amplitude ramp down

Finally, the third test was carried out to find out the preferences of the rig between placing on the table and hand holding when subjects perceiving the vibrotactile patterns. The pattern sample was selected with the amplitude of 2 V and frequency ramp up from 100 to 300 Hz. The subjects were required to hold the rig as usual and to choose one position that they prefer to experience the vibrotactile pattern on smartphones. The preliminary testing protocol took around 10 minutes to complete.

6.3.2 Evaluation of vibrotactile patterns

Five signs with emotional faces and meanings in Table 6.6 were provided in front of the subjects. Four words that are *'confirmation'*, *'positive'*, *'negative'*, and *'annoyed'* are chosen to represent the notification of smartphones because these meanings could represent the importance of the notifications on smartphones. The *'not sure'* sign is also provided in case subjects cannot perceive the patterns.

Table 6.6 – Five signs for the vibrotactile pattern experiment

Signs	Meanings	Sensations
	Confirmation	Can feel the vibration with the most pleasant feelings
	Positive	Can feel the vibration with the pleasant feelings
	Not sure	No feelings of the vibration; No views of the meanings
	Negative	Can feel the vibration with the bad feelings
	Annoyed	Can feel the vibration with the worst feelings

In Figure 6.3, the subjects sat casually and put the hand they used when writing on the soft the pad in order to keep the hand and rig on the same level. Then, they were asked to put the index finger on the top of the haptic rig.

Figure 6.3 - A subject evaluated the vibrotactile patterns

During the experiment, all the patterns were presented individually in a random order. After each pattern, the subjects were required to choose one out of five signs to describe their feelings of the vibration produced that could be represented to the notification of smartphones. There was no time limit for making the judgments. The test protocol took approximately 20 minutes to complete.

6.4 Results

19 younger adults (11 males and 8 females aged between 20-40, and average age 29.1 ± 5.2) and 22 older adults (9 males and 13 females aged between 60-90 years, and average age 69.7 ± 5.3) were invited in this experiment. All the younger subjects were right-handed from the University of Sheffield. All the older subjects were right-handed from the University of Third Age (U3A) society except two older people were left-handed. The temperature of subjects' finger was 26.6 ± 3.3 °C in younger group and 27.6 ± 3.0 °C in older group. In addition, the assessments of haptic rig testing proved that the vibration on the rig remained the same over the verification-testing period.

6.4.1 Results from the preliminary testing

From the preliminary testing, Figure 6.4 shows that 77% of subjects selected the strongest vibration of the pattern 15 at 200 Hz with the amplitude of 2 V; 46% of subjects take the weakest vibration as the pattern at 250 Hz with the amplitude of 1 V. The second preliminary test proved that 100% of younger subjects and 90% of older subjects could differentiate the differences between frequency ramping up and amplitude ramping up, compared to 89% of younger and 85% of older people for the frequency and amplitude ramp down. The third preliminary test showed that 67% of all subjects preferred the vibration when the rig holding on hands, compared to 23% of the subjects when placing the rig on the table.

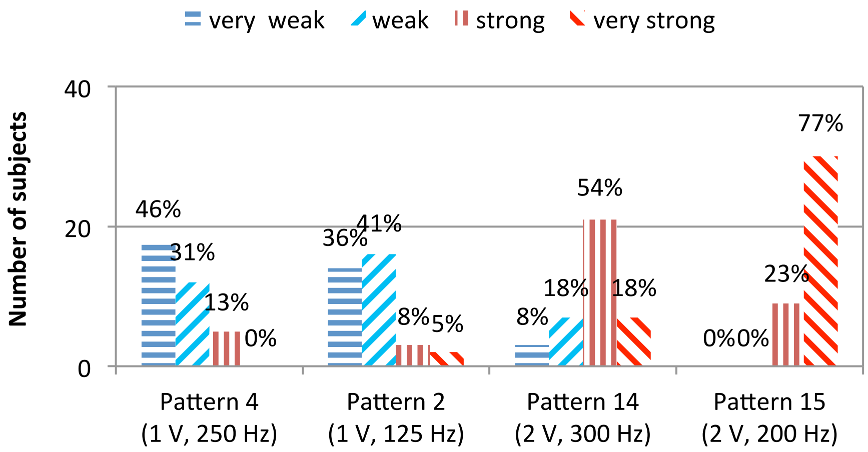


Figure 6.4 - Statistical analysis of perception of vibrations from weakest to strongest

In addition, two older people (one male and one female) failed the first and second preliminary testing that they could not feel any vibration even the strongest one. Thus, 39 subjects (19 younger people and 20 older people) continued in the next stage for the vibrotactile patterns experiment.

6.4.2 Results from the vibrotactile patterns testing

The total numbers of responses in each sign were shown in Figure 6.5. The results show that, for all ages, most subjects cannot tell the meanings of the vibrotactile patterns as the number of the *'not sure'* responses is larger than others. The highest responses are in the *'not sure'* category of 28.7%, followed by the 26.3% of *'positive'*, 19,9% of *'negative'*, 17.0% of *'confirmation'*, and 8.1% of *'annoyed'*. It can be seen that the number of *'not sure'* responses in the older group is much larger than in the younger group. However, the number of *'annoyed'* responses in the younger group is much larger than in the older group. The other meanings account for the similar number of responses between younger and older people.

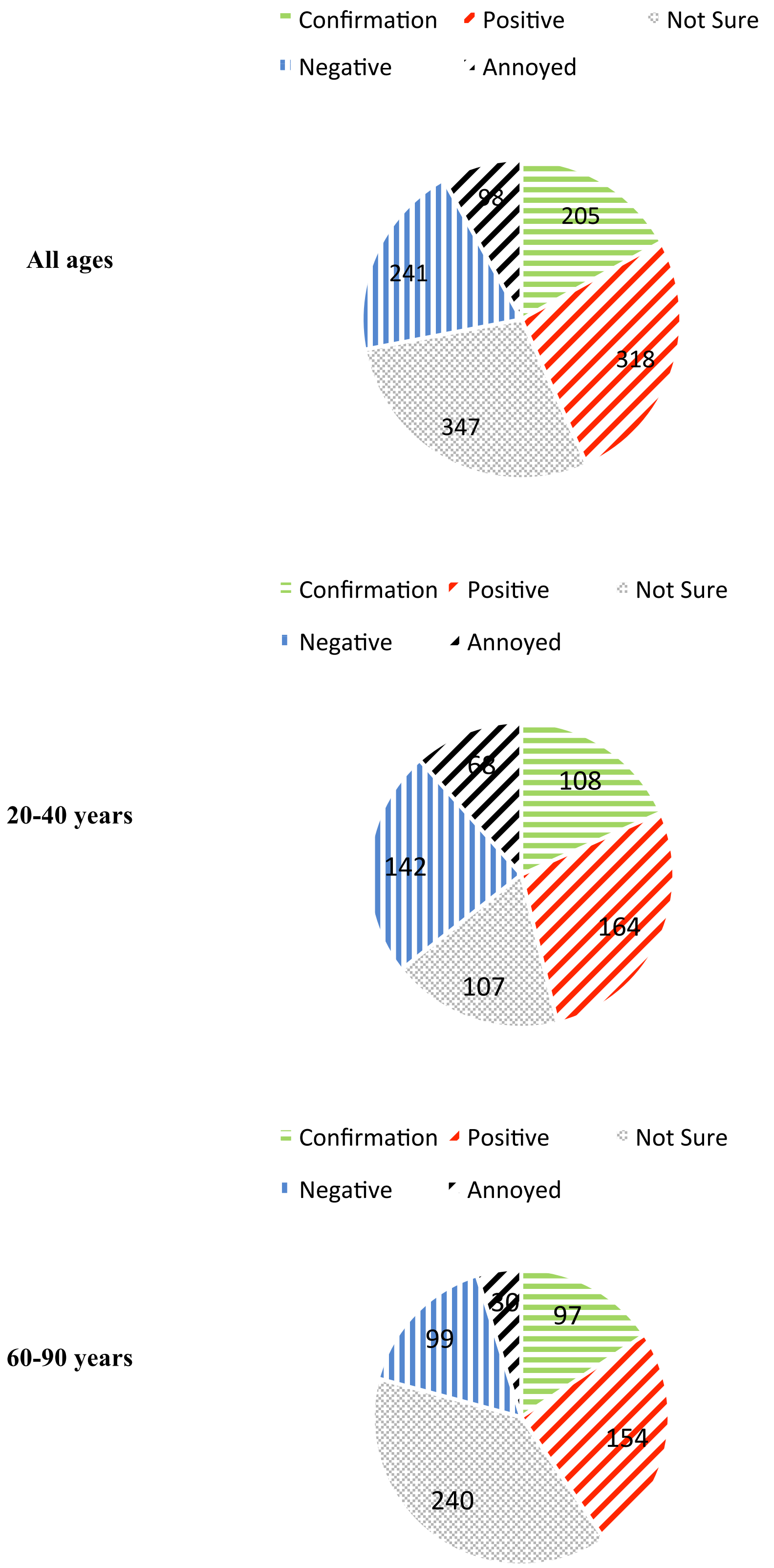


Figure 6.5 - The total number of responses for the *'confirmation'*, *'positive'*, *'negative'*, *'annoyed'*, and *'not sure'* categories

The following results were shown the number of responses in five groups (see Table 6.2) of vibrotactile patterns. The patterns (No. 1-5) in Group A were designed as five frequency points with the low amplitude of 1.0 V and no rhythm. Figure 6.6 proves that older subjects were unsure as to the meaning implied by the patterns in Group A. However, younger subjects had the positive feelings of the pattern at the frequency of 200 Hz whereas the negative feelings of vibration at 300 Hz.

