The role of vibratory cues in affective responses to tactile textures

By

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Publications

One publication has been produced from research that was undertaken as part of this thesis. The publication is listed below with a full reference, a brief outline, and details of its location within the thesis. In the case of the publication listed the candidate was soley responsible for the production of the content, with named authors providing support through the review and modification only.

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This paper discusses the initial findings of Chapter 3, and how vibratory cues could be related to affective texture rating of engraved plastic stimuli.

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Abstract

Innovation and novelty in product design has become increasingly central to engaging consumers and enhancing product experience. This concept, which is based on a multi-disciplinary approach, is primarily concerned with how products engage our sensory organs and the resulting affective influence that these engagements have on the consumer. In touch research, there is limited research into how tactile textures used in product design are perceived when the fingers are run across them. Specifically, how vibrations generated by finger scanning in active touch could be related to affective texture discrimination is not known.

The aim of this research was to ascertain the contribution of vibration to the communication of affective qualities of tactile textures. Specifically, the objectives were to investigate the affective language used in discussing tactile textures, and to determine the salience of vibratory cues in affective texture discrimination. Four experiments were conducted to address these objectives. Experiment 1 was designed to understand the affective language used to describe tactile textures, and whether the vibratory and topographical characteristics of tactile stimuli are indicators for affective ratings. Experiments 2 and 3 discussed how imposed vibration can communicate textural adjectives and that there are perceptual differences between imposed and texture-elicited vibrations. The final experiment, investigated how imposed vibration onto tactile textures can alter affective rating by manipulating the texture's vibratory spectral content.

The results of this work show that tactile textures can be rated using affective language, and that vibration contributes to these ratings as well as to textural descriptors. The results also show that texture-elicited and imposed vibrations are not perceptually similar. A new insight into the role of vibratory parameters in affective texture assessment is offered using imposed vibrations to tactile textures. Recommendations for future research are also given.

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Chapter 1

Introduction

1.1. Overview

Affective qualities of touch have been investigated in this research, specifically, how vibratory stimulation; by both applied and naturally generated vibration through active touch contributes to tactile perception. Although the modality of touch is very active in our everyday lives, little is known about the mechanisms which mediate somatosensory processing, particularly in dynamic exploration of our environment and the consumer products we possess. Indeed, there is a wealth of knowledge in static stimulation (where the finger does not move across a surface) for both spatial and vibratory stimuli (see Chapter 3); how we discriminate between stimuli and the sensitivity thresholds at which they are perceived. For dynamic touch, where the finger is scanned across textures, little has been elucidated. However, these findings have not given clear predictions about how we may perceive a dynamic stimulus. This is a key deficit in knowledge.

Landmark work by Hollins and colleagues (Hollins *et al*., 1993; 2000a) has begun to unravel how we tactually perceive our everyday environment in dynamic touch, and has proposed the following textural dimensions: rough-smooth, hard-soft, warm-cool and stick-slippery. Hypotheses have begun to emerge in recent years about the textural properties that govern our perception of roughness (Bensmaia and Hollins, 2003; 2005), warmth (Ho and Jones, 2004; 2008), stickiness (Bensmaia and Hollins, 2005; Yoshioka *et al*., 2007) and softness (Friedman *et al*., 2008). With the exception of warmth perception, all dimensions appear to be connected in part to the vibration generated through touch. This is unsurprising considering that the channels of touch, and the mechanoreceptors that form these, are activated by vibratory stimulation (Bolanowski *et al*., 1988).

Affective or hedonic descriptors have had little experimental investigation in psychophysical literature. Montgomery *et al*. (2008) stated that 'Concepts such as 'pleasantness' and 'danger' are highly emotive and depend strongly on preference, environment, culture and historical factors'. These adjectives were therefore rejected by Montgomery *et al*. for experimental study as they were not seen as objectively studiable. Studies by Picard *et al*. (2003) and Chen *et al*. (2009a) have shown that participants, when responding to stimuli within a particular context, can uniformly rate stimuli against a range of affective adjectives. These studies have given rise to the possibility of engineering textures to elicit a desired affective response for a given application such as car interior textiles (Picard *et al*., 2003) or perfume bottles (Barnes *et al*., 2004), both studies showing that one can potentially enhance product experience through engaging the sense of touch in a more sophisticated manner. To develop competent hypotheses concerning touch and affective communication through texture, new methods using affective engineering and psychophysical principles must be developed to elucidate the role of vibration in the rating of dynamic texture exploration.

This chapter has been structured to set the context of the research within the relevant research fields, its commercial relevance and finally, to frame the research question and specific aims. The structure of the thesis is then described.

1.2. Research definition

This research focuses on the contribution of vibration, both imposed and naturally occurring in scanning, to the perception of tactile textures. A muli-disciplinary research approach has been adopted, using affective engineering and psychophysical techniques to determine how we describe and evaluate tactile textures.

1.2.1. Relevance

At present in the UK, manufacturing provides 3 million jobs, is responsible for more than half of the country's exports, and conducts 75% of all the country's research and development (Pearson, 2009). More importantly, in the last ten years productivity has increased by over 50%. However, the volume of staff employed by the industry has been in steady decline. In order to continue to grow and dominate current and emerging market sectors, there is a need to add value to manufacturing through innovative design. This is crucial in addressing the growing competitive threat to the UK from the emerging economic powerhouses of China, Brazil, Russia and India (Cox, 2005).

According to the Design Council (2009), for businesses to grow in market share, productivity and profitability can be increased by investing in design. A simple model was proposed: for every £100 spent on design, turnover can be increased by £225. An example of such investment can be seen in Finland. The Finnish government invested heavily in research ad development and innovation in an attempt to re-emerge with renewed economic strength after the downturn in the early 1990's. The success of this initiative is exemplified by the accomplishments of world leading companies such as Nokia, Kone and Matso demonstrating the viability of investment in high value design and manufacture.

The Innovation Survey (PricewaterhouseCoopers, 2003), which looked at revenue generation of the world's top innovators, showed that 75% of their income came from products which had not been in existence 5 years previously. This illustrates the importance of using creativity to meet the needs of dynamic and competitive markets, a theme to which The Cox Review (2005) agreed. The Cox Review of Creativity in Business, commissioned by the Chancellor of the Exchequer, acknowledged that British design is focused on the customer; their needs and desires. It highlighted how the design industry is able to translate these requirements, using advances in technology, into products that are affordable, attractive and useful which have enabled the development of 'product experience'.

1.2.2. Research question

The aim of this research was to determine the extent to which vibratory cues communicate the affective qualities of tactile textures.

Specific objectives of the research question are as follows:

1) To investigate how participants describe and rate a variety of tactile textures and determine which topographical and fingerpad and surface interactions contribute to affective texture discrimination.

2) To establish whether textural descriptors can be assessed through imposed vibration with direct touch as suggested with indirect touch.

3) To determine whether imposed and those vibrations elicited by surface textures are perceptually similar – to what extent can conclusions from static imposed vibration literature predict responses to tactile textures?

4) To determine the extent to which manipulating spectral content of tactile textures through imposed vibration can alter affective ratings and propose affective texture specifications based on vibration profiles.

Figure 1.1 shows how the research objectives are met through four separate experiments. Experiment 4, is fed by the outcomes of the three previous experiments.

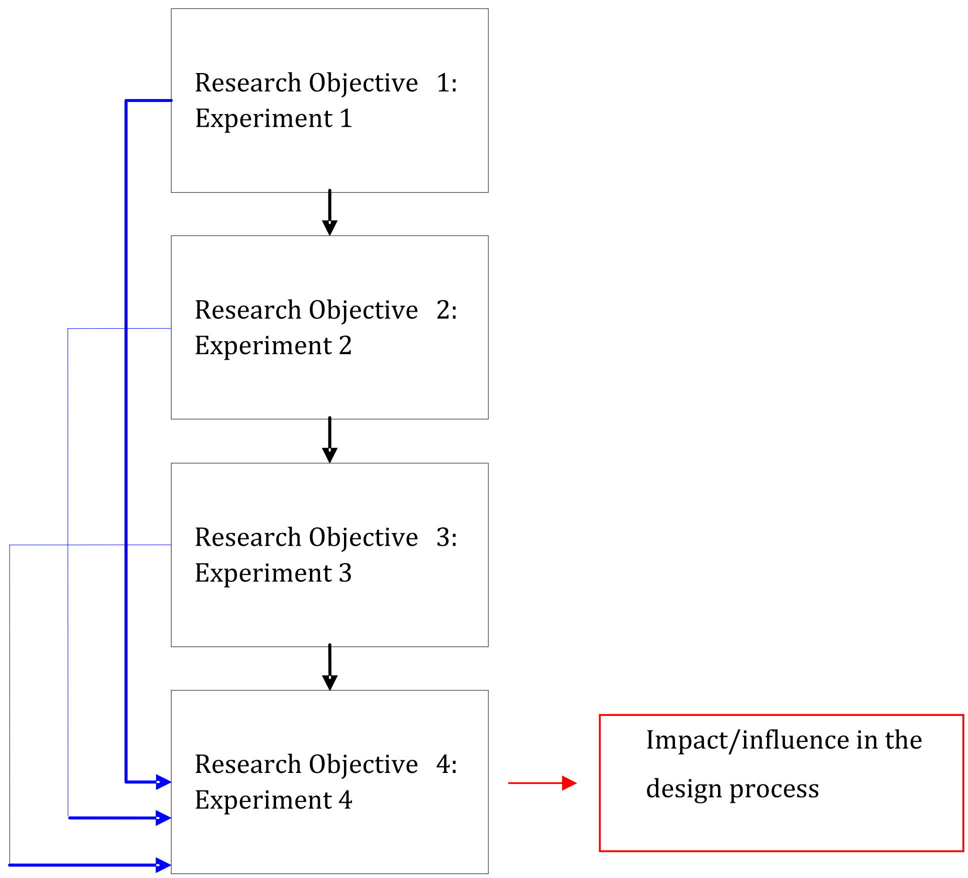

Figure 1.1 Research objectives and experiment plan

1.3. Thesis structure

The objectives outlined in Section 1.4.2 form the following chapters in this thesis. Chapter 2 gives a detailed critical analysis of somatosensory research, exploring neurophysiological, psychophysical and affective engineering contributions to the research field. The key differences in static and dynamic touch modes are also analysed and considered. Chapter 3 details the exploration of tactile textures within an affective engineering framework. Topographical and vibration analyses are conducted which indicate the primacy of vibration as a key contributor to affect based texture discrimination. Chapter 4 proposes a novel method of vibration generation using a piezo-electric actuator with touch platform. Using a psychophysical methodology, participants evaluate vibratory stimuli of varying frequencies and amplitudes against intensity, roughness and softness. Static and dynamic touch is investigated, producing similar results to those published. Softness and roughness information could be carried by vibratory cues which had not been previously investigated. Chapter 5 considers the differences between imposed and naturally occurring vibrations from dynamic touch. Comparisons made between square gratings and the novel vibration generation method demonstrated in Chapter 4 explores these differences and are discussed with current theories in mechanoreception. Chapter 6 returns to affective touch. This final study imposes vibration to surface textures from Chapter 3 to further elucidate the role of vibration in affective texture rating. The study results in new surface texture profiles which are hypothesised to elicit a desired response. Finally, Chapter 7 reflects on the findings of the experimental chapters in conjunction with literature to disseminate the overall contribution to knowledge. Further research directions are offered.

1.4. Product experience

1.4.1. Innovation and novelty in product development

Product experience is defined as the understanding of consumers' subjective opinions to experiences with product interaction (Hekkert and Schifferstein, 2008). This is built upon contributions from various research disciplines including mechanical and material engineering, psychology of perception and human factors. The ultimate goal of this relatively new research is to understand how these experiences are formed by deconstructing two main aspects of experience: the psychophysical perspective, and the interaction perspective.

The psychophysical perspective is informed by the motor and the sensory systems. The motor system enables us to explore and interact with a product, but it is the sensory systems (visual, auditory, tactile, olfactory and gustatory) which allow for the perception of a product and whether a sensation is pleasant or unpleasant. This perspective uses controlled experimentation that has limitations in the investigation of hedonic influences on product experience. These limitations have consequently given rise to research in human-product interaction.

The interaction perspective is centred on cognitive processing of a product based on previous encounters and experiences, which influence the emotional relationship between people and products. Two such research methodologies that aim to quantify emotional engagement are Affective and Kansei Engineering, whose primary objective is to produce specifications for product features which are anticipated to produce specific affective responses by consumers. Significant attention has been given to the aesthetic properties of product development and how this interacts with affect. Examples of such are water bottles (Longstaff, 2009), coffee cans (Ishihara *et al.,* 1997) and milk cartons (Ishihara *et al.,* 1996) but very few with tactile texture interaction. By investigating tactile perception, insight into how textures and materials are selected for affective purposes in product design may be improved (Chen *et al*., 2009).

There are many modes of tactile interaction with objects and reasons why these take place. These are active or passive, dynamic or stationary, and interaction for practical use or for play (Sonneveld and Schifferstein, 2008). The modality of touch plays such a large role in our daily lives and interaction with the physical world around us, (not just with perceptual dimensions of touch such as roughness and softness, but also on an affective level) that a whole new desire for tactually stimulating design can be exploited for industrial gain. If the application of knowledge already available concerning this modality is optimised to develop surface texture specifications for manufacture, surfaces of products can also begin to impart affective characteristics. There is scope in this research to benefit product development and consumer enjoyment. For example, it could be feasible to build a brand identity further than visual communication. A product can embody and convey a specific tactile 'signature', similar to that investigated by Beck *et al*. (2009) with stimulus identification tasks, therefore making a brand tactually recognisable. Through the sense of touch, a company could influence the way it wishes the consumer to perceive their product.