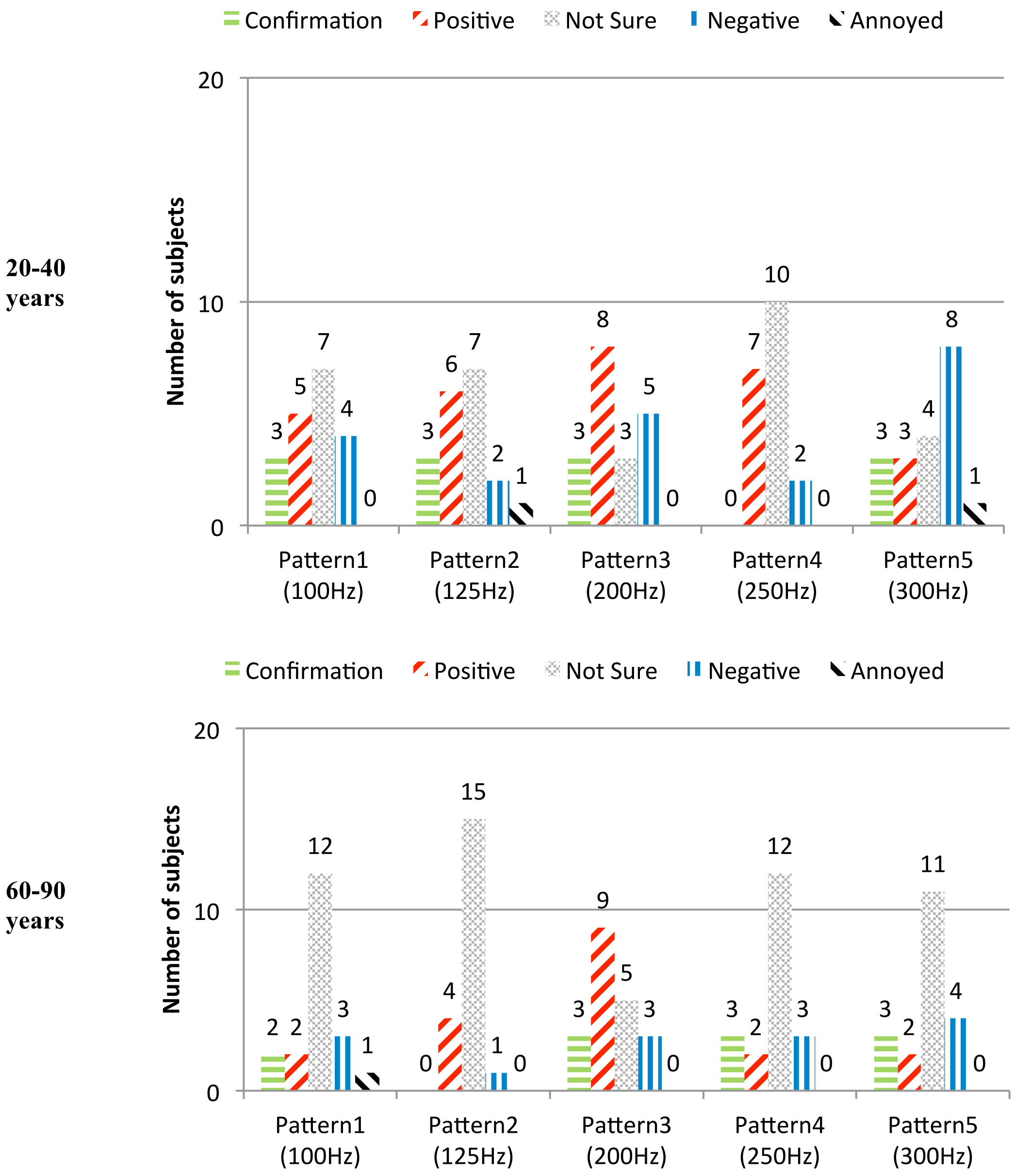


Figure 6.6- Number of responses of vibrotactile patterns in Group A (1.0V, 5 frequencies, no rhythm) between younger and older people

The patterns (No. 6-10) in Group B were designed as the same frequency with the medium amplitude of 1.5 V and no rhythm. In Figure 6.7 the similar trend can be found in both younger and older group. In 20-40 years group, the number of 'not sure' responses at higher frequency (e.g. 200 Hz, 250 Hz, and 300 Hz) decreases, compared to the Group A.

20-40 years

60-90 years

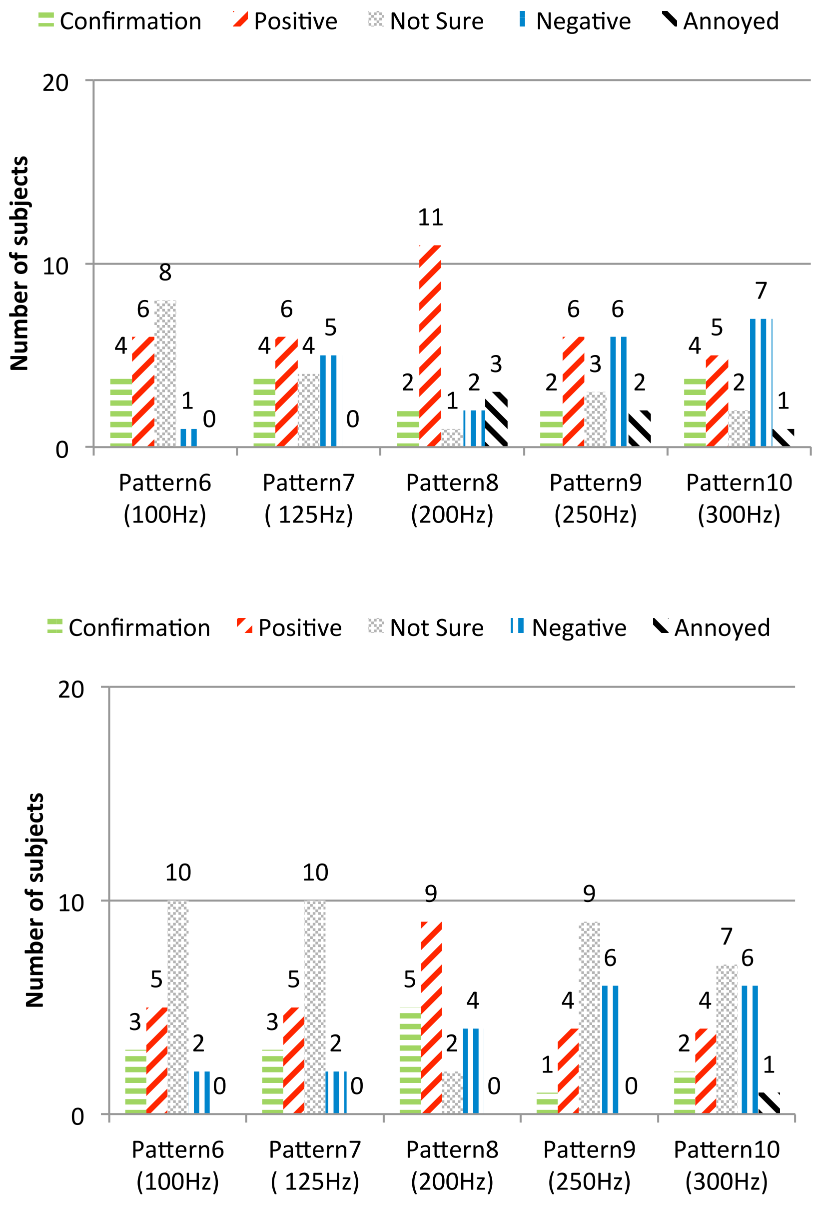


Figure 6.7 - Number of responses of vibrotactile patterns in Group B (1.5V, 5 frequencies, no rhythm) between younger and older people

The amplitude of patterns (No. 11-15) in Group C was set at high level of 2.0 V with the same frequency and no rhythm. Figure 6.8 shows that younger people had the positive feelings of the pattern 12 at the frequency of 125 Hz whereas older people had the positive feelings of the pattern at the frequency of 200 Hz and 300 Hz. The number of *'confirmation'* responses at the pattern 12 is larger than the *'positive'* responses.

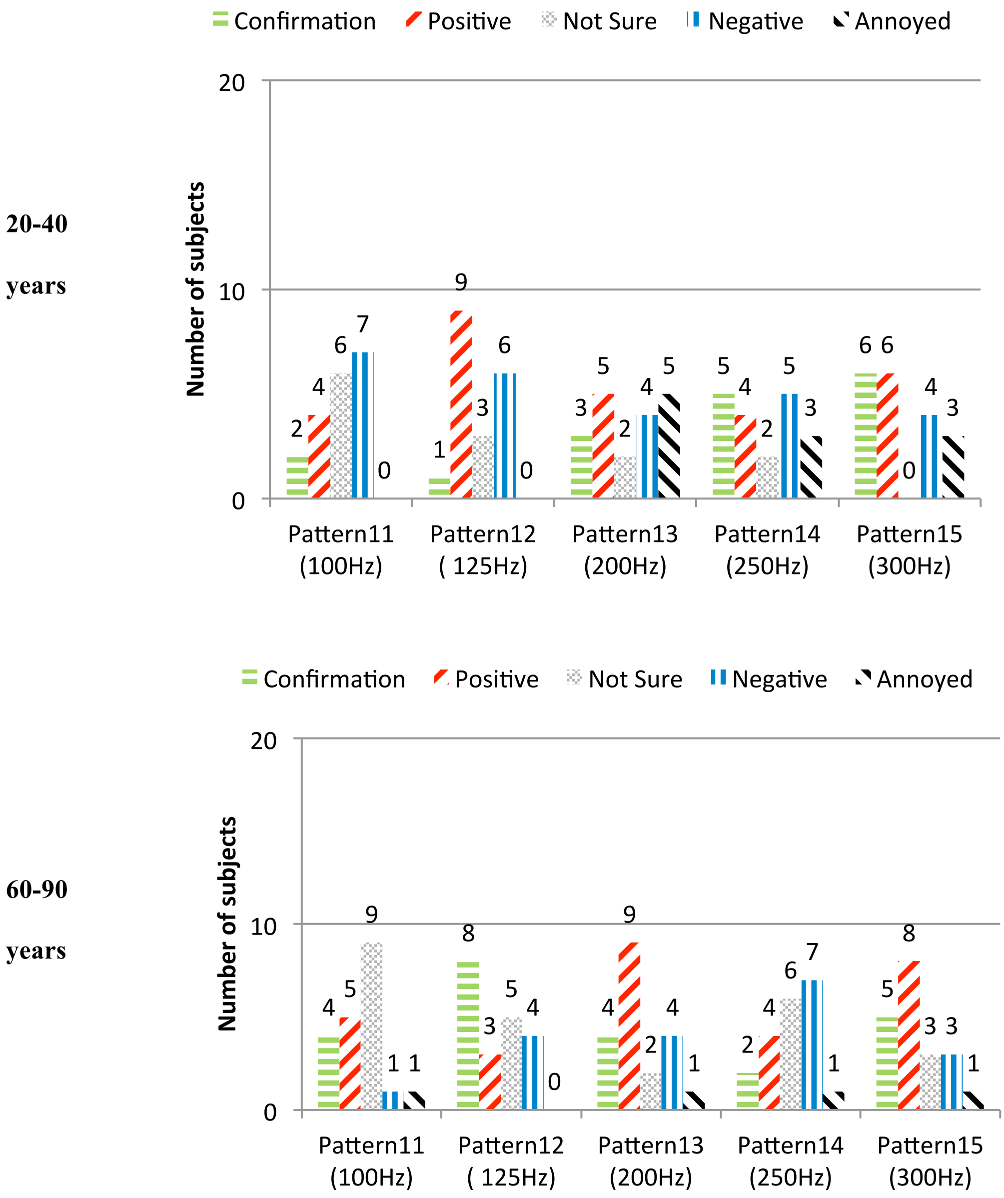


Figure 6.8 - Number of responses of vibrotactile patterns in Group C (2.0V, 5 frequencies, no rhythm) between younger and older people

The patterns (No. 16-20) in Group D were changed with the amplitude ramping at five frequencies. From Figure 6.9 the performance of vibration perception at each pattern is not improved in both younger and older group. Especially, in 60-90 years group, the number of responses at each pattern is similar to the Group A.

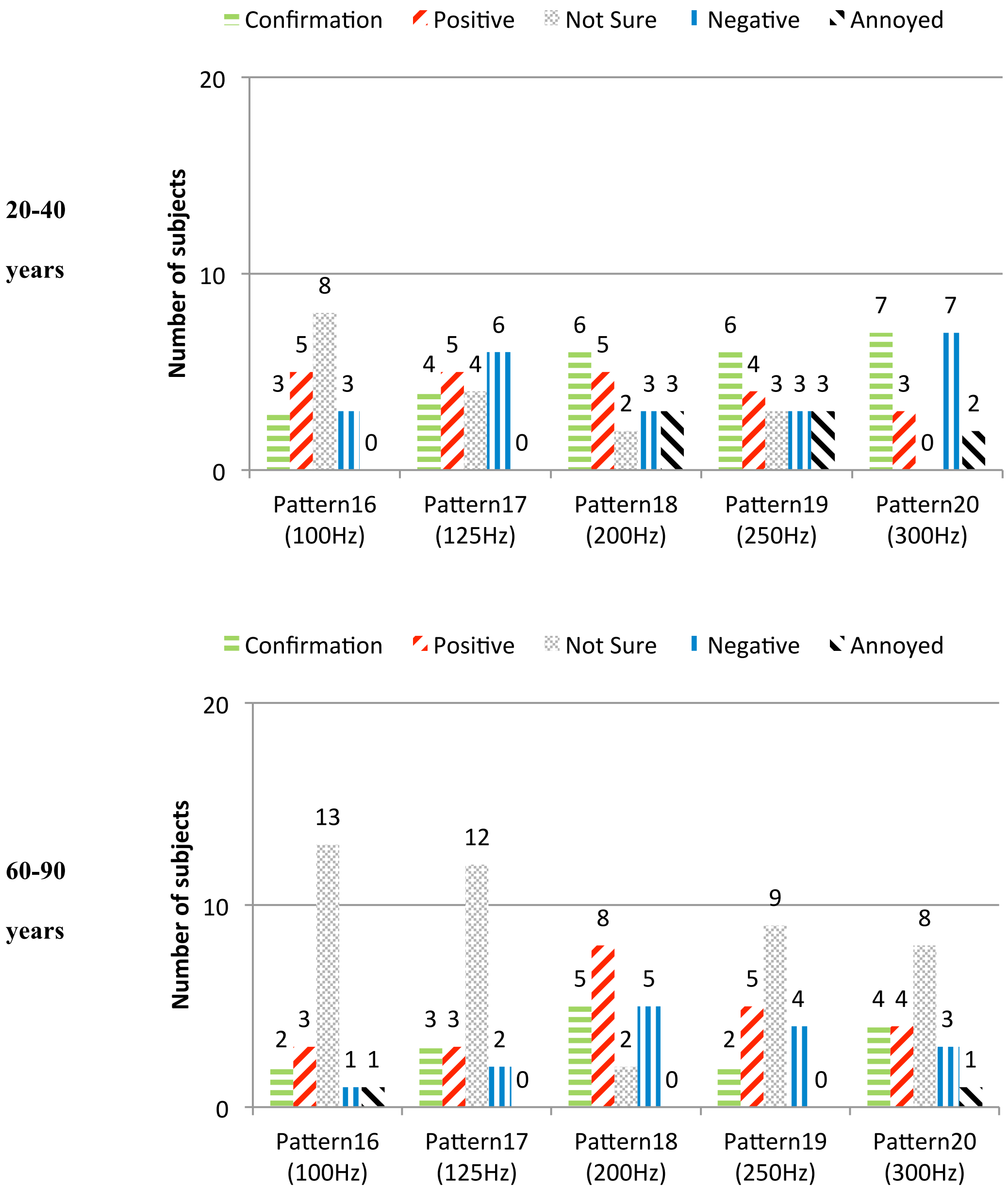


Figure 6.9 - Number of responses of vibrotactile patterns in Group D (amplitude ramping, 5 frequencies) between younger and older people

The patterns (No. 21-26) in Group E were changed with the frequency ramping at three amplitudes. In Figure 6.10 the similar trend can be found that older people had the positive feelings of the patterns at high amplitude with frequency ramping, compared to Group C. In 20-40 years group, the number of 'annoyed' responses at all the patterns increases significantly, especially the pattern 21.

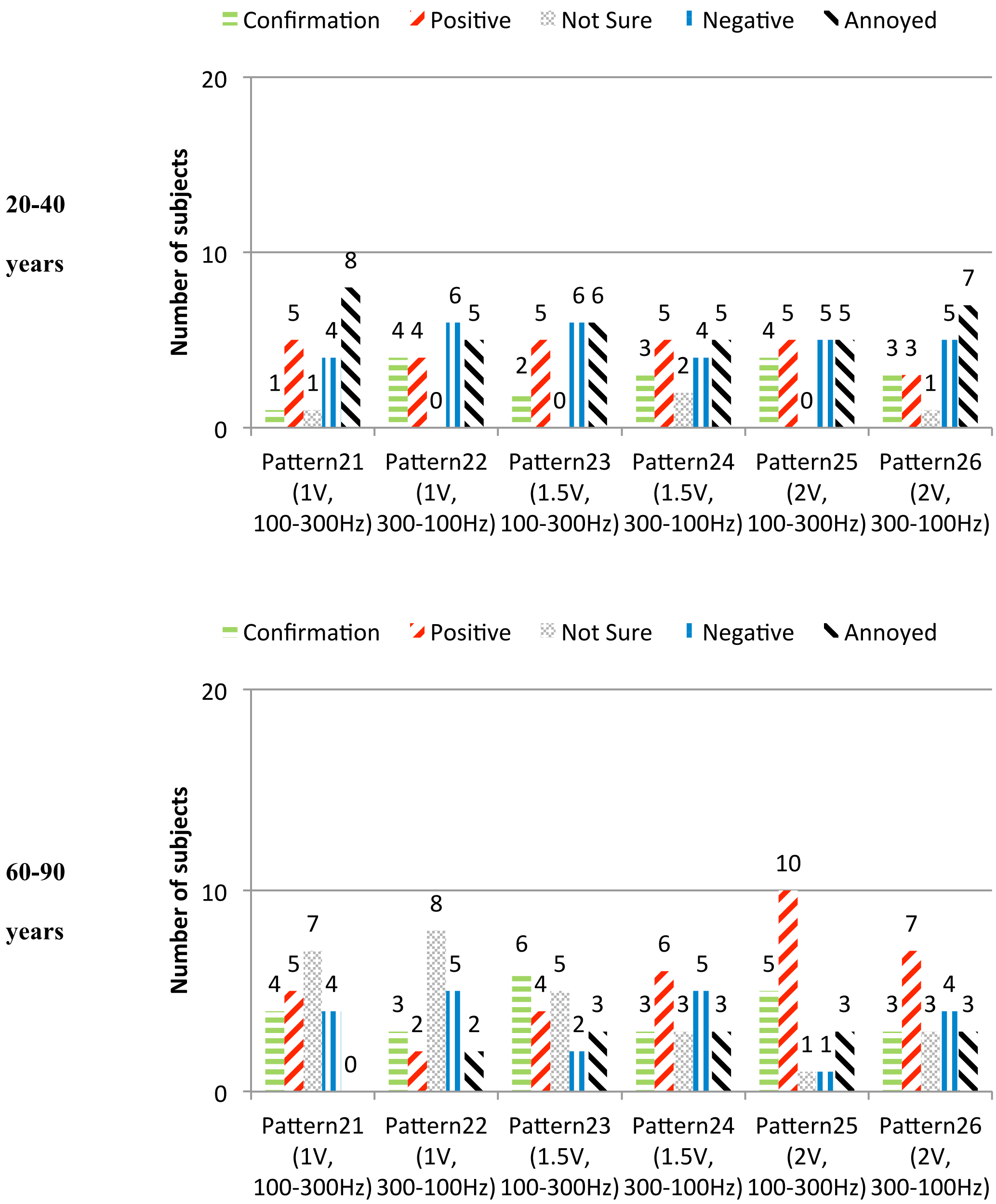
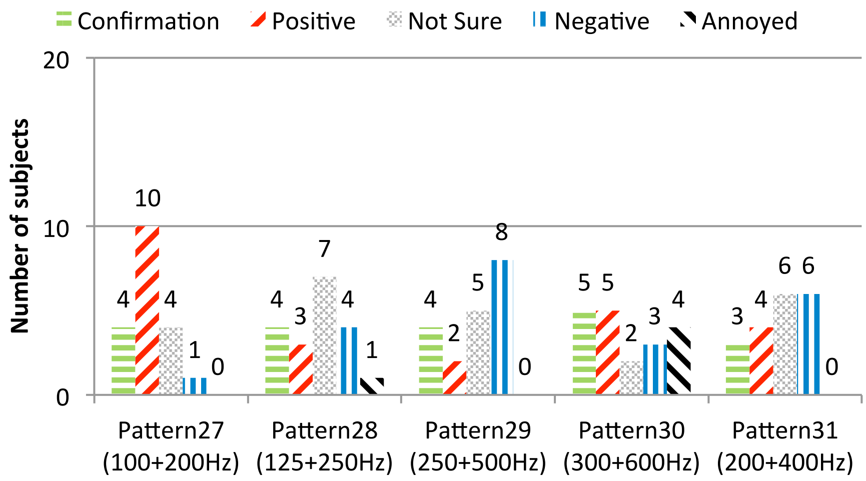


Figure 6.10 - Number of responses of vibrotactile patterns in Group E (3 amplitudes, frequency ramping) between younger and older people

The patterns (No. 27-31) in Group F were designed as the combination of two frequencies with the low amplitude of 1.0 V. In Figure 6.11 there is no significant improvement of the performance at each pattern in 60-90 years group, compared to the Group A. However younger people had the positive feelings of the pattern with two frequency of 100 Hz and 200 Hz and negative feelings of the pattern of 250 Hz and 500 Hz.