It has been acknowledged by Hekkert and Leder (2008) that new and innovative products that join the market are not always liked immediately. Leder and Carbon (2005) showed that for car interiors where innovative features were introduced, participants did not always appreciate these innovative features. It is hypothesised that this may be because the features were seen as frighteningly unfamiliar (Biederman and Vessel, 2006). It is also possible that appreciation for novelty and innovation in design may take time, and repeated evaluation or interactions are a way of measuring the change in appreciation. Hekkert and Leder (2008) suggest that designers need to find a balance between design innovation and novelty, and acceptability to promote a market leading position. Innovative use of texture could help product designers to achieve this balance.

1.4.2. Affective Engineering

Affective engineering employs methods explored in Kansei engineering and attempts to gain a better understanding of the 'internal sensation' that external stimuli evoke. According to the Dainihon Japanese Dictionary, Kansei is the 'sensitivity of a sensory organ when sensation or perception takes place in answer to stimuli from the external world.'

Nagamachi (2001) suggests that there are two ways of measuring the understanding of what causes affect: (1) physiological measures, such as heart rate and body expressions; and (2) psychological measures, such as participants' spoken words and responses to semantic differential questionnaires. These methods are predominantly used to analyse current products within a market, or to aid designers in designing new products or product features. Key methods and techniques used in the packaging industry by Barnes *et al.*, (2007) can be extracted to analyse the affective qualities of touch such as triadic sorting, semantic mapping and self report studies.

Self-report studies are questionnaires giving an arrangement of opposite meaning adjectives separated typically by a seven point scale. Participants are then asked to rate the stimuli against these adjectives that can be analysed through Principal Component Analysis (PCA) to generate an understanding of how people score emotive words against each stimulus. This can then be compared against physiological measurements in order that conclusions and comparisons can be drawn.

Kansei engineering provides a useful framework in not just understanding what consumers like and dislike, but also about how they respond on an emotional level to a product as a whole or its aspects. These tools are especially useful for design teams who are launching a brand new product or making adjustments and updated models (Barnes *et al*, 2004).

1.5. Touch research

Two distinct branches of knowledge exist in touch research. The first has concentrated on the mapping of mechanoreceptor function, using vibratory and indentation based stimuli, and the second more recent branch has begun to investigate how we perceive tactile textures from our daily lives such as textiles. The former field has provided valuable insight into somatosensory processing, such as that embodied in the channels of touch model refined by Bolanowski *et al*. (1988), and the latter to spatial acuity models in static touch (Gibson and Craig, 2002; Craig *et al*., 2008) and predictions for how the finger will respond in dynamic touch (Lederman and Taylor, 1972; Taylor and Lederman, 1975). These models, however, use highly controlled stimuli such as sinusoidal waveforms and square gratings. It is acknowledged though that complex vibrations, such as those encountered in scanning a surface texture comprise of sinusoids, however, this research does not give clear predictions of how naturally everyday textures are perceived which are compositionally complex.

Tactile textures can be described in a variety of ways. Katz's pioneering work (1925) illustrated how we perceive texture by means of Modifikationen, or 'qualities' of touch, and has led to the realization of a textural continuum model for tactile texture perception. This model is based on the perceptual continua of soft-hard, warm-cool, rough-smooth and sticky-slippery (Hollins, Bensmaia, Karloff & Young 2000), which are thought to be linked to the physical properties and topography of the stimuli.

When a finger is move across a texture, vibrations are generated. Recently, within the field of vibrotactile perception, substantial research has been channelled into defining how vibration is perceived. Most notably, understanding how the four mechanoreceptors and their respective afferents in the fingertips process the elements of touch (see Johnson and Hsiao (1992) for a review), and the frequency bandwidths in which each mechanoreceptor operates (Bolanowski *et al*., 1988).

Fine textures, defined by having spatial periods of below 200μm (Bensmaia and Hollins, 2003; Yoshioka *et al*., 2001), generate high frequency vibrations, which are mediated by the Pacinian Channel, with an estimated bandwidth of between 40Hz and 800Hz (Bolanowski *et al*, 1988). Landmark work in understanding this mediation by Bensmaia and Hollins (2003, 2005) shows that for these fine textures, the relationship between vibration and the perception of roughness is linked to vibratory power. As power is independent of scanning speed, it was concluded that speed is not pertinent to roughness perception. The latter investigation (Bensmaia and Hollins, 2005) also indicated that vibration could contribute to the perception of *stickiness* in fine textures.

Coarser textures (spatial periods over 200μm) tend to generate lower frequency vibrations and these are mediated by the rapid adapting Meissner corpuscles, with a bandwidth of between 4 and 40Hz (Bolanowski *et al*. 1988), which has had little experimental investigation (Hollins and Bensmaia, 2007). Although it is known that these vibrations are generated, discrimination of coarse textures is determined predominantly by spatial acuity and not the low frequency vibrations generated. Many studies, mostly by Lederman (Lederman and Taylor, 1972; Lederman, 1974; Taylor and Lederman, 1975) show that irrespective of movement, it is the gaps between texture features that people recognise. One theory reported by Srinivasan, Whitehouse and LaMotte (1990) attributes the Meissner corpuscles to localized slip detection in grasping, so potentially these low frequency vibrations which will occur with dynamic touch. Therefore, the role of these low frequency vibrations is still illusive. It is worth noting at this point that, all research discussed only used participants with 'normal' somatic sensation and not those with sensory impairments therefore this research may not be inclusive of those with tactile-related disabilities.

Chapter 2

Literature review of somatosensory processing and touch perception

2.1. Overview

This research has investigated how the interactions between the fingerpad and surface textures contribute to affective texture discrimination. Before one can begin to elucidate this relationship, a comprehensive understanding of how the somatosensory system processes tactile stimulation is required.

The way a tactile texture is perceived can be simplified to a four stage process beginning with engaging the stimulus (Figure 3.1). When the fingertip makes contact with a surface texture, mechanoreceptors are stimulated sending signals through the nervous system to the somatosensory cortex in the brain. This is the focus of neurophysiology research and has given touch perception a biological insight into how tactile perception is formed.

The third stage of this model relates to psychophysical research that concentrates on measuring the sensation of touch. Focus in recent years has led touch-based psychophysical research from metathetic continua, posing questions to participants such as the location of the stimulus, towards a more qualitative position investigating the magnitude of change between stimuli, for example (Stevens, 1975). The former is more concerned with finding just noticeable difference in two stimuli to establish sensitivity thresholds. This methodology is exemplified in the following sections regarding vibratory and spatial processing. The later, qualitative continua position is more in line with the affective research in this thesis and has been used to quantify how the textural dimensions of roughness, softness, stickiness and warmth are perceived. A critical analysis of the techniques which have been applied to these textural dimensions pioneered by Hollins and colleagues (1993; 2000), is also presented. The final stage in Figure 3.1 represents the main objectives of this thesis. Therefore, in order to present hypotheses on how we might assess a texture from an affective standpoint, a comprehensive grounding in what precedes it is necessary.

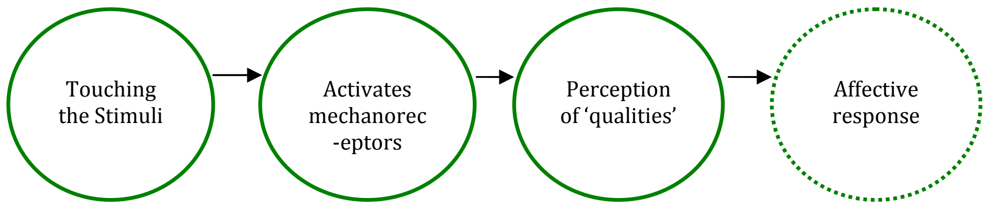

Figure 2.1 The process of touch to affective response

This chapter has been structured to investigate the prominent theories in touch perception. First, an overview is given concerning the afferent systems in the fingers which encode stimulus information. This considers current theories in neuroscience which give hypotheses as to which aspects of our touch experience can be explained by recorded nervous system activity. After that, existing theories on the function and capabilities of the system are discussed in both spatial and vibratory stimuli processing for static and dynamic touch. An overview of theories in dynamic touch introduces the research area of texture perception. Texture perception research has given rise to the identification of textural dimensions – adjectives by which participant's uniformly rate texture parameters. These are roughness, stickiness, softness and warmth and have been associated to changes in fingerpad/texture interactions, such as vibrational power in the case of fine surface textures and roughness perception (Bensmaia and Hollins, 2003; 2005). Relationships between affective qualities of touch and surface texture characteristics are also discussed. Finally in the conclusion, assessments of the research area and key limitations are discussed that justify the experimental approach taken in this research.

2.2. Cutaneous mechanoreception and neurophysiology

There are four cutaneous mechanoreceptive afferent types involved in the somatosensory processing system of glabrous skin. It is the stimulation of these afferents by dynamic or static touch producing a perceptual response to any given tactile stimulus. This perceptual response has been characterised in both objective psychophysical studies of detection, discrimination and identification tasks, and subjective classification and scaling studies. Briefly, these mechanoreceptors are slowly adapting type I (SA I) afferents, rapid adapting (RA) afferents, Pacinian (PC) afferents and to a lesser extent, slow adapting type II (SA II) afferents (Johnson, 2000).

SA I afferents, which end in Merkel cells, densely populate the fingertips and palm of our hands. They are sensitive to the geometric form of a stimulus and provide a detailed neural image of the structure of surfaces and can resolve detailing of 500μm that makes this afferent system highly sensitive to point, edge and curvature detection (Johnson, Yoshioka and Vega-Bermudez, 2000). The SA I system is therefore implicated in coarse texture and fine form perception. It has also been shown in the work of Bolanowski *et al*., (1988); the Merkel discs are also responsive to frequencies of 0.4 to 4Hz, which may also explain why Johnson *et al*. (2000) have reported the system to be at least ten times more sensitive to dynamic, as opposed to static, stimulation.

The RA system is known to end in Meissner corpuscles which are highly sensitive to mid range vibrations. They transmit robust information of skin deformation in dynamic touch which is associated with object grip and localised slip detection. This range is approximated to be between 4 and 40Hz (Bolanowski *et al*., 1988). They are even more densely populated than the SA I cells and four times more sensitive than the SA I afferents detection of skin movement (Johnson *et al*., 2000).

The Pacinian system is extremely sensitive to high frequency vibrations and is perfectly positioned in the skin to filter out low frequency vibrations, which would otherwise overwhelm the system (Johnson, 2001). The Pacinian system has also been implicated in the perception of distal site (indirect contact, through a probe for example) objects through vibration. Their spatial resolution is poor as they are not as densely populated as the other vibration stimulated afferents, but have excellent sensitivity for frequencies in the range of 40-400Hz (Bolanowski *et al*., 1988).

Studies discussed in this chapter concerning mechanoreception have concentrated on the measurement of intensity, and more recently, roughness. It is these psychophysical findings that have been paired with neurophysiology experimentation, which in the last three decades aimed to understand how 1) neural activity relates to physical stimulus parameters and 2) what relationship best describe how neural activity elicits perception. The implications of meeting these objectives will inform how people perceive the intensity of any arbitrary stimulus. The significance of this has been well defined by Johnson (2000), that if we are able to understand how higher lever information processing is coded in the brain, valuable insight into the neural mechanisms of perception and cognition can be gained.

From these observations, there are two clear branches of theory around neural processing, which are intrinsically linked to the most popular use of somatosensory stimulation; the intensity and frequency of vibration. Bensmaia (2008) investigates how perceived intensity of a stimulus is coded. Numerous theories have been discussed and rejected such as that tactile intensity is coded by the number of active afferents by type, for example, Pacinian or RA. Bensmaia also stated that although afferent types can be isolated and targeted by stimulation, skin contact generally excites several afferent types. It is acknowledged by Bensmaia also, that in a real world context, tactile explorations are complex, and that all afferent populations are involved in the neural coding stages of processing, signifying an evolving general hypothesis. More specifically, all afferent types contribute in producing a unified percept, but the frequency of the signal is also contributing.

Johnson *et al*. (2000) discuss how important it is to understand neural coding for the subjective assessment of the textural dimensions of touch outlined by Hollins, Faldowski, Rao and Young (1993) may be subsequent reactions to 'built-in neural mechanisms'. This is a theory that would be supported by Bensmaia and Hollins (2003; 2005) research in roughness perception and vibratory power with PC activation. It could also be the case that these subjective dimensions are based upon sensory experiences. Nevertheless, determining the physical quantities of textural dimensions remains elusive from a sensory evaluation perspective. Neurophysiological studies are clearly underpinned by rigorous psychophysical experimentation. Therefore, to explore the hypotheses of Johnson *et al.,* (2000), concerning textural dimensionality and neural coding, extensive perceptual research still needs to be conducted.

2.3. Spatial processing

There are two main areas of research that have focused on defining the limits to which people can resolve surface features. The first is how difference discriminations are made between stimuli without the assistance of vibratory cues in dynamic touch. Lederman (1982) agreed that vibrations do occur in active touch, but they are not required in roughness perception of coarse surface textures, such as the gratings used in the explorations as spatial processing was dominant (Lederman and Taylor, 1972; Lederman, 1974). The second has focused on shaping the exact spatial resolution of the SA I afferents, with the evaluation of neural coding from different static touch methods.