20-40 years



60-90 years

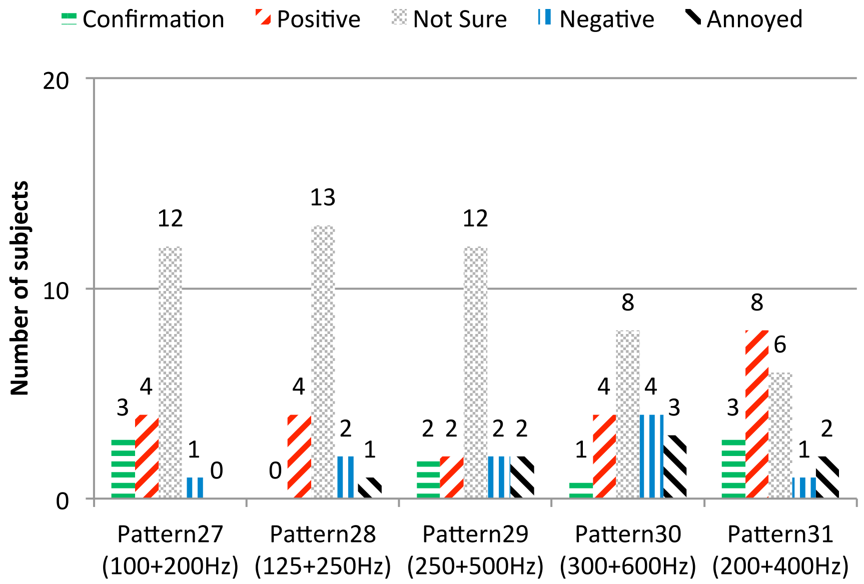


Figure 6.11 - Number of responses of vibrotactile patterns in Group F (1.0 V, combined frequencies) between younger and older people

To summarize, most subjects were unsure the meanings implied by the vibration due to the large number of *‘not sure’* responses. Taking account of the influences of each parameter, Table 6.7 reviews the findings in each group between younger and older people.

Table 6.7 – Conclusions of the vibrotactile patterns from younger and older people

Pattern	Group	Conclusions
(1.0v, 100hz)	A [1.0V, 5 frequencies, No rhythm]	No agreement in both younger and older group
(1.0v, 125hz)		
(1.0v, 200hz)		
(1.0v, 250hz)		
(1.0v, 300hz)		
(1.5v, 100hz)	B [1.5V, 5 frequencies, No rhythm]	The frequency of 200 Hz could be implied as ‘positive’ and 300 Hz as ‘negative’ in younger group; No agreement in older group
(1.5v, 125hz)		
(1.5v, 200hz)		
(1.5v, 250hz)		
(1.5v, 300hz)		
(2.0v, 100hz)	C [2.0V, 5 frequencies, No rhythm]	The frequency of 125 Hz could be implied as ‘positive’ in younger group; The frequency of 200 Hz and 300 Hz could be implied as ‘positive’ in older group
(2.0v, 125hz)		
(2.0v, 200hz)		
(2.0v, 250hz)		
(2.0v, 300hz)		
(1-2v, 100hz)	D [Amplitude ramping, 5 frequencies]	No agreement in both younger and older group
(1-2v, 125hz)		
(1-2v, 200hz)		
(1-2v, 250hz)		
(1-2v, 300hz)		
(1v, 100-300hz)	E [3 amplitudes, Frequency ramping]	The frequency ramping with low amplitude could be implied as ‘annoyed’ in younger group. The high amplitude with frequency ramping could be implied as ‘positive’ in older group
(1v, 300-100hz)		
(1.5v, 100-300hz)		
(1.5v, 300-100hz)		
(2v, 100-300hz)		
(2v, 300-100hz)		
(1v, 100hz+200hz)	F [1.0V, Combined frequencies]	No agreement in both younger and older group
(1v, 125hz+250hz)		
(1v, 250hz+500hz)		
(1v, 300hz+600hz)		
(1v, 200hz+400hz)		

From the Table 6.7, both younger and older subjects had the positive feelings of the pattern at the frequency of 125 Hz and 200 Hz when the amplitude increases. However, the performance had no improvement when the amplitude of the patterns was ramping as well as the pattern of two combined frequencies. The number of *'annoyed'* responses increases in younger group when the frequency was ramping.

6.5 Discussion

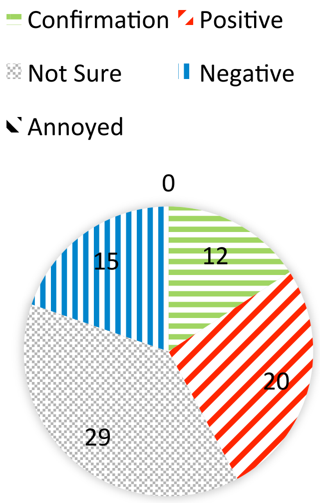
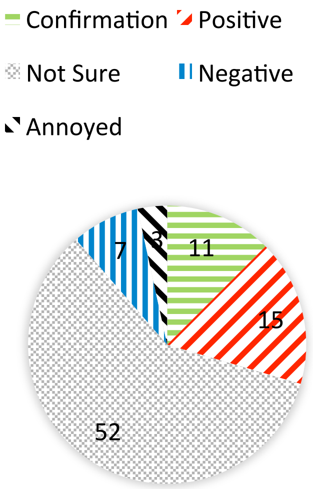
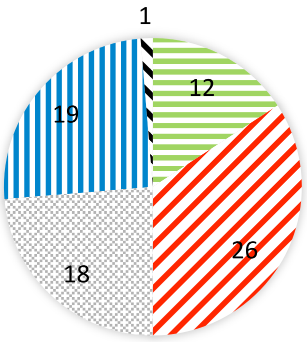
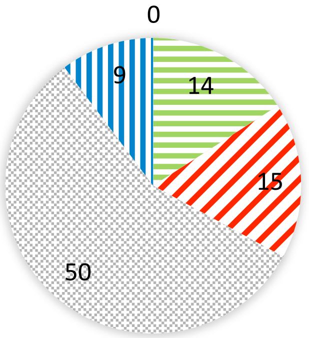
The results in this experiment showed that the performance was improved significantly when the amplitude increased from 1.0 V to 2.0 V. The study also showed that, for younger people, the pattern at 200 Hz with the amplitude of 1.5 V could be understood to have a *'positive'* meaning for the vibrotactile interaction whereas the frequency of 300 Hz at the same amplitude could be as a *'negative'* meaning. Furthermore, older people would like to experience the signals at the frequency of 200 Hz as well as 300 Hz with the amplitude of 2.0 V. Finally, the patterns with the effect of frequency ramping within 100-300 Hz at all tested amplitudes had greater *'annoyed'* responses in younger group compared to other patterns. Whereas, the patterns with the effect of amplitude ramping between 1-2 V had no significant influence in differentiating the vibration language because a large number of older people were unsure the meaning of the patterns. In addition, there was no clear agreement of the meanings of these patterns for younger people.

The following sections discuss the factors that could influence the vibration perception as a language.

6.5.1 Amplitude and Frequency parameters

The ability to detect the vibration depends on the amplitude. When increasing the amplitude, people could tell the feelings of vibration with different frequencies. Hence, the amplitude parameter is not appropriate to develop a haptic language according to the findings in Table 6.7.

In addition to the frequency parameter, Figure 6.12 calculates all the responses at each frequency level between younger and older people.

Frequency	**20-40 years**	**60-90 years**
100 Hz		
125Hz		

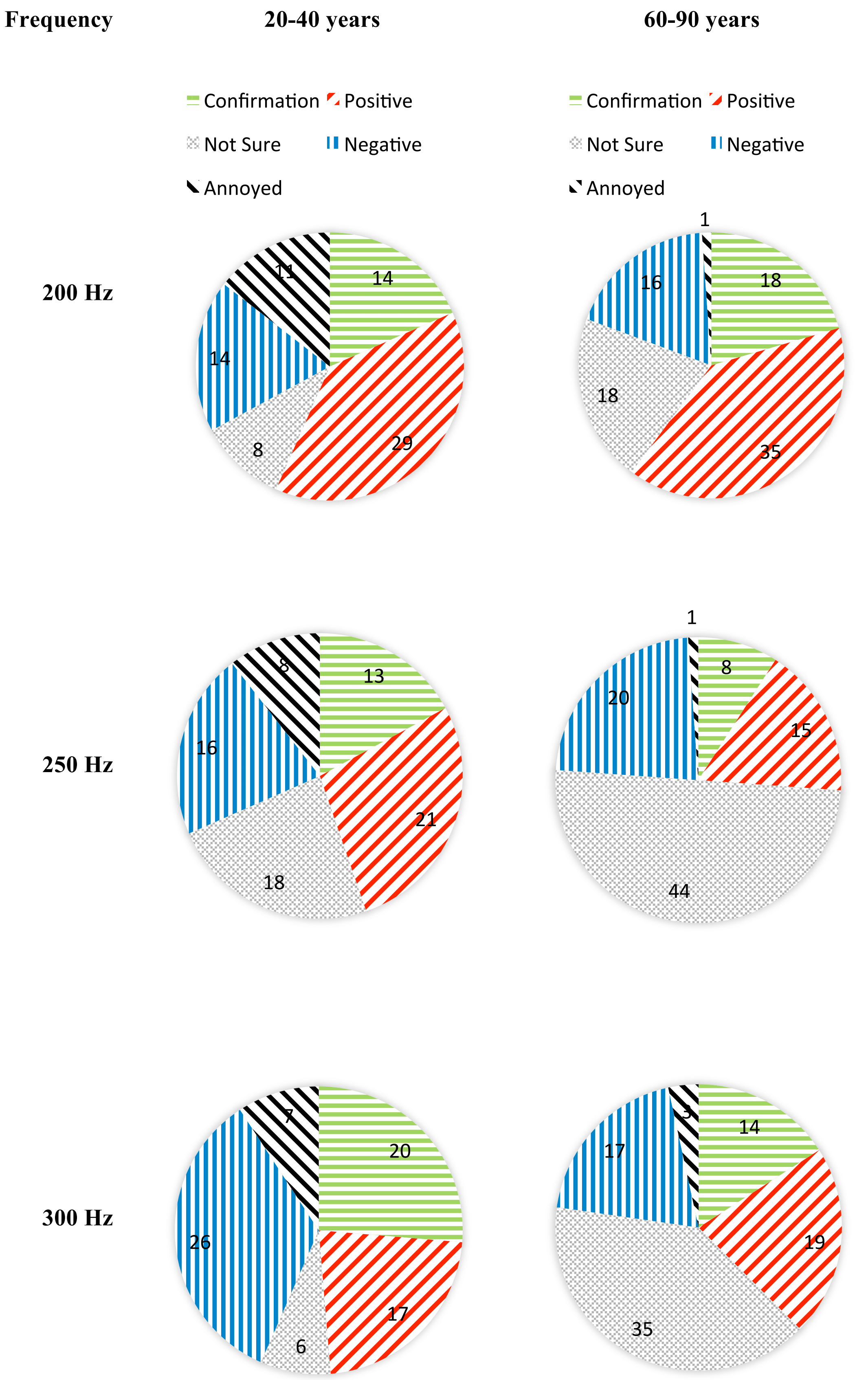


Figure 6.12 – The number of responses at each frequency between younger and older people

It can be seen that the number of *'positive'* responses at the frequency of 200 Hz is larger than other meanings for both age groups. There are a majority of *'not sure'* responses at the frequency of 100 Hz, 125Hz, and 250Hz in the 60-90 years group, whereas the performance is better in the 20-40 years group. Furthermore, younger people could differentiate the *'negative'* patterns at the frequency of 300 Hz, whereas older people were uncertain the sensations at this frequency. Therefore, frequency could be the key parameter that affects the haptic perception of vibration.

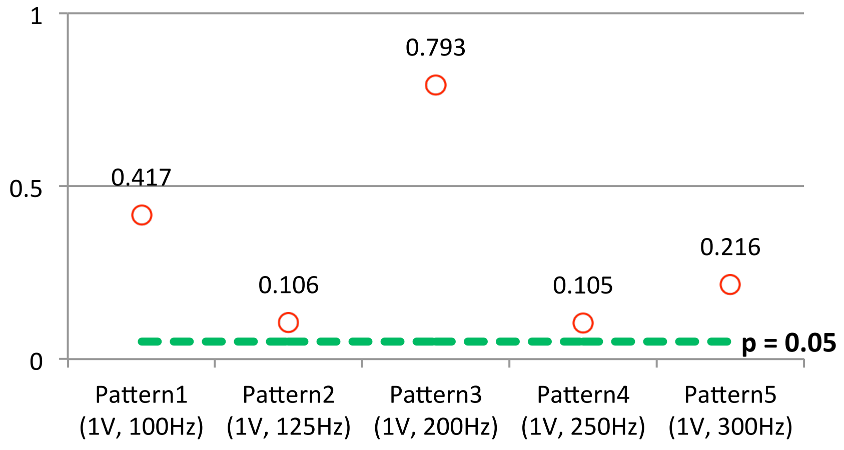
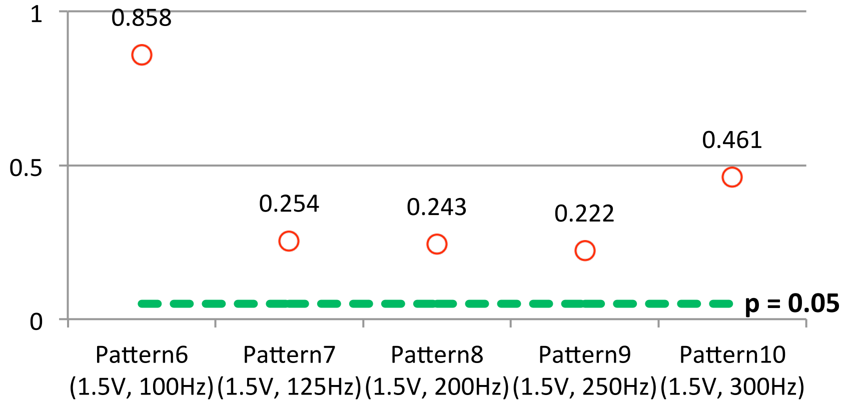
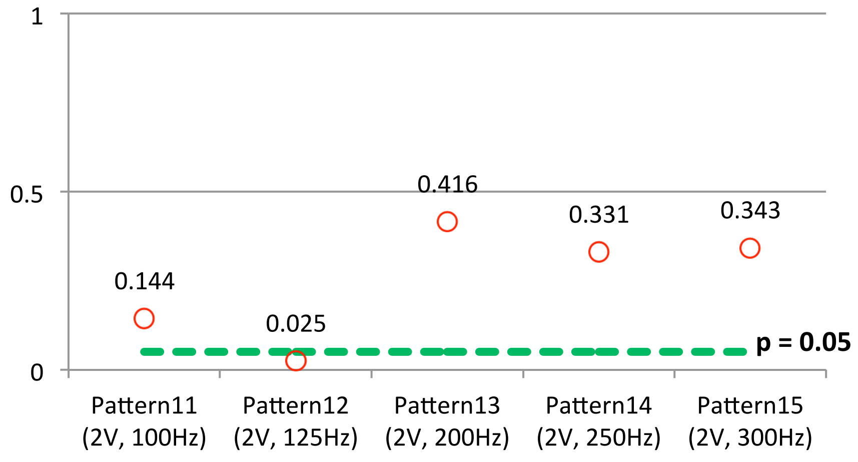
6.5.2 Rhythm parameter

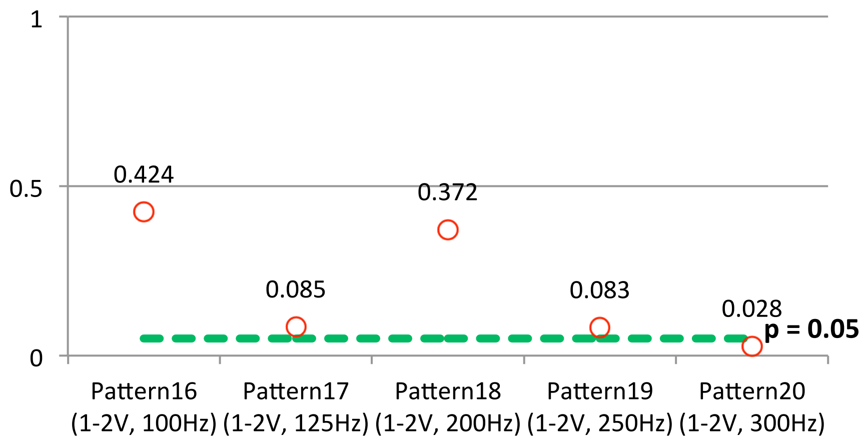
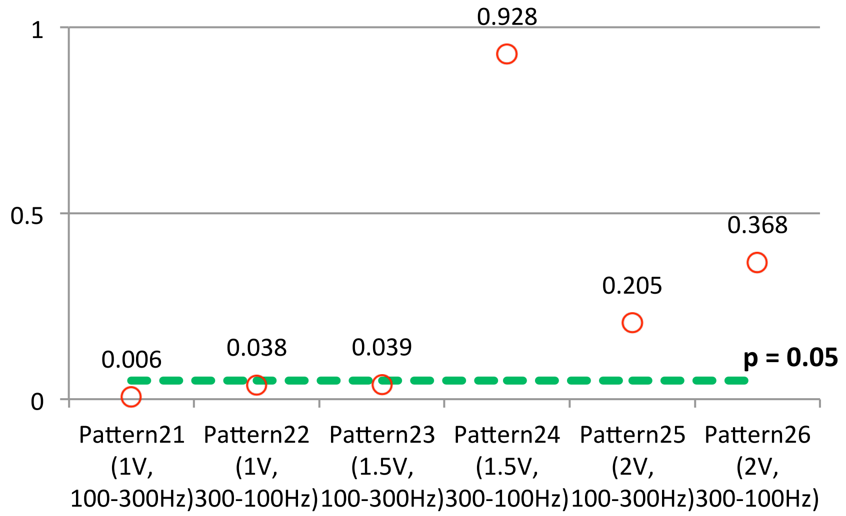
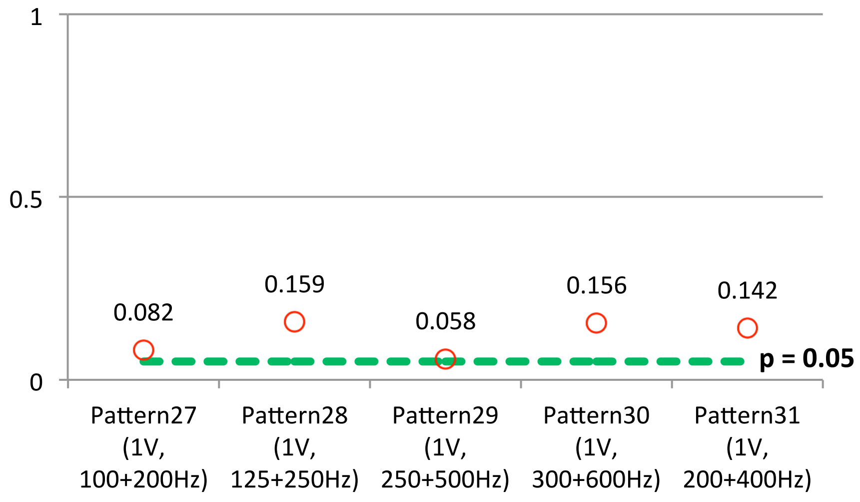
There is no improvement of vibration perception with the amplitude ramping as well as the combination of frequencies. However, the frequency ramping has a great influence in discriminating the patterns. Figure 7.8 showed that the number of the *'annoyed'* responses increased dramatically in younger group however the number of 'positive' responses increased in older group. There is no difference of ramping up and down when people perceived the vibration. Thus, the rhythm parameter can help with the development of haptic language together with the frequency parameter. However, the meanings of ramping are not easy to be understood. People could be trained to learn the effect of ramping up and ramping down.