2.3.1. Dynamic touch

Lederman and Taylor (1972) determined the basic surface parameters that govern roughness perception for grated stimuli. These stimuli were machined aluminium alloy plates, which had constant depth of 0.125mm and varying groove and ridge characteristics. In the first experiment, the ridge width (0.25mm) remained constant and the grooves between stimuli varied from 1.25mm to 1mm, in increments of 0.125mm. The forces employed were 28g, 140g and 700g, and participants were required to give numerical magnitude estimations of roughness, so the rougher they felt the surface to be, the higher the assigned number. Analysis showed that as groove width (and spatial wavelength) increased, so did the perception of roughness. There were also modest increases in roughness with increased force, although as Lederman and Taylor noted, it was improbable that in free haptic exploration, participants would employ such force. As the roughest surfaces had the largest groove width, but also the biggest spatial wavelength, a second experiment was conducted and also altered the ridge width, which had previously remained constant. Pairs of grooved plates were manufactured that had the same spatial wavelength, but the ratio of groove and width was altered, therefore if spatial wavelength was the dominant factor in roughness perception, the pairs should be judged as equally rough. The results of the experiment showed again an increase in roughness with increased groove width produced higher judgements of roughness, and a decrease in roughness with increased ridge width but at a much shallower rate of change in comparison to groove width. As there were differences in roughness perception with these two parameters, Lederman and Taylor ruled out the effect of spatial wavelength being dominant in roughness perception.

With regards to exploration force, Lederman and Taylor suggest that the perception of roughness may increase with the amount of skin that is unsupported by the surface texture. Lederman and Taylor (1975) added to this by observing that at groove widths of 8.5mm, the linear increase in roughness perception begins to flatten which has been attributed to 'bottoming out', when the finger pad has full contact with the bottom of the grooves.

There is a key limitation to the data and theories proposed in these researches; that there is no precise definition of what is perceptually smooth, because the judgements are not made against a non-machined stimulus. The finest surface used by Lederman and Taylor (1972) had a spatial wavelength of 0.250mm, which is classified as a coarse surface texture based on the subsequent findings of Blake *et al*. (1997) who reported between 100µm and 200µm, Yoshioka *et al*. (2001) who reported 100µm, and Bensmaia and Hollins (2003) who specify a transition period from spatial to vibration dominance at 200µm. This casts doubt on whether they can regard any of their surfaces as smooth, or whether they should be seen as smooth spatial textures.

Stevens (1990), states that with the perception of roughness, which was the primary focus of the Lederman and Taylor explorations, other cues other than spatial resolution play a part. As Katz (1925) and Lederman (1982) have acknowledged, vibration does occur between the finger and the stimulus in dynamic touch and will contribute to forming a percept, and integration of afferent signals must occur. In an experiment using vibrating gratings with a dense array stimulator, Bensmaia *et al*., (2006) showed that RA signals interfered with SA I afferent processing. Indeed, the vibrations were not caused by the scanning motion, therefore indicating that vibrations are part of the perception forming process.

2.3.2. Static touch

A second focus on spatial acuity has been directed towards detailing the absolute resolution of the somatosensory system by using grating orientation and smooth-grooved tasks in static touch. Grating orientation tasks involve placing a grated stimulus either perpendicular or parallel to the length of the finger and asking the participant to determine which direction the grooves are running. A smooth-grooved task asks the participants to determine whether the stimulus placed on the finger is smooth, or whether it is grooved. Both methods have a high element of chance biased results, which is why psychophysicists commonly employ a 75% correct answer rate to determine thresholds (Ulrich and Miller, 2004).

Experimentation using static stimulation (therefore eradicating any movement based vibrations) grating orientation and grooved-smooth tasks has been conducted to determine the precise resolution of our spatial processing afferents (Craig and Gibson, 2002). Gibson and Craig's primary interest was to investigate spatial acuity on different hand sites. The study showed that between the grating orientation and the smooth-grooved task, different thresholds were obtained, giving rise to new theories in spatial processing. There was a marked difference between hand sites also, for example at the base of the finger and the finger tip. The difference in threshold between the fingertip and the finger pad (which is the area located just above and including the whorl) with the grating orientation task shed some doubt on whether the two methods of acuity testing were complementary, or are investigating two different factors in touch perception. Gibson and Craig attributed these differences to the dermal ridge formation of the skin, because at the tip the ridges run more parallel to each other, a theory that was also supported by Wheat and Goodwin (2000). Wheat and Goodwin concluded that sensitivity is heightened when the grooves run perpendicular to the dermal ridges. To reinforce the claim that skin mechanics may influence sensitivity on particular tasks, Gibson and Craig also reported a difference in thresholds for the orientation task with the base of the finger, attributing it to the underlying tissue fibres that run along the finger. Despite the differences in results, the smooth-grooved tasks yielded a fingertip threshold of 1.2mm groove width. This was consistent with Johnson and Philips (1981) whose threshold level was 0.94mm with similar testing procedure and the SA I affect spacing in the fingertip which is approximated at 1mm (Johnson and Hsiao, 1992).

The main working theories that emerged from Gibson and Craig (2002) revolve around the differences in threshold level between the grating orientation task and the smooth-grooved task. In the smooth-grooved task, the stimulus identification was hypothesised to be based on intensity cues and yielded much lower sensitivity thresholds than the grating orientation task. This means that the smooth and grooved surfaces were indicated as different by the participants based on the difference in neural activity triggered by contact with each stimulus. In other words, the smooth surface had just the outside edge of the stimulus pressing into the skin and a larger contact area. The grooved stimulus had more edges and less contact area with the skin which creates a less intense neural response. It is this which makes it easier to differentiate between a smooth and a grooved stimulus. An interesting paradox therefore existed between the two procedures. If spatial acuity is based on an intensive code alone, then in a grating orientation task an arbitrary stimulus should feel exactly the same regardless of orientation. This was not observed in the experimental results, prompting the reconsideration of the spatio-intensive code. The spatio-intensive code was first explored by Taylor and Lederman (1975) who hypothesised that roughness perception was a function of intensive and spatial deformation of the skin in static touch, so the amount of neural activity and where is it occurring on the skin is important in perception. This theory was subsequently explored by Craig, Rhodes, Gibson and Bensmaia. (2008) to further understand the findings described by Gibson and Craig (2002). Grating orientation and smooth-grooved tasks were employed and informed by theory based on the mechanical continuum model of afferent response to static loadings on the fingerpad (Sripati, Bensmaia and Johnson, 2006). To challenge the intensive coding theory of smooth-grooved decision making, different forces were employed in the experiment in a random order. For example, the smooth stimulus could be presented at a moderate penetration into the skin followed by the grated at a much greater force. It was hypothesised that a change in force (therefore stimulus intensity) could make discrimination more difficult and raises the threshold. The three forces used were 27g, 100g and 430g with mid penetration depth between 1500μm and 4500μm across participants and ± 500μm and ±1000μm. The spatial wavelengths of the gratings were 0.5mm, 0.75mm, 1mm, 1.2mm, 1.5mm and 2 mm. The experimental results showed that there was no significant main effect of stimulus penetration depth on the smooth-grooved task. There was a slight increase on the accuracy of grating orientation discrimination however, which was consistent with previous research conducted by Gibson and Taylor (2006) using a similar methodology. Using the data from the experiment, and neural data presented by the mechanical continuum model, it was shown that in the discrimination of smooth-grooved stimuli, participants make judgements based on the absolute difference in baseline (for example, afferents which lie in the gap of a groove) and the peak neural activity produced by contact between the skin and the stimulus. This is linearly related to the absolute difference in tensile strain also. For the gating orientation tasks, relative strain was a good predictor.

The research described above in spatial processing, is valuable in showing how the somatosensory system processes what have been defined as coarse surface textures, but there are limitations. For example, the work of Lederman and Taylor (1972, 1975) only concentrates on the perception of roughness. Roughness is a useful dimension in which to explore the capabilities of the somatosensory system, and gives some physical texture parameters which relate directly to how we perceive our environment. It is clear that groove width does affect perception of roughness, but still, there are no published neurophysiological data to underpin this theory. Furthermore, the texture parameters described are limited to grated surfaces and it remains to be seen whether these groove findings are easily translatable to a pattern which was not as periodic. Meftah *et al*. (2000) used raised dots for their roughness perception study and saw a reduction in the perception of roughness between 3 and 4mm dot spacing. In contrast, Klatzsky and Lederman (1999) saw a linear increase with their gratings and roughness up to a groove width of 8.5mm. Both are periodic in element arrangement, yet roughness perception was different, which suggests the primacy of skin deformation as a dominant contributor to coarse texture perception. Also, that findings could be stimulus specific.

Taylor and Lederman's (1975) model of skin penetration was purely designed for static stimulation, as was the work of Craig *et al*. (2008). Although both offer valued insight, it can only be inferred that this would be the same for dynamic touch, without experimental investigation.

2.4. Vibration processing

2.4.1. Static stimulation with mechanical waveforms

There are two principal structures for determining exactly what the somatosensory system is cable of processing. The first was developed by Bolanowski and colleagues, and specifies the Pacinian channel (P), and three others called Non Pacinian, or NP I, NP II and NP III, as the channels, which mediate touch perception. The second classification, which appears to be the more widely adopted system, describes the channels by afferent type, as discussed in section 2.2. These two classification types can sometimes lead to confusion from a lay person's perspective. Indeed, it is true that the P and NP systems are stimulated by vibration and that there are four channels which mediate touch (Bolanowski *et al*., 1988), but how these integrate to form a unified perception of a texture remains elusive.

Gescheider *et al*. (2001) described the P and NP classification style as a means to understand how channels are tuned to a particular part of the energy spectrum, with a view to being able to gauge relative activity levels from each of the channels and determine the exact response to any given stimulus. Bolanowski *et al*. (1988) showed that their four channel model comprises four graphically segmented curves. This suggests that all mechanoreceptors are responsive to vibratory stimulation, but with different levels of sensitivity, as shown by the threshold levels. Threshold levels are determined by the technique of 'just noticeable differences'; at what point can subjects either feel a difference between stimuli, or feel no stimulation at all. The technique used by Gescheider *et al*. (2001), is a standardised method in defining the function of these four channels. A constant level of detectability of a vibratory stimulus exclusively within one channel was maintained, in this instance specifically, measuring the tuning capability of the P Channel. This method is called selective adaptation. The P Channel, mediated by Pacinian corpuscles, is very sensitive to high frequency vibrations, with peak sensitivity at approximately 250Hz (Bolanowski *et al*., 1988). Gescheider *et al*. (2001) used a 250Hz test stimulus to isolate the corpuscles (with a 1.5cm^2 contact stimulator) and amplitude between 25 and 30dB lower than any other channel's sensitivity range. The 250Hz sine wave was delivered to the thenar eminence at 1mm indentation into the skin with a rigid surround on the contactor to limit the spread of surface waves; this channel is known to be affected by spatial summation. Skin temperature was maintained also, as a body of literature has proven that this also affects vibrotactile sensitivity (Green 1977; Verrillo and Bolanowski 2003, Stevens 1977; 1982, Stevens and Hooper, 1982). First, thresholds were calculated using a two alternative forced choice paradigm, with the amplitude of the adapting delivered waveform being reduced by 1.0dB for every three correct answers to whether the second waveform was different or the same to the first. Once a threshold for the participant was established, the adapting stimulus is set to 10dB above this for the 250Hz waveform. The tuning capabilities of the P Channel were established by using the same paradigm, with the adapting waveform presented first, and a second of a different frequency (between 2Hz and 400Hz) 0.2s after. The participants were required to indicate in which time interval the 250Hz stimulus was presented. The results of this study showed that there was no cross channel adaptation; that the P Channel was unaffected by the adaptation employed. Gescheider *et al*. also compared their tuning curve with others and concluded that skin mechanics plays no role in Pacinian corpuscle stimulations as their results compared to the neurophysiology curves in humans, cats and monkeys. The second experiment, using the same methodology, focused on the NP I channel, which is mediated by the RA fibres and are sensitive to vibrations extending for 2 to 100Hz. The NP I channel was stimulated with a 22Hz adapting stimulus, with a threshold 10dB below NP III, 13dB below that of the P Channel and 20dB below the NP II channel (Bolanowski *et al*., 1988). The results were in close agreement to the research on single RA fibre recordings in monkeys (Mountcastle *et al*., 1972) and in humans (Johansson *et al*., 1982). Finally they tested the tuning of NP II, which is though to be mediated by SA II afferents and has the same stimulation frequency range as the P Channel. This time, a 0.008cm^2 contact stimulator was used which would be too small a contact area to stimulate the P Channel. Again, results were consistent with Bolanowski *et al*. (1988). This study gives psychophysical validation to previous neurophysiology data which has been collected from monkeys and humans. The new model, which has built on those previous, sheds more light on the temporal aspects of channel activity to sinusoidal stimulation, and how data collected from monkeys and cats are comparable to human perception. These models, however, do not account for complex stimulation, even as basic as di- or tri-harmonic vibrations. It is acknowledged by Johnson (2000) that if channels can be mapped accurately, researchers can begin to understand how any arbitrary stimulus may be perceived, but there are large assumptions that the channels remain separate. This may very well be the case if the stimulation was designed to target a designated channel by being in a particular threshold range. However, real world stimuli are very unlikely to fit these parameters. The idea of creating a real world stimulus that excites only one afferent group is unlikely to be achievable.

Makous *et al*. (1995) agreed that without parallel channels, a stimulus could only be experienced as a unitary dimension, such as amplitude for one afferent type and therefore channels must combine to create a response. This concept was investigated with the P channel and the NP channels by delivering sine waves combined with white noise to determine whether the somatosensory system is able to extract information from a complex stimulus. The sine waves ranged from 10Hz to 400Hz, across the Pacinian and RA receptive fields. The noise consisted of five low frequency centred signals from 25 Hz to 55Hz with bandwidths between 8Hz and 25Hz. A single high frequency noise at 218Hz with a bandwidth of 70Hz was also used. Using a 0.13cm^2 contact stimulator at in indentation of 0.5mm, participants were presented with a test stimulus, then a further two were required to identify as the same as the test stimulus. The results of the experiment revealed that when a high frequency sine wave was combined with a pass band noise masker, the noise made the matching process more difficult, but when the noise was outside of the pass band (not in the highly sensitive range on the Pacinian range) there was no interference at all. Interpretation of these results suggested that the P channel uses a power filter within its critical frequency band (40Hz to 400Hz), and frequencies outside or on the periphery have little or no effect on the power summation process. In other words, the Pacinian channel is able to reliably identify similar stimuli based on extracting the relevant power information from the strongest frequency components. Makous *et al*. argue in favour of the somatosensory classification system of Bolanowski *et al*. (1988) in that the P channel works differently to the NP channels. However, their research only focused on the Pacinian and the RA afferent types. It could be argued, though, that the inclusion of noise, which is random, could have excited the other afferent types. As no neurophysiologic data was collected, this remains to be investigated.

Morley and Rowe (1990) explored whether vibratory frequency (referred to as pitch by Morley and Rowe) and the number of PC and RA afferents recruited influenced participants' perception of a vibratory stimulus. The hypothesis of the experiment predicted that as the amplitude of a 150Hz waveform was increased, there would be a fall in perceived frequency as more PC afferents would be recruited than RA afferents. A contact stimulator with a 12.6mm^2 contact surface was applied to the finger pad. No indentation depth was given. Eight participants were presented with two vibratory stimuli of the same frequency (either 30Hz or 150Hz) and differing amplitude, and were asked to say whether the frequency of the second stimulus was higher or lower than the first. They were not aware that the signals were the same frequency, but with different amplitudes. At the 150Hz level, the participant data showed differences. Five reported an increase in frequency with increased amplitude; one felt no change and two reported a decrease in frequency with an increase in amplitude. These results prompted Morley and Rowe to reject the ratio coding of afferent recruitment hypothesis in favour of a temporal pattern concept or afferent firing rates.

Morley and Rowe (1990) also presented the threshold values of their participants to a 30Hz and a 150Hz sinusoid waveform. For the 30Hz signal, the range was larger, from 4.0 to 8.0μm displacement, whereas the range of thresholds for the 150Hz signal was smaller, from 0.8 to 1.5μm. These threshold measurements are important because they highlight how there are large differences in sensitivity among participants. In these psychophysical studies, threshold levels are mostly identified so that data across participants can be compared using a sensation level system. Therefore participants feel the same level of stimulation. These particular figures clearly show the variability in tactile sensitivity, most notably at lower frequencies which may have implications on tactile displays or remote site operations using either probes or virtual reality. This issue was explored by Pongrac (2007) for a haptic force-feedback device. Pongrac also used a contact stimulator (143mm^2) to determine thresholds and just noticeable differences in high frequency sine waves. It was concluded that it was not necessary to calibrate a haptic device to suit individual sensation thresholds because the difference was too small to detect.

Gescheider *et al*. (2002) addressed vibration data and the site of the hand which was stimulated by vibration and compared the thenar eminence to the finger tip. The thenar eminence which is the area of the palm directly below the thumb has been a popular site for stimulation (see Bolanowski *et al*., 1988) for reasons unspecified by the authors. Gescheider *et al*. (2002) investigated the differences in people's perception/threshold to vibrations applied to the finger tip and the thenar eminence, the area of the palm directly below the thumb. The shape of the threshold curves between the two sites was similar. For the NP I (RA) and the NP III (SA I) channels especially, the receptor densities are 5.7 and 8.8 times higher at the tip respectively than at the thenar eminence, which shows that these two channels do not spatially summate. The P channel was expected to have a lower threshold at the finger tip as there is a higher population of afferents, but the thresholds were very similar. It was suggested that although the densities of the two sites are different, individual receptors are thought to vary in sensitivity and one or more receptors would be activated at each of the sites. It is known that the Pacinian corpuscles are capable of spatial summation, therefore Gescheider *et al*. tested the two sites with varying sizes of contact stimulators. The results, using the same threshold detection technique described previously, showed that at both sites a larger stimulation area produced lower thresholds. However, at the smaller contact area, the fingertip had a lower threshold by approximately 8dB. The thenar eminence function was approximately linear with an approximate 3dB drop per doubling of contact area whereas the finger tip was more of a curved reduction in threshold, almost meeting the thenar eminence at the largest 0.75cm^2 contact area. Gescheider *et al*. proposed a probability summation model, that the larger the contact area, the more likely the chance of activating a highly sensitive corpuscle which is why at a smaller contact area, the more densely populated fingertip site had a lower sensitivity threshold. Temporal summation was consistent across sites.

Whitehouse *et al*. (2006) also suggest that vibrotactile sensitivity of different finger sites could influence texture perception. They focussed more on different parts on the finger as opposed to the thenar eminence. It was stated that with low frequencies, up to 31.5 Hz, thresholds decreased as they reached the tip of the finger, but were the same for the two contact areas of $7.1mm^2$ and $79mm^2$. This is consistent with the NP I channel not changing sensitivity with increased stimulation area. At the higher frequencies of 63Hz, 125Hz and 250Hz, thresholds were lower with the larger stimulation area, with the exception of the finger tip, which is consistent with the spatial summation properties of the Pacinian channel. Thresholds tended to be higher at the centre of the whorl, half way between the whorl and the tip, and between the whorl and the first finger joint crease. This information could be useful in future studies which analyse how participants touch, and whether they naturally use the most sensitive parts of the fingers to explore textured surfaces. It also draws attention to the variability in sensation across the finger and the potential importance of regimenting how participants touch in active dynamic exploration.

Bensmaia and Hollins (2000) studied how complex vibratory stimuli are perceived by the RA and PC afferent types. Again, a contact stimulator was used to excite the somatosensory afferents, with a surface area of $19.6mm^2$ at a 500μm indentation into the skin of distal index finger pad. Thresholds were calculated for 10Hz, 30Hz, 100Hz and 300Hz sine waves. For the complex waveforms, the 10Hz and 30Hz sine waves were added together at phase angles of 0°, 90°, 180° and 270° to create different peak formations for each cycle. The same was done for the 100Hz and 300Hz pairing. All amplitudes were set at 30dB above threshold to ensure detectability. Participants were presented with pairs of each frequency grouping and asked to make same-different judgements. For the low frequency waveforms, discrimination could be made which suggests that the RA system can detect differences in peak order/formation. For the higher frequencies, the waveforms were not discriminable. This is consistent with the theory of the PC afferents distinguish stimuli by power summation. This was re-tested with different amplitudes for the higher frequencies as the thresholds for 100Hz and 300Hz are different based on the curve of Bolanowski *et al.* (1988). With this adjusted, modest discrimination was found, therefore strengthening the theory of power summation in the PC afferents. Vibratory adaptation was also used to determine whether the PC afferents contributed to the low frequency discrimination ability of the participants. A slight improvement was seen, suggesting that the PC afferents are active at frequencies as low as 30Hz.

Bensmaia and Hollins (2000) suggest that the RA system is well suited to encoding the complex vibration that a texture may elicit. They also suggest that in the RA afferents, there is a membrane recovery process. This means that after the first peak of a stimulus is felt, subsequent peaks may be partially suppressed. They proposed that a response to a stimulus may be a ratio code between the first and subsequent peak, and this may explain the subjective differences in their data for some waveforms. This theory remains to be proven by further psychophysical or neurophysiological testing, especially for coarse texture discrimination and subjective scaling. Bensmaia *et al*. (2005) further investigated complex waveforms in the PC system and, using an adapting vibration of 10Hz, suppress the RA systems involvement. The stimuli varied from di-harmonic to poly-harmonic vibrations. It was concluded that intensive cues are undoubtedly important to the discrimination of these waveforms; however, some were discriminable and did have the same spectral power. Bensmaia *et al*. (2005) suggested that a temporal element must exist in high frequency vibration processed by the PC system and possibly not just power summation. Using a similar method, paired with neurophysiology data from monkeys, Muniak *et al*. (2007) proposed that vibratory stimulation is best accounted for by analysing the firing rates of afferents under or near the locus of stimulation. It was also agreed by Mukiak *et al*. that discrimination was possibly more than an intensity code, and that frequency and temporal patterning must play a part in perception.

2.4.2. The vibrations of texture

Hollins and colleagues (2000; 2001; 2003; 2005) introduced a new line of investigation to vibration studies by considering other ways that we encounter or experience vibration.

Hollins *et al*. (2000) concentrated on the hypothesis that vibrations could influence perceived smoothness. They mounted a grated stimulus (298μm spatial period) to a mini shaker and set it vibrating. Participants were required to move their finger at a consistent speed of at least $100mms^{-1}$ (this was believed to be fast enough for the participants to not notice that the surface was vibrating). Participants used between $106mms^{-1}$ and $228mms^{-1}$. The experiments consisted of two identical grated stimuli being presented at a time, one was static, and the other was mounted on a mini-shaker that vibrated the stimulus at the desired frequency and amplitude. In the first

experiment, the frequency was kept constant at 150Hz, and the amplitude was alternated between 0, 5, 10 and 15μm displacement. After feeling both stimuli, the participants were required to indicate which of the two was the smoothest. The results of this experiment showed that the greater the amplitude, the less smooth the sample felt. This was recorded across all participants, even though half realised that the stimulus on the mini shaker was vibrating. The second experiment used different frequencies: 150, 220, 300 and 400Hz with the same amplitude of 15μm peak-to-peak (approximately 41dB in sensation level based on individual thresholds). These frequencies were used to excite the PC afferent group. Finger scanning speed was trained at 30mm/s. The results showed that it did not matter what the frequency of the vibration was, the vibrating stimulus was perceived as less smooth than the stationary tile.
Hollins *et al.* (2000) suggest that coarser materials may be required to understand frequencies below 100Hz which would be best suited to excite the RA afferents. That the amplitude of the vibration made the same stimulus feels less smooth to its identical stationary counterpart, is evidence that vibration has a role in texture perception. Hollins *et al*. (2000) also demonstrated the efficacy of the application of vibration to influence texture perception by means of an intensity code. This was determined by the amplitude component of a waveform which, again, is consistent with the PC fibres extracting power information for perceptual responses.

Johnson and colleagues (2006) developed a dense array stimulator which was used to map afferent activity to a variety of tactile stimuli. The tactile array (Killebrew *et al*., 2006) consists of four hundred independently controlled pins over a $1cm^2$ area and was used to deliver a variety of indented and scanned patterns across the finger pad using vibration. The stimulator is, however, limited to the range of DC to 300Hz, but is capable of displacements of 2000μm at 0Hz to 100μm at 250Hz. This device surpasses the displacement capabilities of a device built by Summers and Chanter (2002) that has a reported maximum displacement of 50μm peak-to-peak at 40Hz. Also, the dense array has twice as many pins than that of Chanters and Summers in each direction, meaning that the pins have a spacing of 0.5cm. This coincides with the SA I afferent spacing (Johnson and Hsiao, 1992).

Bensmaia *et al*. (2006a) used this array to present static and vibrating gratings to the finger pad of a monkey to model the responses of both SA I and RA afferents. The spatial periods of the grated stimuli were 1, 2, 4, 6, 8 and 10mm with a static indentation of 235µm. The vibrations used were 5, 10, 20, 40 and 80Hz and amplitudes of 232, 169, 124, 45 and 47µm respectively. The study showed that the vibration frequency had no effect on the afferent response to the spatial properties of the gratings. They also asserted that stimulus dynamics, such as the movement mimicked by the vibrations employed do not alter the spatial image of the stimulus. Furthermore, the SA I afferent response to the gratings was also independent of amplitude, showing that level at which the stimulus indents the skin does not alter neural activity. In an accompanying paper, Bensmaia *et al*. (2006b), psychophysical data was collected and analysed using the same stimuli. They reported that RA afferent activity interfered with spatial tasks such as grating orientation and the adaptation of the RA afferents improved spatial acuity. It was also observed that interference decreased, as the adapting frequency increased. This was expected, as the RA afferents become more sensitive as frequency increases across its bandwidth.

To further elucidate the vibratory findings of Hollins *et al*. (2000), Hollins *et al*. (2001) used specially designed surfaces with defined spatial periods to illustrate that the PC afferents are important to the discrimination of fine, and not coarse, texture perception. The adaptation technique was used to block either the PC afferents or the RA afferents to determine which are being used for the discrimination of textured stimuli. The stimuli used were separated into two groups, the first having spatial periods ranging from 16µm to 80µm, and the second set ranging from 944µm to 3200µm. A series of adaptation experiments were conducted to determine whether adaptation of the finger would impair texture perception of the two sets of stimuli. It was determined that with 100Hz adaptation, designed to target the PC afferents, discrimination was severely hampered for fine texture (those below 100µm), whereas coarse texture perception remained unaffected. To test whether these results for the fine texture set were dependent on the frequency selected; the same experiment was conducted with 10Hz and 250Hz adaptation. Also, this experiment was designed to establish whether the PC afferents are necessary in fine texture perception.

In conclusion to these findings, Hollins *et al*. (2001) stated that if the spatial period of a texture is less than 100µm, then PC afferents (therefore high frequency vibration) are responsible for fine texture discrimination. This shows that there is evidence for a duplex theory (Hollins and Risner, 2000) of texture perception. The duplex theory, originally derived from the work of Katz (1925), reinforced the notion that coarse surfaces (those over 100µm spatial periods) could be discriminated almost as successfully when the finger was moving as when it was stationary. This, however, was not the case for finer textures. They conclude that it was the movement, and therefore the vibrations generated by touch, which made discrimination possible. Hollins and Risner also stated that 'above 100μm, spatial mechanisms are progressively engaged and gradually become the dominant contributor to texture perception.' This hypothesis is based on the Hollins *et al*. (2000) study, who's fine texture set had the maximum spatial period of 100μm followed by a jump of 866μm to the next stimulus. This resulted in a large range in spatial periods which could be considered fine. This transition value differs from studies conducted by the laboratory of Kenneth Johnson who suggested that the spatial and vibrotactile mechanism transition is between 100 and 200μm (Blake *et al*., 1997), although Yoshioka *et al*. (2001) were in agreement with 100μm.