6.5.3 Age factor

The Chi-Square test was carried out to determine whether there is a significant difference between age groups for adjective ratings as the collected data (the number of responses) are designed in the ordinal level (five words for the notifications of smartphones). Table 6.8 shows that there is no significant difference between younger and older people in discriminating the patterns (p>0.05). However, younger and older people have a significant difference when discriminating the patterns of frequency ramping up/down.

Table 6.8 - Statistical analysis of Chi-Square test for vibrotactile patterns

p **Value of Chi-Square test**	**Group**
	A [1.0V, 5 frequencies, no rhythm]
	B [1.5V, 5 frequencies, no rhythm]
	C [2.0V, 5 frequencies, no rhythm]

p **Value of Chi-Square test**	**Group**
	D [Amplitude ramping, 5 frequencies]
	E [3 amplitudes, frequency ramping]
	F [1.0V, Combined frequencies]

6.6 Summary

This chapter has evaluated 31 vibrotactile patterns with respect to the parameters of amplitude, frequency and rhythm. It was found that the patterns at the frequency of 125 Hz and 200 Hz could be understood to have a positive meaning for both younger and older people at high level of amplitudes. However, the performance of identifying the message implied by vibration had no improvement with the effect of amplitude ramping as well as two combined frequencies. Hence, the amplitude of vibration is the key parameter to determine whether people can detect the message of vibration but may not be beneficial for the vibration language.

Furthermore, at the same amplitude level, the vibration at 200 Hz could be implied as a positive meaning for the vibrotactile interaction whereas the frequency of 300 Hz could be as a negative meaning for younger people. The number of *'annoyed'* responses increased in younger group when applied the patterns with the frequency ramping to the subjects, whereas older people would like to experience the vibration with the frequency ramping.

The developed vibrotactile patterns still have a large number of *'not sure'* responses with the exception of the patterns generated at 200 Hz. Hence, the haptic language can be communicated through vibration however it is not easy to discriminate as a language. Humans have no pre-conception of vibrations other than as an alert.

Finally, due to the limited number of subjects used in this experiment no significant patterns were found to represent a haptic language. Therefore it is recommended that for the future experimental design vibrotactile patterns can be designed with the parameters of amplitude (3 levels from low to high), frequency (100-300 Hz) and rhythm of frequency. Another parameter of duration should also be investigated for the design of the patterns. As human need training to discriminate vibration as a language, a scenario (e.g. emergency calling during a meeting, texting on the train) should be provided to the subjects for the evaluation of vibrotactile patterns on the touch screen devices in order to acquire the emotional response link to the vibrotactile patterns precisely. The subjective evaluation can also be designed with the semantic differential pairs using the magnitude estimation technique in order to establish the haptic language that can be utilized on the touch screen devices. It is suggested that the words such as ‘urgent’ or ‘happy’ can be initially studied in order to develop the fundamental haptic language.

7 Final Discussion, Conclusions and Future Work

This chapter discusses and summarizes the findings from the study. Some suggestions for further research into haptic language design are also outlined.

7.1 Final discussion

In the literature review, previous work found that haptic feedback with vibration could improve the usability of mobile touch screen devices as an assistive cue to visual and audio aids [68, 69]. Therefore, it is important to develop a haptic language to enhance the quality of haptic feedback on touch screen devices as well as ascertain its accessibility into later years of life. The following discussion section focuses on this challenge.

7.1.1 An appropriate frequency range for vibrotactile feedback in smartphones

The range of vibrotactile feedback appropriate for typical smartphones was examined in order to guide the haptic language development. This study (see Chapter 3) demonstrated the natural frequency of the smartphone (Samsung galaxy S3) is around 400-500 Hz in a free-free hanging condition and over 2000 Hz in a platform supporting condition. Thus, these natural frequencies should be avoided where designing the vibrotactile patterns on smartphones because resonance may occur if the excited frequency of vibrotactile feedback reaches the natural frequencies, potentially causing damage. The vibrotactile feedback on current smartphones is generated by a single actuator with sinusoidal waveforms. It was also found that the eccentric rotating mass (ERM) actuators and the linear resonance (LRA) actuators are commonly used in current smartphones to provide vibrotactile feedback and the major frequencies used by Samsung galaxy S3, Apple iPhone 5 and Sony Xperia are 200 Hz, 175 Hz and 125 Hz respectively. Therefore, it is clear that the vibration responses of the same smartphone have different characteristics in different boundary conditions.

Thus, different smartphones showed different features of vibrotactile feedback due to varied structures and materials and the range found was 100-200 Hz, which aligned with the previous research findings that the pacinian corpuscles in the literature review (see section 2.5). And also, the natural frequency testing can guide the structure design of the phones in order to provide a good performance of vibrotactile feedback and no phone damage or faults occur.

7.1.2 Finger sensitivity for vibrotactile feedback

The first research question raised was: "*What is the threshold of finger sensitivity to vibration when younger and older people interact with vibration?*" A study of haptic perception (see Chapter 4) was conducted in order to validate the threshold in the range of 20-800 Hz and find human capability to discriminate vibration, the previous work had shown that human perception of vibration has a U-shape curve in the frequency range of 60-800 Hz and remains stable in the range of 20-60 Hz [94]. The study confirmed that the threshold of vibrotactile perception shows a U-shape trend in the full range for younger people and human ability to detect vibration decreases gradually with age due to the sensitivity of pacinian corpuscles decreases quicker than other three receptors (ruffini ending, merkel cells, meissner's corpuscles) [96]. It is also concluded that the optimal sensation to vibration for both younger and older people is in the range of 100-300 Hz. Moreover, 60 % of both younger and older people can discriminate two vibrations with the frequency of '100 Hz - 125 Hz', '300 Hz – 2500 Hz', '350 Hz – 250 Hz', and '375 Hz - 250 Hz'. Younger and older people showed a better performance to discriminate vibration around a base frequency of 250 Hz, compared to that around a base frequency of 125 Hz.

From the threshold and discrimination experiments, it was found that the best sensation of vibrotactile interaction for younger and older people is in the range of 100-300 Hz. This range was utilized for the development of vibrotactile patterns in the next stage. The findings that both younger and older people have the same ability to discriminate vibration establish the foundation of haptic language development for all ages.

7.1.3 Description of vibrotactile effects

The second research question was: "*What distinguished vibrations can be utilized as a haptic language for younger and older people*?" In order to address this question, seven semantic differential pairs ('*slow-fast', 'vague-distinct', 'bumpy-smooth', 'light-heavy', 'weak-strong', 'soft-hard'* and *'dull-clear')* were assessed and evaluated in younger and older people with the purpose of finding the appropriate adjectives to describe the sensation of a *'ramp-up and click'* compared to a *'click and ramp-down'* effect generated on an eccentric rotating mass (ERM) actuator and a linear resonance (LRA) actuator (see Chapter 5). It was found that most of the pairs gave little agreement in a description of the vibration with only two pairs that were *'slow-fast'* and *'light-heavy'* being suitable to describe the vibrotactile sensation for younger people. However, there is no clear agreement of any pairs for older people showing that they were unable to understand the message merely through vibration.

In order to improve the experiment design, **it is recommended that each adjective pair should be provided such as 'Slow – not Slow' instead of 'Slow – Fast' for human evaluation of vibrotactile effects. The magnitude estimation technique [139] is also suggested to measure judgments of the vibrotactile stimuli by assuming numerical values proportional to the vibration magnitude human can perceive**. This technique is robust enough to yield statistically significant results, compared to the 5- or 7- likewise scale.

Hence, there is still a possibility that the pairs of '*slow-fast*' or '*light-heavy*' may have potential as language for all ages, with training.

Interestingly, regarding to the actuator types, both younger and older people agreed that the vibration produced on the ERM actuators has the faster, more distinct, heavier, stronger, harder and clearer sensation, but bumpier, than on the LRA actuators, especially with the effect of *'click and ramp-down'*. Finally, over 30% of younger and older subjects would like the vibrotactile effect of *'click and ramp-down'* from the ERM actuator as an alert vibration on smartphones.

Therefore, older people perceived vibration with no clear meanings other than an alert message whereas younger people could tell the meanings of *'slow-fast'* or *'light-heavy'* through vibration, which could guide to select the proper notifications on smartphones, that should consist of two opposite meanings for the evaluation of vibrotactile patterns in the next step**. It was also seen that the actuator type and ramping effect have an influence in vibration perception.** Thus, the ramping effect was chosen as a parameter for the experiment of the vibrotactile patterns in order to develop the haptic language.

7.1.4 Development of vibrotactile patterns

A study of vibrotactile patterns was carried out in order to develop distinguishable patterns based on three parameters (amplitude, frequency, and rhythm) to represent common notifications (*'confirmation', 'positive', 'negative', and 'annoyed'*) for the application of smartphones (see Chapter 6). Another meaning of '*not sure'* was also provided to represent no sensation or people having no views on the meanings. It was found that the parameters of amplitude, frequency, and frequency ramping can be used to develop a haptic language and each parameter has different influences to the language design. The amplitude of vibration plays a key role to determine whether people can perceive the message at all. The frequency can be used to imply meaning. The study found that a signal at 200 Hz could be understood to have a positive meaning for the vibrotactile interaction for both younger and older people. The frequency ramping, but not the amplitude ramping, could be an essential parameter to design a negative vibrotactile interaction but younger and older people have different preferences of the meaning of the vibration with the effect of frequency ramping.