Bensmaia and Hollins (2003) estimated this change in dominance from spatial to vibrotactile mechanisms to be below 200μm with the same stimuli used by Hollins *et al*. (2001). Furthermore, they proposed that these vibrations elicited from fine textured surfaces were processed by the Pacinian corpuscles by means of vibrational power. In their study, a novel method of capturing the vibrations elicited by dynamic contact between the skin and the surface textures was developed using a Hall Effect transducer (HET) and a magnet. The magnet was adhered to the finger just below the whorl, and the transducer was mounted on the finger opposite the magnet. When the finger was moving, the movements of the vibrating magnet were detected and recorded with the HET. Data traces were subsequently amplified and digitalised for analysis. From these traces, Fourier transforms were applied which produced power spectra for each stimulus. It was these spectra that enabled Bensmaia and Hollins to propose the Pacinian power hypothesis. The same method was used in a subsequent study with everyday surface textures (Bensmaia and Hollins, 2005), such as silk and poplar, also showing that vibrational power was important for texture discrimination. Bensmaia and Hollins also alluded to textural timbre (which looks at frequency characteristics in a spectral analysis) as a possible cue for texture perception. Current researches (Yau *et al*., 2009a; Yau *et al*., 2009b) also consider frequency in tactile perception, but in an auditory sense and how this may interfere with tactile perception. Using two alternative forced choice, participants were presented with a standard vibration to the finger and a comparison which was accompanied by an auditory pure tone or band-pass noise distractor. Participants had to indicate which of the tactile stimuli was higher in frequency. Results showed that the auditory distractor interfered with judgement process but only if the auditory and tactile frequencies were similar to each other. A further experiment showed that participants' judgements of tactile intensity were not affected by the auditory distractors. These findings indicate that texture perception may then, be multimodal but this remains to be tested as naturally occurring vibrations such as texture interactions, are spectrally complex and only sinusoidal waveforms were considered here.

Cascio and Sathian (2001) explore the role of perceived frequency (due to movement of the finger) on the roughness of tactile gratings. Their findings showed that when the surface parameter or ridge width was considered with the temporal frequency, which is determined by scanning speed, was significant. A paradox in their publication emerged concerning temporal processing of coarse textures. It has been observed by Morley and Goodwin (1987) that neural responses correlate with temporal patterning. However, psychophysical data shows that frequency is not important to the decision making process. SA I afferents are the most useful for predicting the response, in this case, of roughness, but Cascio and Sathian (2001) found correlations with the PC and RA afferents too. Therefore, they assert, groove width is the predominant factor in roughness perception for coarse surfaces, but movement induces vibratory stimulation of afferents which was manifested as part dependence on temporal activity. Gamzu and Ahissar (2001) also concluded that temporal factors are important in some capacity to texture judgments with their study using direct and indirect touch.

2.5. The dimensions of texture processing

2.5.1. Texture classification techniques and models

A simple way of determining participants' discrimination of tactile textures is to present them with two textures at a time and ask them whether they are the same or different. Culbert and Stellwagen (1963), presented participants with forty embossed stimuli manufactured from visual stimuli patterns, and asked for 'different, not different' judgments. They were able to find eleven stimuli that were reliably discriminable from the larger set, which they specify could be used in tactile aids for the blind.

Hollins *et al*., (1993) designed a series of experiments which were conducted to investigate 'the subjective dimensionality' of tactile texture perception. Seventeen stimuli, such as wood, sandpaper and velvet were scanned across each participant's finger pad. The participants were then asked to describe the surfaces in words, not for what they thought the material could be, but for subjective adjectives that describe the texture. Next, participants were asked to make similarity judgements between two surface textures. This was continued until the stimuli were grouped based on tactile similarity. The participants were told from the outset that they had to make a minimum of three groups, but no more than seven (the authors did not specify why the maximum was seven). The participants were allowed to feel stimuli more than once on request and could revise the groups until each participant was satisfied with their final decision.

Finally, each stimulus was presented again and the participants were asked to rate the surface according to the following scales: smooth-rough, soft-hard, slippery-sticky, flat-bumpy and warm-cool. These scales were delivered in a random order and presented by a 12.8cm line on which the participant marked their response accordingly. To analyse the results, multi dimensional scaling (MDS) analysis was used to position the results from the twenty participants in the second experiment in perceptual space, and then using regression modelling, the participants' rating scales were fitted to the perceptual space.

The adjective scale of smooth-rough had a high R^2 value in that most of the variance is scoring was accounted for by the MDS model, proving its primacy as a texture descriptor. Soft-hard ran perpendicular to smooth-rough which made it a likely second dimension. Flat-bumpy was closely correlated to smooth-rough that seems to indicate that the participants used the two scales in a very similar fashion. The purpose of the flat-bumpy scale was to allow participants the freedom to discriminate large surface features; however, it correlated closely with smooth-rough. This moves some way to showing that there are few 'quality' descriptors to describe surface textures. The stimuli most likely to form a third dimension were those that one might call springy such as cork, scouring pad and Styrofoam. On the opposite end of the same dimension are materials such as brick, sandpaper and plastic, which have an opposite feeling to springy, although this was not an adjective used in the study. The other scales did not appear to constitute a third dimension on their own but could be seen as contributing towards it.

Hollins *et al*. (1993) concluded that surfaces can be successfully rated and displayed by means of MDS. The experiment was repeated by Hollins *et al*. (2000b), and two textural dimensions were found; smooth-rough and soft-hard. This second study revealed the third dimension of stick-slippery, which was not as salient because it was not entirely independent. This was hypothesised to be due to participants having disagreement in their semantic ratings, and was also attributed to semantic overlap which Hollins *et al*. (2000) described as an adjective which have a related meaning to other adjectives.

Picard *et al*. (2003) examined everyday textures using three phases designed to systematically explore the semantic language associated with touch in the context based environment of car interior textiles. They were able to identify a diverse language bank used by participants to describe their interactions with the textiles including qualities such as soft and harsh, and also hedonic qualities such as pleasantness. The participants were then given car interior fabrics and asked to group them. After the grouping was completed, descriptors were asked for each group of textile stimuli. The final task was to rate each fabric on a given scale. Therefore, the first phase was used to provide corroborative data to interpret the perceptual dimensions of textural space, and the second was designed to develop adjective scales for testing the relevance of the derived dimensions of the third experiment.

Picard *et al*. (2003), conclude that dimensional importance of the touching experience is intrinsically related to the type of material used. This means that the space determined for textiles in this study would not correlate if plastics were used either in the car interior environment, or with a separate context.

Picard *et al*. (2003), much in the same way as Hollins *et al*. (1993; 2000) and Culbert and Stellwagen (1963) made no attempt to investigate the physical features of the stimuli which may be indicative of grouping or dimensionality. Gescheider *et al*. (2005) attempted to achieve this by asking participants to judge the perceived dissimilarity of two dotted surfaces at a time on a fifteen-point scale choosing their own descriptive adjectives. The stimuli consisted of seven dotted patterns of truncated cones with the height of 0.35mm and width at the base of 0.7mm. The spacing between the dots ranged from 1.34mm to 5.93mm. The participants were trained to pull their finger across the stimuli at 40mms^{-1} and at a 40g force, which was consistently performed before taking part in the experiment. Using multi-dimensional scaling three dimensions were determined; blur (the degree that individual dots could be felt), roughness of the overall stimulus and clarity (the degree of contrast between the dots and the background). Pacinian adaptation was also performed on this task to assess the involvement of the system with the three salient dimensions. Adaptation affected the clarity of each individual dot, making them perceptually smoother. However, this did not affect the overall perception of roughness. Gescheider *et al*. (2005) assert that the Pacinian channels can be involved in the perception of roughness in microstructure but not necessarily in the macrostructure. If the frequency for the smallest dot spacing is calculated with the scanning speed as given in the paper, the highest frequency experienced by the receptors is 29.85Hz which would activate the RA and not the PC afferents. This is consistent with the overall roughness perception not changing as the PC afferents may not have necessarily been recruited at such a low frequency. As the microstructure of the stimuli material has not been specified, one can assume that it would be fine enough to generate high frequency vibrations, enough to excite the PC afferents. This may explain why clarity was affected by high frequency adaptation.

Recent research by Chen *et al*. (2009a, 2009b) have also shown links between 'qualities' of touch as well as affective dimensions with measurable characteristics of friction coefficients, compliance and thermal conductivity using multiple regression modelling. From these researches, conclusions can be made about the most salient dimensions of touch which can be readily employed on a variety of stimulus types. These are those documented primarily by Hollins *et al*. (1993; 2000) which are rough-smooth, hard-soft, sticky-slippery and warm-cold. Chen *et al*. (2009a; 2009b) and Picard *et al*. (2003) also used affective or hedonic dimensions of touch which, although context based, are candidates for further exploration.

2.5.2. Roughness Perception

In a study investigating roughness, smoothness and preference (Ekman *et al*., 1965), participants were asked to rate seven surfaces on their perceived roughness, smoothness and preferences using magnitude estimation. With these seven surfaces, twenty one different pair combinations were presented to the participants in three blocks, one for each of the tested criteria. The data was scaled for each of the participants and normalised to produce comparable results. There was little difference between participants for each of the criteria, roughness, smoothness and preference, and any difference that was presented was suggested to be due to sensitivity thresholds of the mechanoreceptors. Individually, the participants presented the same trend against the friction coefficients.

Bauer (1952) made observations about his participants' preferred scanning methods for roughness judgements. For smooth surfaces the participants would draw their finger the whole length of the sample whereas with the rougher surfaces only a small surface area was required to make a decision. It is possible that the discrimination of rough surfaces can be made quickly due to a large amount of information being received from a small area, or that a smoother surface is more pleasurable to touch and consequently touch is more sustained.

Morley *et al*. (1983) stated that the use of materials such as wool were unsuitable for tactile texture discrimination because surface characteristics were unquantifiable. The proposed solution was to use metal gratings made to a defined specifications, thus making surface characteristic analysis simpler and more accurate. Three surfaces were presented to the participants at a time in a three alternative choice experiment, two of which were the same with spatial periods of either 770 or 1002μm and participants were asked which one was different from the other two. The participants were able to use any finger movement and pressure. This was recorded and measured. Morley *et al*. (1983) decided that pressure was a better measurement than force as participants may use the same forces, but their finger contact area would be different. Pressure was calculated from the average force and contact area of each of the participants' fingers. This discussion illustrates the problem with allowing uncontrolled active touch. Different participants may produce different results based on the pressure or force used to feel a surface. The introduction of pressure and velocity measurements help to counteract these differences from participant to participant by normalising the data across them, giving a more natural yet accurate set. With the use of pressure information and normalisation, Morley *et al*. (1983) conclude that there is a relationship between perceived roughness and spatial periods of the surface.

Verrillo *et al*. (1999), concentrated on the perception of roughness and the feeling of pleasantness. Eleven stimuli of varying grades of sandpaper were used. Verrillo *et al*. (1999) noted the convenience of testing roughness with sandpaper stimuli as each type has a pre-defined roughness specification based on particle size. The stimuli were explored unseen by the participants during the experiment. These samples were mounted on a titanium steel plate and were measured for roughness with a diamond tipped stylus. Participants were asked to give a subjective magnitude estimation to show their perception of roughness and pleasantness after instructed movement of a light brushing motion was allowed. This was then scaled for analysis. The major finding of this study was that the pleasantness of the tactual sensation was inversely proportional to the perceived roughness for both the finger and the thumb. This is the first research to include hedonic assessment in tactile sensation and the results suggested that pleasantness was consistently rated across participants therefore could be considered as a potential dimension of touch.

In another experiment using subjective magnitude estimation as a tool to better elucidate roughness (Smith *et al*., 2002); contact force and friction were investigated as possible indicators of judgments. The two experiments conducted investigated force normal to the surface and tangential forces. It was reported that the tangential force in tactile exploration was a significant determinant of roughness perception. This was attributed to the rate of change in the tangential stroking motion, which was strongly correlated with the subjective roughness estimations. To test these data further, a second experiment was conducted using a comparison between a dry and a lubricated surface. The difference in correlation coefficient with subjective roughness with both conditions showed that changes in tangential force rates, rather than the absolute value, are thought to be of importance when determining roughness.

Smith *et al*. (2002) noted that the periodic fluctuations in the tangential stroking force could be due to more skin penetrating wider spacing in a texture which will increase tangential drag especially, a theory consistent with Lederman and Taylor's research outcomes with spatial period and roughness magnitude increase (Lederman and Taylor, 1972; Taylor and Lederman, 1975).

Bergmann Tiest and Kappers (2006) used a free sorting task of 124 different materials ranging from metals to textiles to analyse the haptic perception of roughness and compressibility. It could be suggested that a 124 material sorting task without the use of sight is a very difficult task to complete, especially as it has been noted that results can suffer from fatigue bias (Barnes *et al*., 2007). No restrictions were given on the mode of touch with regards to the number of hands or part of the hand used. The participants were unable to see the samples and were asked to put them in groups. There was a minimum of two groups specified, but no upper limit. They were allowed to re-touch tiles, change their opinion and adjust their material groupings. All participants tended to group the materials according to their type, for example, woods, metals and textiles. Based on the MDS analysis, four descriptionless dimensions were derived based upon material grouping. For example, dimension one ran from metals through to woods, papers and textiles, and dimension two from textiles, to metals and then papers. The vectors of rough-smooth and hard-soft were added to the MDS dimensions. However, as the Bergmann Tiest and Kappers did not include organic materials, they suggested that there could be further dimensions. From this analysis, which integrated roughness and compressibility data, compressibility plays a role in the perception of soft-hard, but not as significantly as in the perception of roughness.

Bensmaia and Hollins (2003; 2005) observed that for fine textured surfaces, perceived roughness was a function of spectral power; the relative amplitude component of the dominant frequencies being mediated by the Pacinian corpuscles. Specifically, Bensmaia and Hollins (2003) conducted a study to determine the relationship between vibration and the discrimination of texture roughness. The movement of each participant's finger was controlled via a belt. The vibrations were measured using a Hall Effect transducer attached to the finger. Eight stimuli were used with spatial periods of 16, 40, 80, 124, 184, 276 and 416μm, and the eighth surface was null, the control surface. In the first experiment, participants gave magnitude estimations of perceived roughness. From the results, Bensmaia and Hollins derived two hypotheses. First, that perceived roughness of fine textures was a function of the frequencies generated when running a finger across a surface. Specifically, the lower the fundamental frequency was, the higher the perceived roughness. Secondly, that the perceived roughness is a function of the intensity of these vibrations, so the higher the relative amplitude, the rougher the surface was perceived.

A further experiment, which was designed to test the two hypotheses, used two scanning speeds, $20mms^{-1}$ and $40mms^{-1}$. Only two surfaces were used, with spatial periods of 80 and 184μm. There was no effect of speed on the perception of roughness. If the temporal frequency (scanning speed related) was important in roughness judgements, the ratings would have decreased with an increase in temporal frequency. It was concluded vibrational power was strongly indicative of roughness perception as a function of Pacinian sensitivity thresholds. Further research drew upon the knowledge of previous studies concerning frequency and spatial coding (Bensmaia and Hollins, 2005). In this study, five subjects had their finger drawn by a mechanical device across twelve different tactile stimuli. Vibration was measured and the participants were asked to rate their dissimilarity using free magnitude estimation as well as measuring against four textural continua: roughness, hardness, stickiness and warmth. Vibrational power was, again, the best indicator of perceived roughness.

2.5.3. Softness perception

There has been little psychophysical research on softness perception. Srinivasan and LaMotte (1995) created a series of experiments to elucidate how people perceive softness using two stimulus sets and a variety of touching methods. The stimuli comprised of rubber composites with a range of compliances and a set of spring loaded cells which varied in compressibility. Three touch methods were used to separate tactile and kinaesthetic (related to muscles and joints in the hand and arm) cues by using active and passive touch, as well as anaesthetic to disable cutaneous (skin) sensation. Across these experiments, in which participants were required to perform ranking and pairwise comparisons (two alternative forced choice), it was evident that the rubber stimuli were more discriminable than the spring loaded cells. For the rubber stimulus set, when only kinaesthetic cues were available, participants could not successful rate softness. When only tactile (cutaneous) cues were available, the participants could rate softness even when the pressure and speed of contact with the stimuli were varied. For the spring cell stimulus set, it was clear that participants could not rate softness with tactile cues alone. This was thought to be because the compliance of the material used to produce the spring cells was the same and therefore perceived as similarly soft. For the spring cells then, kinaesthetic cues were important in forming a perception of softness.

In an experiment mapping subjective softness against the physical compressibility of the 124 everyday materials, Bergmann Tiest and Kappers (2006) discuss an exponential relationship between these two measures in multi-dimensional space. To measure the compressibility of the materials, an 11.5mm diameter metal rod was pressed into each sample. Eight forces ranging from 0.2N to 4N that was thought to be in the range of natural touch. These measurements were plotted against the subjective scores and a moderate correlation was found (r=0.56). This method of compressibility measurement may be flawed in that the rod, even though it was specified as having the same contact area as the human fingerpad, does not have the same compliance. A further limitation is that thin samples, such as papers, were mounted on fibreboard, which would have contributed to the compliance profile of some materials.

An alternative method for measuring compliance has been employed by Chen *et al*. (2009b). A 10mm steel ball was pressed into papers, foils and fibreboards onto a soft rubber sheet which was chosen to simulate the flattening of the human fingerpad. Results from self-report studies showed that hardness was a correlate of compliance.

Friedman *et al*. (2008) used a variety of experimental procedures to quantify the perception of softness, including direct and indirect touch. With direct touch, both tapping and pressing the stimuli could be used to identify softness. Friedman *et al*. also used a psychophysical discrimination task to ascertain that participants perceive a material as soft if its compliance is greater than that of the human finger. Furthermore, force and deformation of the finger pad with the surface texture was a good indicator of softness. The results for indirect touch though, did not show such correlations. It was predicted that with touch through a tool, tactile force information must be supplemented by vibrational cues produced during contact with the surface texture, however, as the deformation of the finger at a distal site is not the same as in direct touch. Considering this prediction, and the findings of Yoshioka *et al*. (2007), who also provide evidence that direct and indirect touch mechanisms are different, it seems plausible that vibratory stimulation could carry softness related cues when compliance information is either missing, or softness perception is being synthesised on a hard surface texture. Whether vibration-linked softness is directly attributed to mechanoreceptor activation induced through tapping the stimulus, or the associated sensory signals from muscles and joints, remains to be determined.

2.5.4. Stickiness Perception

Stickiness is another dimension which has had little experimental investigation. Smith and Scott (1996) investigated the role of kinetic friction in stickiness perception. Asperities in the surface textures were eliminated by selecting macroscopically smooth stimuli; rosin coated glass, glass, satin finished aluminium, PVC plastic, Teflon and nyloprint plastic. Ten participants were required to explore each surface and mark on an 18cm line that had the descriptors of slippery at one end and most sticky at the other, their perception of each stimulus. A new scale was given for each stimulus. Kinetic friction was measured. Results showed that participants could accurately assess the slipperiness of each surface and could adjust the force employed for scanning. Smith and Scott show that kinetic friction is a good indicator of subjective stickiness and that SA II afferents, which are associated with skin stretch, could be implicated. Grierson and Carnahan (2006) used a similar scaling methodology to compare static and dynamic stickiness ratings. They too concluded that friction was responsible for stickiness assessment.

In a different line of enquiry, Bensmaia and Hollins (2005) indicated that in texture scanning and rating, stickiness could be a function of vibrational cues such as those created as the fingerpad skitters across a surface texture. These are acknowledged as a tentative conclusion because only a small stimulus set was investigated.

2.5.5. Warmth perception

For the perception of temperature there are two receptors, the warm and the cold. The cold receptors are more numerous than the warm, at a ratio of approximately 30:1 (Jones and Berris, 2002). These receptors respond to temperature decreases between 5 and 43°C. The warm receptors fire up to 45°C. When the skin is maintained at 30-36°C, no thermal sensation is noted, although both receptors are known to fire because this is the regular skin temperature range at room temperature. When outside of this range, only one receptor will be firing at any given time. When the temperature is changing at a rate of less that 0.5°C per minute, then it is possible for the participants to not detect a change of 5-6°C if in the 30-36°C range. If the change is more rapid, say at 0.1°Cs^{-1}, small changes in temperature can be detected. Thermal transience is thought to be perceived at a rate of 0.3°Cs^{-1} (Jones and Berris, 2002). This suggests that there is a trade-off in warmth perception and that it is a function of both area and temperature. For example, thermal thresholds can be maintained by halving the intensity of the stimulus and doubling the contact area (Jones and Berris, 2002).

Lederman and Klatzsky (1997) state that the time to respond to thermal cues is significantly longer than encoding roughness and compliance, taking on average 900ms^{-1} to make a decision between two stimuli at different temperatures. This is consistent with the experiment carried out by Jones and Berris (2002). It took at least 200s^{-1} for the temperature of the fingerpad to stabilise after contact with the copper stimuli. Furthermore, the reported change in skin temperature was much slower than that of other published literature (Ino *et al*., 1993).

Ho and Jones (2004) conducted research to investigate whether participants could identify real stimuli based on their thermal properties. This experiment was also repeated with virtual reality versions of the same stimuli using a Peltier device. The stimuli were copper, stainless steel, granite, ABS and foam, which all had the same surface roughness with the exception of the foam. A thermistor was adhered to the skin away from the pad so that it would not interfere with the touching process. No lateral scanning was permitted. The participants were shown the materials at the beginning of the experiment and asked to tell the experimenter during the experiment to say which sample they were feeling. They were blindfolded and were given no indications as to whether they were correct or not.

The ABS and foam were the most easily identified and copper was the most difficult. No reason for this was offered. For the simulated surfaces, stainless steel was the most difficult. Copper and stainless steel and granite and stainless steel were often confused. A repeated measure ANOVA was used to analyse the data and it was concluded that there was a significant effect between all stimuli. There was no significance reported between the real and simulated temperatures. Ho and Jones (2009) reported smaller decreases in the skin temperature than theoretical predictions although it was consistent with the contact coefficients (kpc) $^{1}/^{2}$.

In an experiment investigating the effect of pressure on the temperature change of the human fingerpad, Ho and Jones (2008) investigated five pressures: 0.73kPa, 1.68kPa, 3.13kPa, 5.90kPa and 10.98kPa. The temperature changes in the fingerpad were recorded using an infra red device and with a thermistor for comparison purposes. The infra red method did appear to record more accurate information because it was able to detect finger temperature changes in the region of 3-5°C, whereas the thermistor detected a maximum change of 0.03°C. It has been suggested that temperature change in the finger when it comes into contact with a surface is affected by pressure in 2 ways: (1) compression of the cutaneous tissue may enhance thermal sensation by increasing contact area and (2) compression can change the finger temperature by collapsing the blood vessels. There is a 70% difference in progressive blood flow from 2.9N pressure compared with 0.5N (Jay and Havenith, 2006). Repeated measures ANOVA revealed that there was a significant difference between pressures and temperature decrease, except with 1.68kPa and 5.90kPa.

A study of an aluminium beverage bottle (Han *et al*., 2006) presented a different view of tactile heat sensation by providing an application; optimum contact between the hands and the bottle with regards to heat transferral. The design problem presented by Han *et al*. is that of a hot beverage container which will be dispensed from a vending machine at 60˚C to meet the demands of a recyclable aluminium hot beverage container in the winter months for Japanese consumers. Optimisation of the shape of the contact ribs was carried out to obtain a decrease of at least 30% of the transferral of temperature to the finger compared to the current designs. They conducted contact analysis between the hand and the ribs, showing that ribs can lessen heat transfer to the fingers. The methodology consisted of analysis of contact deformation of the finger on the proposed rib design and heat transfer analysis whilst the finger was held at a constant temperature of 35˚C.

Taking into consideration the embossing formability of the bottle, the optimum design for the bottle consisted of sharper mountains for the ribs which give a smaller contact area and no 'bottoming out' (Green *et al*. 1979) gave less contact area between the bottle and the fingers which ultimately resulted in less heat transfer. It was also concluded that this gave a better touch feeling.

2.5.6. Affective qualities of touch

The affective qualities of touch have not been investigated the extent of the textural dimensions of touch and all context based.

Picard *et al*. (2003) state that in their study, the adjectives collected for textiles may not necessarily translate to another product which it to be made from plastic, therefore are context specific. Picard *et al*. (2003) conducted a multi-dimensional scaling experiment with the inclusion of hedonic descriptors such as pleasantness as described in Section 2.5. Pleasantness was included as participants used the adjective to describe textiles encountered in everyday tasks. Montgomery *et al*. (2008) discuss how naturalness is a measurable adjective because it is not highly emotive or 'dependent on strong preference'. This argument suggests that emotive or affective adjectives are not measurable. Chen *et al*. (2009) conducted a study which attempted to correlate psychophysical adjectives such as warmth, roughness, stickiness and hardness and physical properties of the stimuli to affective adjectives. It was shown that the feeling of natural was correlated with the perception of warmth, delicate with stickiness and hardness, and simple with the perception of roughness. This indicates that affective descriptors can me measured.

In an experiment with similar principles, Barnes *et al*. (2004) investigated the use of frosted glass for perfume packaging. They found that the adjectives feminine, expensive and delicate were most related to the physical roughness of the frosted glass, more specifically that positive feelings were related to stimuli that had a lower roughness then the human fingerpad. Again, in a product based study, Fenko *et al*. (2008) investigated which product attributes contribute to warmth and freshness by specifically looking at colour, smell and texture. Results showed that the product experience was multi-dimensional and that sensory integration takes place. Also, that the experience is product dependent, so the parameters for creating a pleasant scarf would not necessary be the same for a breakfast tray for example.

2.6. Summary

This chapter has given an overview of the key areas of knowledge that contribute to understanding how the somatosensory system processes cutaneous stimulation, resulting in tactile texture perception. From critical analysis of these research areas, key deficits in knowledge have been identified and discussed.

In spatial processing, it is very clear that there are two main areas of research: dynamic and static touch. The goals were to elucidate the resolution of the SA I afferents which are attributed to spatial processing of indentations of the skin and by extension, coarse surface texture perception. There are no clear models which predict how the skin behaves in dynamic touch, therefore only hypotheses exist based on static models. One dominant hypothesis is that vibration is not important in assessing roughness for coarse surface textures (Lederman, 1982) however Bensmaia *et al*. (2006) have shown that RA afferent activity does interfere with SA I activity. Vibration may not be needed to judge roughness; however it does occur and must therefore have a purpose. Key limitations in results from studies using coarse textures and roughness perception exist also in that the results are stimulus specific. This was demonstrated between experiments using gratings and raised dot stimuli. Low frequency vibrations exist in the scanning of these surfaces, but little attempt has been made to understand their purpose in perceiving texture.

The extensive research conducted in vibratory stimulation has given psychophysists fundamental knowledge on how each of the afferent types in glabrous skin responds to (sinusoidal) stimulation. The most progressive works have stemmed from Makous *et al*. (1995) who simulated more real world stimuli by embedding sinusoids in noise. The model was carried forward by Bensmaia and Hollins (2003) in texture discrimination whose signal processing methods revealed clear spectral power peaks amongst what could be considered as noise. A new body of research is also emerging which suggests that frequency plays a role in texture perception and not just amplitude as has been shown in the numerous studies discussed. This still remains to be experimentally investigated.