The study also found there were a large number of *'not sure'* responses to the developed vibrotactile patterns with the exception of the patterns generated at 200 Hz. **This study has shown that meaning can be communicated through vibration yet it was not easy to discriminate as a language because humans have no pre-**

conception of vibrations other than as an alert. Most people would require a certain level of training to learn a haptic language.

Although the sample size of subjects in this study is less than 50 and as such is too small to fully represent the whole population, the statistical analysis still showed that, for the groups tested, younger and older people have the same ability to discriminate vibrotactile patterns as a language because the p values for most vibrotactile patterns were greater than 0.05. This can now be used as a starting point for haptic language studies with larger populations.

Finally, **it is recommended that an appropriate scenario should be provided to the subjects for the evaluation of vibrotactile patterns in order to link the subjective responses to the vibrotactile patterns precisely. And also, the magnitude estimation technique can be used to design the semantic differential pairs in order to establish the haptic language that can be utilized on the touch screen devices.**

7.2 Conclusions

Main conclusions from each section of the study are outlined below.

7.2.1 Assessment of vibrotactile feedback

- Natural frequencies of current smartphone are around 400-500 Hz in a free-free hanging condition and over 2000 Hz in a platform supporting condition.
- Existing signatures of vibrotactile signatures for smartphones are within the range of 100-200 Hz.

7.2.2 Vibrotactile perception threshold and discrimination in vibration

- The optimal sensation to vibration for both younger and older people is in the range of 100-300 Hz and human ability to detect vibration decreases gradually with age.
- The ability to discriminate vibration around a base frequency of 250 Hz was improved compared to that around a base frequency of 125 Hz.
- The appropriate frequency range was 100-300 Hz and established the foundation of haptic language development for all ages.

7.2.3 Description of vibrotactile effects

- The *'slow-fast'* and *'light-heavy'* semantic pairs could be appropriate to describe the feelings of vibration for younger people but no clear findings resulted for older people.
- The magnitude estimation method should be included to experimental design.
- The actuator type and ramping effect both influence vibration sensation.

7.2.4 Vibrotactile pattern to haptic language

- Haptic language could be developed using vibration with the respect to the parameters of amplitude, frequency, frequency ramping and duration.
- Amplitude plays a key role to determine whether people can understand the meaning of vibration and the amplitude of 2.0 V had the best sensation for all ages.

- Frequency can also be used to imply meaning. 200 Hz was found to have a positive meaning for the vibrotactile interaction for both younger and older people.
- Frequency ramping has potential to emote a negative feeling, but amplitude ramping that has no significant influences for communication. This study has shown that meaning can be communicated through vibration.
- Humans have no pre-conception of the language, other than as an alert, particularly for older people. A certain level of training is therefore required.
- An appropriate scenario should be provided to the subjects for the evaluation of vibrotactile patterns.

7.3 Future Work

There is still potential for further research in this area, as outlined below.

Vibrotactile feedback parameter design

Amplitude, frequency, and rhythm are three common parameters to design vibrotactile feedback. Further work could take account of the interval time between vibrations as a new parameter to design the haptic language in order to fully understand the characteristics of vibration as a language.

Vibrotactile sensation by different actuators

It is recommended that the three actuators (LRA, ERM and piezoelectric) can be designed in the same rig in order to understand and compare the sensation from different actuators.

Sample size

Further research should be studied in the large population for the evaluation of vibrotactile patterns in order to find the representative patterns as a haptic language.

Other factors that affect haptic perception to vibration

The factors such as thickness of skin, contact area of vibrations and force pressure may also affect the performance of haptic perception. It is suggested to include those factors in the experimental design so that the haptic language developed would be acceptable to all.

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Appendix 1 Events of Smartphones

No	Events	Haptic feedback (y/n)	Additional cues (audio/visual)
	Basic operations		
1	Turning on	y	audio, visual
2	Turning off	y	visual
3	Low power	n	audio, visual
4	Charging start	y	audio, visual
5	Charging	n	visual
6	Full charging	n	visual
	Screen		
7	Sliding screen	n	audio
8	Password input	n	audio
9	Fingerprint (iPhone 5s)	n	audio
10	Rotate screen	n	none
11	Slide screen	n	none
12	Lock screen	n	audio
13	Adding/Removing widgets/apps/folders	y	none
14	Selecting widgets/apps/folders	n	audio
	Calling		
15	Dialing number	n	audio
16	Calling out start	n	audio, visual
17	During a call	n	visual
18	Calling out end	n	none
19	Incoming call	y	audio, visual
20	Busy call out	n	audio
21	Missed call in	n	visual

No	Events	Haptic feedback (y/n)	Additional cues (audio/visual)
	Messaging		
22	Receiving message/voice mail	y	audio, visual
23	Receiving Email	y	audio, visual
24	Text entry	y	audio
25	Selecting contact	n	audio
26	Sending out	n	none
27	Deleting Email/message	n	none
	Calendar		
28	Creating events	n	audio
29	Setting up events	n	audio
30	Text entry	y	audio
31	Reminding events	y	audio, visual
	Camera		
33	Taking photos	n	audio
34	Recording video	n	audio
35	Swiping screen	n	audio, visual
36	Setting wallpaper	n	audio
37	Editing photos/videos	n	audio
38	Deleting photos/videos	n	audio
	Connections		
39	Wi-Fi/mobile data set up	n	audio, visual
40	Web search input	y	audio
41	Web browsing	n	none
42	Multi window set up	n	visual
43	Download complete	n	visual
44	Bluetooth	n	audio, visual
45	S Beam	n	audio, visual
46	Connect computer	y	audio, visual
47	Disconnect computer	n	visual

No	Events	Haptic feedback (y/n)	Additional cues (audio/visual)
	Calculator		
32	Numbers input	n	audio
	Navigation		
48	Zooming map	n	none
49	Scrolling map	n	none
50	Browsing map	n	none
51	Voice searching	n	audio
52	GPS set up	n	audio, visual
53	Location input	y	audio
	Others		
54	App store	n	audio
55	Music/Radio/Video Player	n	audio, visual
56	Flight mode	n	visual
57	Roaming	n	visual
58	S Memo	n	audio
59	Clock/Alarm	y	audio, visual
60	Facebook/Twitter/Youtube/Google+ /what's apps …	y	audio, visual
61	Games	y	audio, visual
62	Personal apps	n/a	n/a

Appendix 2 Description of Six Modes on DRV2603EVM Kit

Mode	LED	Button	Haptic Effects	Actuator Mode
Mode 0	off	B1	Ramp-up and click	LRA (auto-resonance on)
		B2	Click and ramp-down	
		B3	Ramp-up and click	ERM
		B4	Click and ramp-down	
Mode 1	M4 On	B1	LRA Alert (Buzz)	LRA (auto-resonance on)
		B2	LRA Alert (Buzz)	LRA (auto-resonance off)
		B3	ERM Alert (Buzz)	ERM
		B4	LED Flash (Visual Alert only)	-
Mode 2	M3 On	B1	Click with braking	LRA (auto-resonance on)
		B2	Click no braking	
		B3	Double-click with braking	
		B4	Double-click no braking	
Mode 3	M2 On	B1	Keyboard Click (Click with braking)	LRA (auto-resonance on)
		B2	Space Effect (Click and Release)	
		B3	Backspace Effect (Double-click)	
		B4	Scroll Wheel Effect	
Mode 4	M1 On	B1	Click with braking	ERM
		B2	Click no braking	
		B3	Double-click with braking	
		B4	Double-click no braking	
Mode 5	M0 On	B1	Concentration Game	ERM and LRA (auto-resonance on)
		B2		
		B3		
		B4		

Appendix 3 Subject Consent Form from University of Sheffield

Title of Project: Interaction between adults and touch screen devices

Name of Researcher: Xueqing Zhang

Subject Identification Number for this project:

Subject ID Number for Questionnaire (if applicable):

Please initial box

1. I confirm that I have read and understood the information sheet for the above project and have had the opportunity to ask questions. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason. ☐

   I may also request that my data/recordings be deleted at any time.

3. I understand that my responses will be anonymised before analysis. I give permission for members of the research team to have access ☐

   to my anonymised responses.

4. I understand that video footage of task performance will be taken during the testing session and that I am free to stop any video of me being taken. ☐

5. I agree to take part in the above project. ☐

_________________________ _______________ ____________________

Name of Subject Date Signature

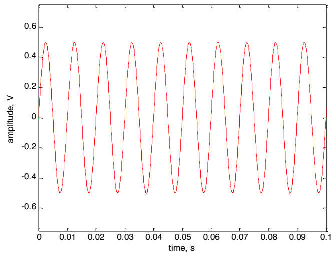
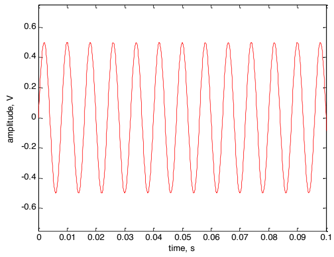
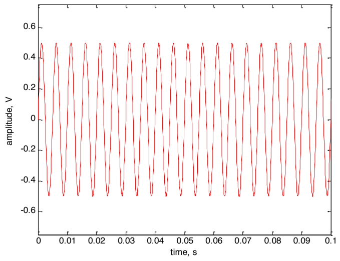
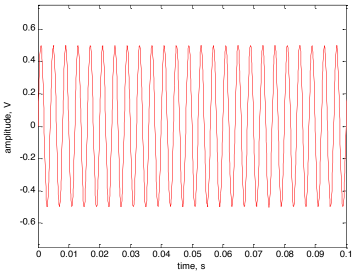
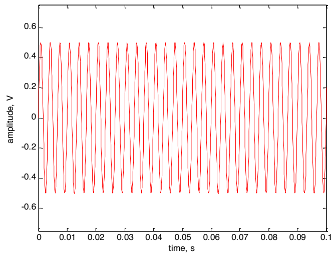
_________________________ _______________ ____________________