From the landmark work of Hollins and colleagues, four clear dimensions of texture perception have transpired, these being rough-smooth, hard-soft, warm-cool and slippery-sticky. All of these dimensions have been shown to involve cutaneous cues relating to vibration to varying degrees with even warmth perception being affected. In affective or hedonic assessment of surface textures, very little research has been conducted. Verrillo *et al*. (1999) suggested that pleasantness was a studiable descriptor for surface textures, and Picard *et al*. (2003) included hedonics also in their modelling of tactile texture. The latter study however, did not take texture topography or fingerpad/surface textures into consideration unlike Barnes *et al*. (2004) who considered topographical roughness. Such limited research shows that affect and tactile texture can be studied and that there is much research needed to understand the connection between the two areas of study.

In summary, there has been extensive research towards elucidating how the somatosensory system processes both vibratory and positional stimulation. In recent years, the focus of psychophysics has moved towards understanding how we form a perception of the tactile world that surrounds us. Clear, studiable dimensions relating to either the material properties or the vibrations that occur in dynamic touch are becoming understood, yet these are not fully explained especially concerning the role of frequency. Furthermore, an interest in understanding how we might assess textures from an affective standpoint is starting to develop. For this to be effectively investigated, hypotheses need to be built from psychophysical techniques and existing knowledge. Table 2.1 gives an overview of the main findings in the literature discussed in this chapter. The following experimental chapters aim to characterise the affective assessment of tactile textures and role in which low and high frequency vibrations has in this

Table 2.1 Summary of literature review key findings and techniques

Literature topic	Key findings
Dynamic touch (spatial processing)	Roughness of coarse surface textures is governed by groove width. Vibration is not dominant in course texture perception (Lederman).
Static touch (spatial processing)	Grating orientation tasks, using 2AFC was the most successful method of determining the spatial limits of the human finger tip.
Vibration processing	Sinusoidal stimulation has traditionally been used to determine the function of mechanoreceptors (Bolanowski *et al*. 1988). Makous *et al*. (1995) used more natural stimuli, marking a change in the way vibration research was conducted.
Texture classification	Multi-dimensional scaling techniques have been used to determine dimensions of the touch experience (Hollins *et al*. 1993; 2003, Bergmann Tiest and Kappers 2005) using textures encountered in every day life.
	Techniques for quantifying participants' subjective experiences include magnitude estimation and differential questionnaires with opposing adjectives such as rough and smooth. (Hollins *et al*. 1993; 2003, Chen *et al*. 2009a; 2009b, and Picard *et al*. 2003)
Roughness perception	Vibratory power is a good determinant of roughness perception for fine textured surfaces (Bensmaia and Hollins, 2005)
Softness perception	Softness perception is a correlate of stimulus compliance (Chen *et al*. 2009b) and vibration cues

	from impact may also be involved (Yoshioka *et al*. 2007).
Stickiness perception	Caused by changes in kinetic friction (Friedman *et al*. 2008) or changes in vibration profile due to the finger skittering on the surface (Bensmaia and Hollins, 2005).
Warmth perception	Less temperature transfer between the fingers and a surface texture occurs, when there is less contact with the surface texture (Han *et al*. 2006).
Affective qualities of touch	Some affective qualities have been shown to be correlated with textural dimensions (Chen *et al*. 2009a) and that affective qualities are specific to the context and textures which are rated (Picard *et al*. 2003).

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Chapter 3

Affective responses to tactile textures

3.1. Experiment rationale

This current series of experiments has been designed to explore the duplex theory of touch (Hollins and Risner, 2000) and how this could relate to the affective properties of touch. The duplex theory explains how the vibrations generated through the dynamic exploration of a surface texture creates two clear texture categories divided by texture spatial wavelengths of 200μm, fine and coarse textures. This division is crucial in understanding the physical mechanisms which mediate touch, therefore influencing how we perceive tactile stimuli. Indeed, it has been shown that vibration is not needed in roughness judgements for coarse textures (Lederman, 1982) and that vibratory power is the key determinant in fine texture-based roughness judgments (Bensmaia and Hollins, 2003; 2005), but how do these spatial and vibratory cues contribute to forming an affective judgement?

The aim of this study is to determine whether textured plastic stimuli used for car interiors could be distinguished from each other using affective adjectives and which characteristics of the stimuli evoked particular feelings. Specifically, the objectives were (1) to establish how participants describe and evaluate tactile textures and whether affective constructs can be determined through Principal Component Analysis (2) to identify whether texture topography such as feature spacing are cues for affective responses or (3) whether naturally occurring vibrations through finger scanning dominates affective response.

3.2. Experiment 1: Adjective collection and stimuli selection

The aim of experiment 1 was to evaluate the descriptive language used by adults when asked to discuss car interior and exterior design. Two sets of stimuli, visual, and visual and tactile, were chosen for two separate focus group studies. It was hypothesized that participants would use a variety of adjectives including hedonic, affective and textural descriptors. These descriptors were then used to generate a list which was used to evaluate tactile textures in Experiment 2.

3.2.1. Method

3.2.1.1. Participants

Thirteen male undergraduate students from the School of Mechanical Engineering were recruited through email to participate in the focus group studies, six in the first and seven in the second. All were naïve with respect to the aim of the study other than that they would be asked to talk about their attitudes and feelings about the interiors of cars, and that it would be audio recorded.

A further six male undergraduate students, also from the School of Mechanical Engineering, were recruited to participate in stimulus mapping. None had been involved in the focus group studies and all were naïve to the aim of the study.

3.2.1.2. Stimuli

Stimuli for this study were samples of moulded decorations, used in car interior environments. These Acrylonitrile Butadiene Styrene (ABS) tiles were purchased from Standex (Standex International). From the fifty available textured tiles available, twenty-eight were selected with touch being the sole discriminator to ensure that a range of roughness's and patterns were included. Many of the tiles provided had the same 'pattern' design but different grades of roughness, so it was decided that for this study, all pattern types with a variety of roughness's be used. Therefore, the set comprised tiles with a variety of micro- and macro-topographical properties. These tiles were cut to 75x65mm and placed inside black boxes, which had a front entrance with a small window through which the participants could feel a section of each surface. The boxes were black to match the colour of the tiles, none of which could be seen. This ensured that the results yielded were based wholly on the tactile qualities of the tiles.

3.2.1.3. Procedures

The first activity in each session was an icebreaking exercise to encourage conversation and interaction within the group who were not familiar with each other. They were asked to talk about cars that they liked and disliked.

In the first focus group, adjectives were generated using the triad method (Thomson and McEwan, 1988) on pictures of cars. Six images of car exteriors and 6 images of interiors were mounted on A3 boards and randomly ordered. The images of the car exteriors were shown to the group, three images at a time. Participants were asked the similarities and differences between the three images and their answers were audio recorded. The group was then shown the images of car interiors in the same way. The two sets of images were arranged in a random order again, but this time with both interiors and exteriors within each triad. Once again, the pictures were shown to the group in triads and they were asked the similarities and differences. Finally, the participants were shown the all 12 images again, one at a time, and asked to choose one adjective that best described their feelings.

For the second focus group study, the triad method was used, and the stimuli used were 18 parts of car interiors, such as steering wheels, which were pre-arranged into triads comprising all aspects of the interior. Participants were encouraged to feel each stimulus and, again, find similarities and differences between them. After the focus group studies were completed, adjectives were collected from the session recordings.

For the stimulus mapping exercise, participants were presented with a 2-dimensional semantic map which had axes reading cheap-expensive and relaxing-exciting. Cheap-expensive was chosen because it was frequently used in the focus group studies and relaxing-exciting was chosen for its affective connotation. 28 textured stimuli and correspondingly numbered wooden markers. In pairs, the participants were asked to determine where on the map they would best place the stimuli, with regards exclusively to the way the tile felt when touched, by positioning the wooden markers. The participants were permitted to revisit their initial decisions and revise them if required and tile markers could be placed on top of each other. During the study, the participants were asked to keep the theme of car interiors in the forefront of their minds throughout the decision making process.

3.2.2. Results

Using adjective reduction guidelines (Delin, Sharoff, Lillford and Barnes, 2007), unsuitable words were rejected and the most popular and strongest words were retained (Table 3.1). Examples of the words rejected using this framework would ambiguous such as annoying or horrible. Emotive adjectives were arranged into appropriate groups of similar meaning in an affinity diagram (Figure 3.1).

FUNCTION	QUALITY	AFFECT	TOUCH
Comfortable	Safe	Animalistic	Cold
Functional	Reliable	Executive	Hollow
Practical	Detailed	Mundane	Shiny
Simple	Lasting	Exciting	Hollow
(un)Complicated	Raw	Sexy	Hard
Engineered	Cheap	Relaxed	Warm
	Unique	Dangerous	
	Hard-wearing	Sporty	
		Fashionable	
		Unique	

Figure 3.3.1 Affinity diagram showing the groupings of adjectives under the given headings: function, quality, affect and touch after adjective reduction.

Table 3.3.1. Adjectives from both focus groups.

Adjectives				
Simple	Small	Horrendous	Hard Wearing	Rigid
Amazing	Sleek	Masculine	Ergonomic	Style
Animalistic	Classic	Worn	Detailed	Young
Cheap	Smooth	Shiny	Grippy	Decent
Cold	Classy	Fun	Thick	Hollow
Comfortable	Fun	Average	Substantial	Textured
Cool	Old	Future	Integrated	Horrible
Designer	Aesthetic	Cheap	Plasticy	Strong
Efficient	Refined	Lasting	Smart	Mass produced
Functional	Executive	Unattractive	Stiff	Feminine
Nice	Basic	Minimal	Solid	Dangerous
Offensive	Reliable	Disappointing	Annoying	Raw
Plain	Engineered	Relaxed	Frustrating	Dreary
Powerful	Boring	Racy	Expensive	Lightweight
Practical	Aspirational	Tactile	Warm	Ugly
Quality	Tacky	Different	Flexible	Hard

Safe	Weird	Sustainable	Obtrusive	Fine
Sporty	Understated	Mundane	Dated	Thin
Uncomplicated	Exciting	Bland	Discrete	

Twelve words were selected: quality, masculine, engineered, warm, cheap, exciting, comfortable, sophisticated, relaxed, unique, sporty and fashionable.

A photograph was taken of each of the completed maps. Using Adobe Photoshop, the markers from each map were made translucent so that all three maps could be placed over one another to allow comparisons to be made (Figure 3.2). These comparisons of marker placement were made to identify agreements between each of the maps. The eleven stimuli were selected to cover all aspects of the map, so each of the quadrants and the extremes of the axes were represented. These stimuli are presented in Table 3.2.

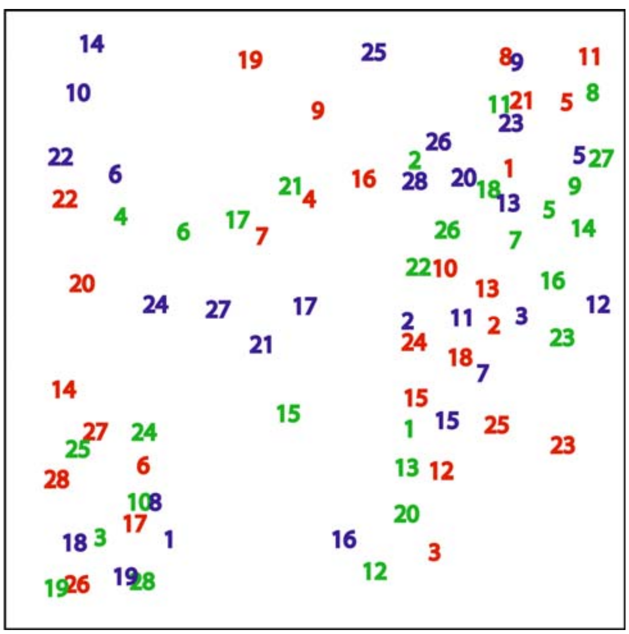


Figure 3.2 Layered photograph showing the semantic maps of three pairs of students. Each colour represents a separate map.

3.3. Experiment 2: Self report studies of affective adjectives for textured tactile stimuli

Experiment 2 combined a semantic differential questionnaire, which was informed by the outcome of Experiment 1, with topographical and vibratory analyses of each textured stimulus to determine whether textures can be affectively rated. Also, to determine whether the vibratory or topographical elements of these textures are related to the participants' affective responses.

3.3.1. Method

3.3.1.1. Participants

Fifty eight male undergraduate students from the School of Mechanical Engineering were recruited through email to participate in a semantic differential questionnaire. Compensation cash gifts were given as a token of appreciation.

3.3.1.2. Stimuli

Eleven stimuli (Figure 3.3A-K) were presented to the participants in black boxes as described in section 3.2.1.2. The stimuli are described by their manufacturer number in Table 3.2.

3.3.1.3. Procedures

3.3.1.3.1. Semantic differential questionnaire procedure

Semantic differential questionnaires were prepared which used a seven point scale to separate the words in Section 3.2.2 (*quality, masculine, engineered, warm, cheap, exciting, comfortable, sophisticated, relaxed, unique, sporty* and *fashionable*) with the opposite polarity of each adjective, indicated using 'not'. The words were presented in a random order and with random polarity for each stimulus. Participants were organised into small groups, with a maximum of six per session, to complete the questionnaire. This activity took place in a controlled environment in a special purpose affective evaluation room. Each group was read the same introduction sheet, explaining the purpose of the study and what they were required to do. They were asked to fill out a practise sheet with stimuli that were not part of the experiment thus familiarising them with the style of questionnaire. The participants were asked to complete the questionnaire in silence so not to disturb or influence the opinions of other participants.