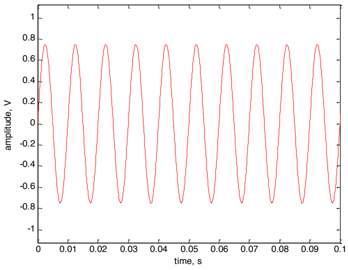
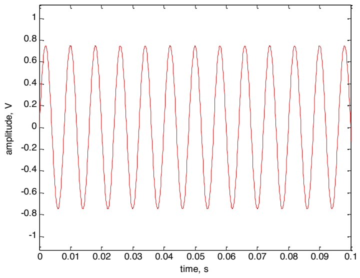
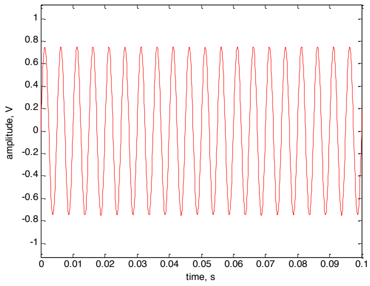
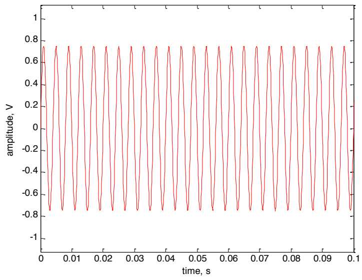
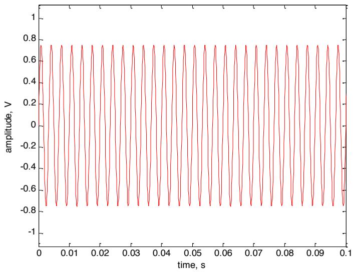
Researcher Date Signature

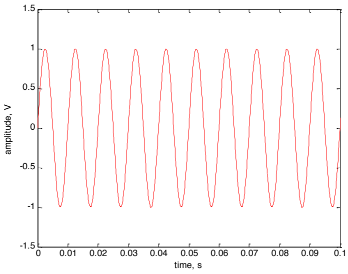
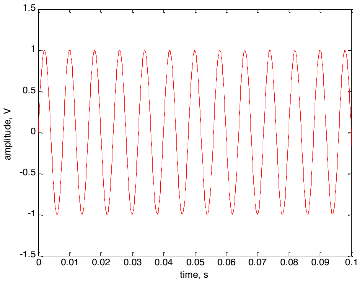
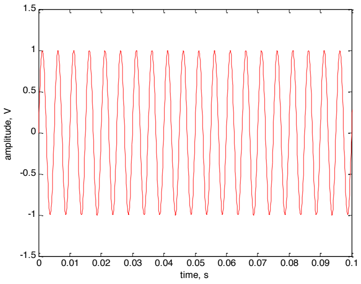
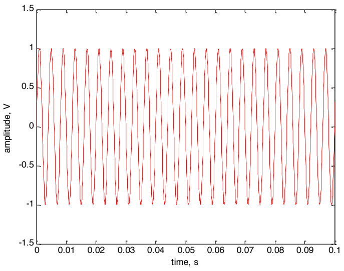
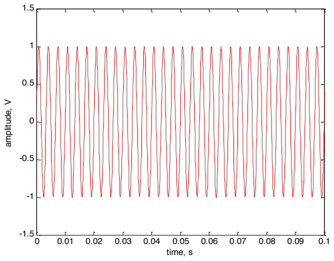
Copies:

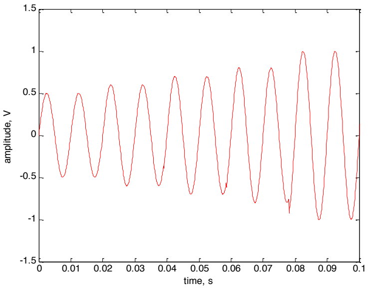
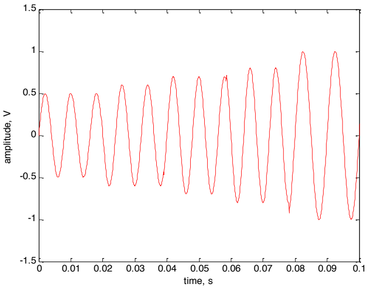
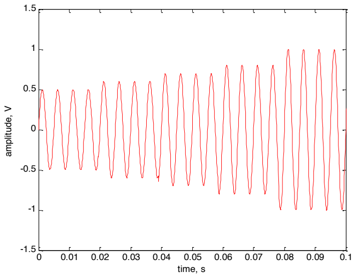
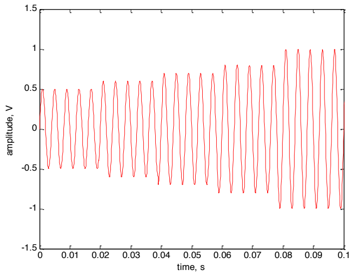
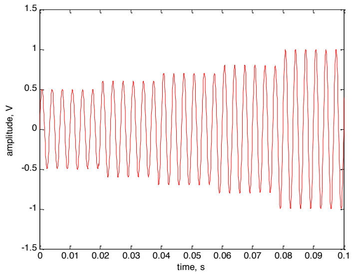
One copy for the subject and one copy for the Principal Investigator / Supervisor.

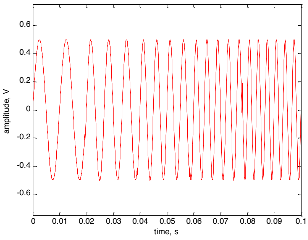
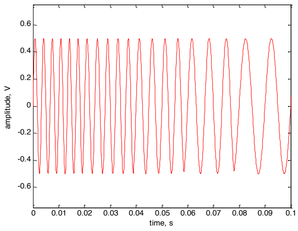
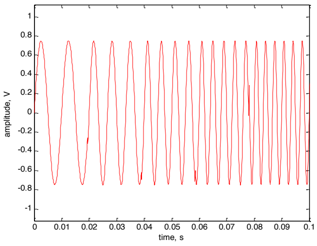
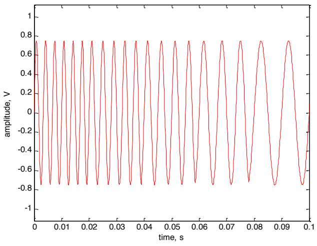
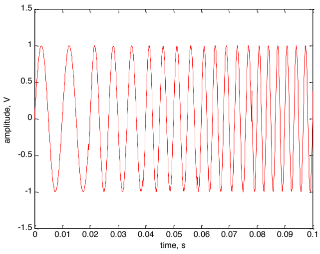
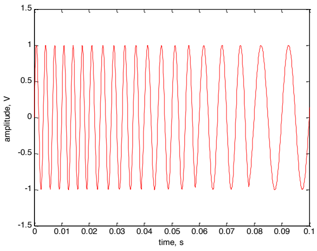
Appendix 4 Features of Vibrotactile Patterns Design

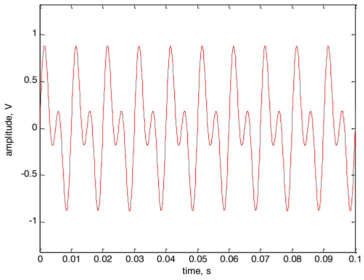
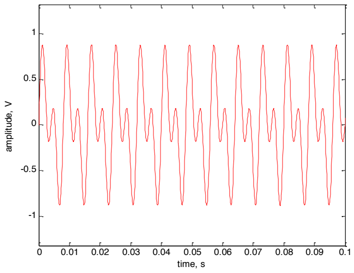
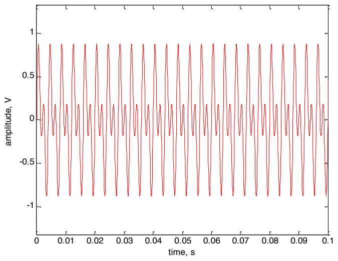
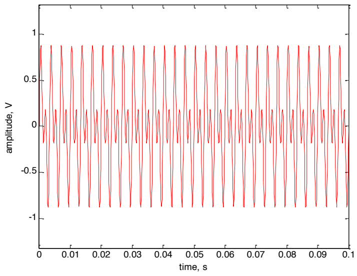
No.	Group	Pattern	Vibrotactile Pattern Design
1	A [Low amplitude, Different frequency levels, No rhythm]	(1.0v, 100hz)	
2		(1.0v, 125hz)	
3		(1.0v, 200hz)	
4		(1.0v, 250hz)	
5		(1.0v, 300hz)	

No.	Group	Pattern	Vibrotactile Pattern Design
6	B [Medium amplitude, Different frequency levels, No rhythm]	(1.5v, 100hz)	
7		(1.5v, 125hz)	
8		(1.5v, 200hz)	
9		(1.5v, 250hz)	
10		(1.5v, 300hz)	

No.	Group	Pattern	Vibrotactile Pattern Design
11	C [High amplitude, Different frequency levels, No rhythm]	(2.0v, 100hz)	
12		(2.0v, 125hz)	
13		(2.0v, 200hz)	
14		(2.0v, 250hz)	
15		(2.0v, 300hz)	

No.	Group	Pattern	Vibrotactile Pattern Design
16	D [Amplitude ramp-up, Different frequency levels]	(1-2v, 100hz)	
17		(1-2v, 125hz)	
18		(1-2v, 200hz)	
19		(1-2v, 250hz)	
20		(1-2v, 300hz)	

No.	Group	Pattern	Vibrotactile Pattern Design
21	E [Frequency ramp up/down, Different amplitude levels]	(1v, 100-300hz)	
22		(1v, 300-100hz)	
23		(1.5v, 100-300hz)	
24		(1.5v, 300-100hz)	
25		(2v, 100-300hz)	
26		(2v, 300-100hz)	

No.	Group	Pattern	Vibrotactile Pattern Design
27	F [Low amplitude, Two frequencies]	(1v, 100hz+200hz)	
28		(1v, 125hz+250hz)	
29		(1v, 250hz+500hz)	
30		(1v, 300hz+600hz)	
31		(1v, 200hz+400hz)