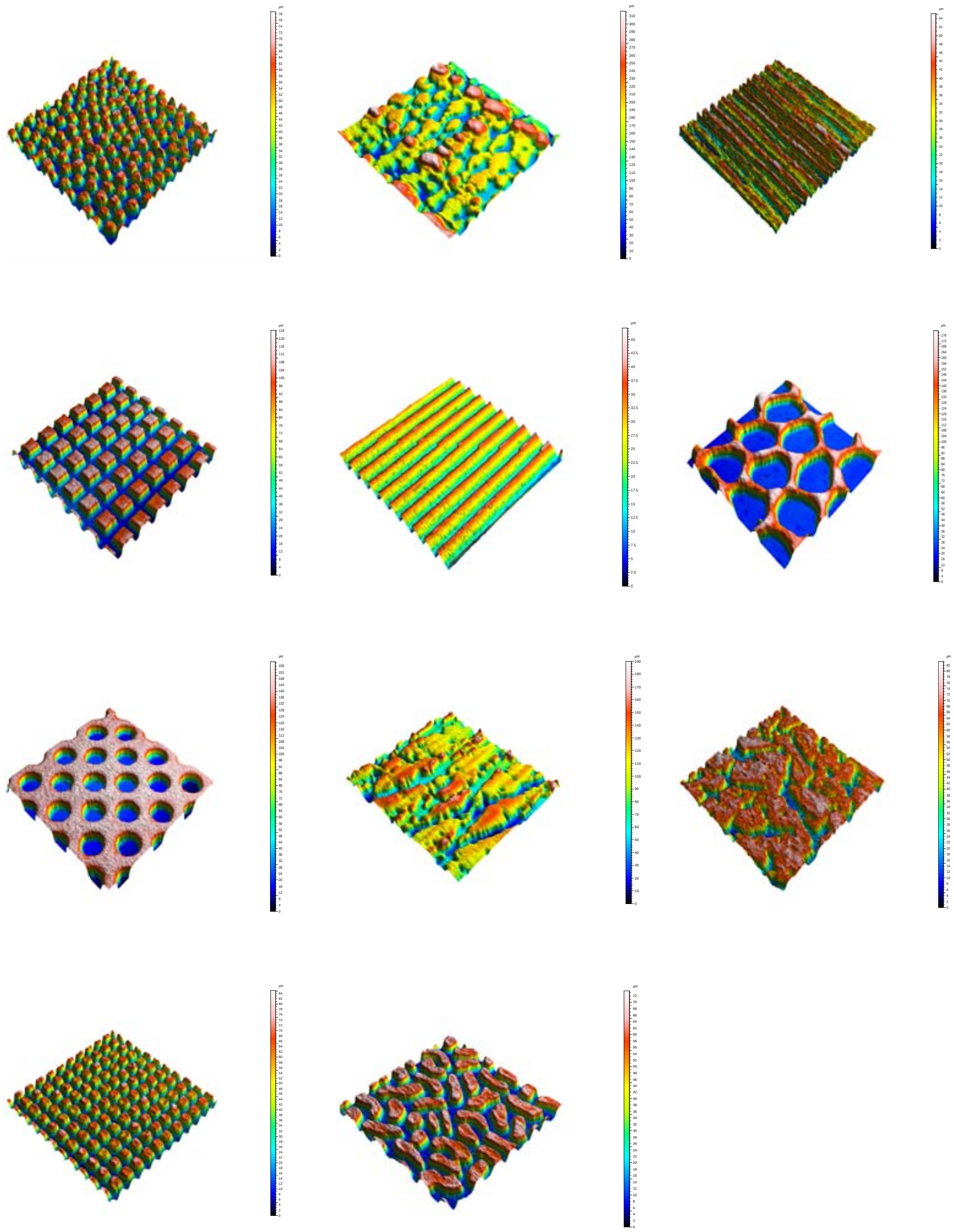


Figure 3.3.3A-K. Stimulus 1 to 11. Figures show a thumbnail size part of the textures, at 10mm by 10mms. These are not presented to scale.

Table 3.3.2 Stimuli used in the study which correspond to Figure 4.3A-K.

Tile	Standex no.
1	MT 9022
2	MT 9015
3	MT 9097
4	MT 9081
5	K9000G
6	MT 9124
7	MT 9002
8	MT 9112
9	MT 9049
10	MT 9080
11	MT 9030

Figure 3.3.4. Standex mould decorations before cutting them into separate plaques.

3.3.1.3.2. Stimulus property recording procedure

In order to acquire roughness data from each of the 11 tiles, a Talysurf 120L was used. The diamond tipped stylus took trace measurements from 8 positions on each tile, generating 3-dimensional topographical profiles.

3.3.1.3.3. Vibration recording procedure

To record the vibration experienced by the finger in active scanning, a Hall Effect transducer was used. This was secured to the finger using a purpose built finger ring shown in Figure 3.5A. A magnet was secured to the finger pad, just below the whorl which is opposite the transducer unit. The oscillations between the magnet and the transducer represent the vibrations caused by the scanning of the texture. The unit was powered by a TTi EL302T power supply set to 9v and 0.1amps. The signal from the Hall effect transducer was amplified by a Stanford Research Systems Amplifier (Model SR560) with the following settings: Coupling=AC, High pass filter = 6, Filer cut-off = 1, Gain Mode = High, Gain=2x102 . The finger was held stationary on the tile for the first 5 seconds of recording to allow the HET to stabilise. This was monitored on screen. The finger scanned the stimulus after this had occurred.

In addition to the Hall Effect transducer, each surface texture was mounted on a Kistler two-axis load cell force platform (Type 9256C2) to record the force which was employed by the participant to ensure that they employed the same force for each stimulus. To ensure that a constant scanning velocity was used, a purpose built electronic circuit, mounted on stripboard, comprising 10 red light emitting diodes spanning 50mm, was programmed to flash sequentially in 1 second (Figure 3.5B). A PIC 16F685 microcontroller was programmed using Flowcode (Matrix Multimedia) to generate a ‘running lights’ C program code. This device was used as a visual cue for the participant to run at 50mms^{-1}.

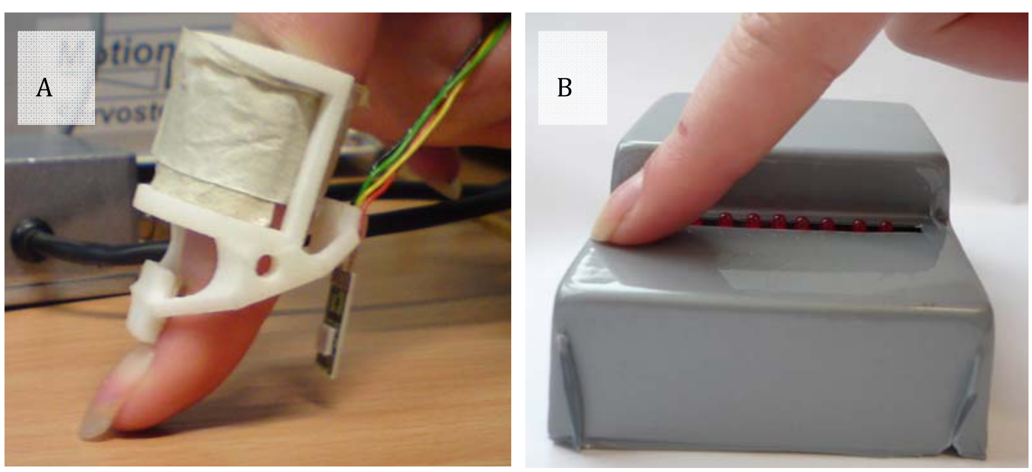


Figure 3.3.5 A-B. (A) Hall Effect transducer secured to the finger with a purpose built finger ring. (B) Scanning speed training device.

A practice session was run using the recording equipment so that the participant was familiar with the procedure. This was recorded but the data was not processed.

3.3.1.4. Analysis

Data from the semantic differential questionnaires was independently transcribed twice to spreadsheets, compared and corrected. Missing responses were replaced with mean values. The data was analysed using principal components analysis in SPSS 14. Varimax rotation was used and components with an eigenvalue greater than 1 were retained. Tile positions in the semantic space were calculated.

Physical recordings from the TalySurf were analysed with TalyMap software (Taylor and Hobson). Roughness values, autocorrelation matrices and spatial wavelength data were obtained for each stimulus including the magnitude value of the dominant spatial frequency.

Fast Fourier Transform (FFT) analysis was performed on the Hall Effect Transducer data. Firstly the data for each stimulus were transferred to Matlab (Mathworks, 2006b) where a matrix was built to hold the 20 obtained traces. From these traces, 500ms of data was extracted from when the finger was in motion, which was after the first 5 seconds of recording as described in Section 3.3.4.3. From these samples, an FFT was performed on each trace, which was then averaged to produce a final spectrum for each of the stimuli.

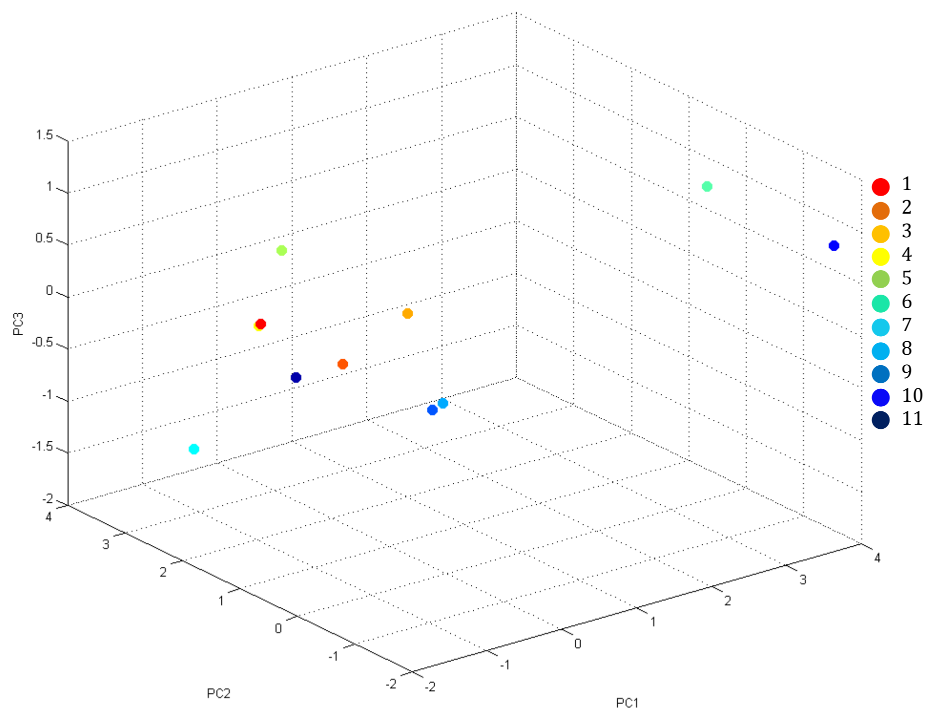
3.3.2. Results

At first, the principal components analysis was unable to generate a positive definite correlation matrix. This was resolved by removing the averages for the word fashionable from the analysis, because it correlated highly with the word *sophisticated*. Subsequent analysis identified three components (Table 3.3). Component 1 accounted for 49.2% of the variance; component 2, 25.8%; and component 3, 14.0%. The words that loaded most highly on component 1 were *exciting* and *unique*; on component 2, quality and *sophisticated*; and on component 3, *warm*. The semantic space is illustrated in Figure 3.6A-D.

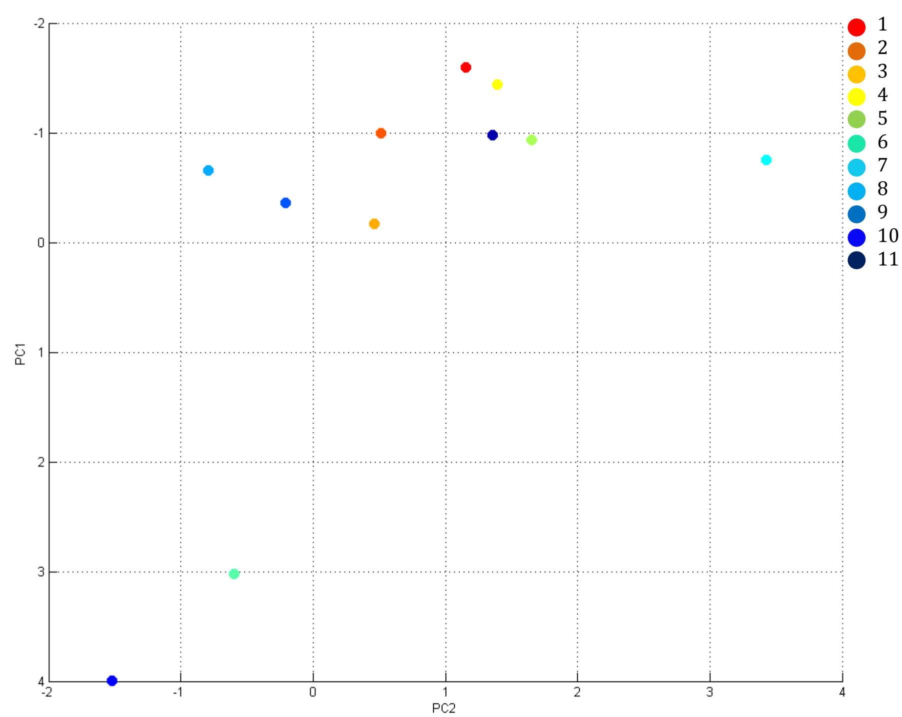
Table 3.3.3. PCA loadings for the 11 affective adjectives

Adjective	Component		
	1	2	3
Quality	-0.165	0.929	-0.094
Masculine	0.476	-0.491	0.691
Engineered	0.743	-0.153	-0.104
Warm	-0.207	0.001	0.952
Cheap	-0.210	-0.787	-0.095
Exciting	0.870	0.332	0.293
Comfortable	-0.828	0.524	0.079
Sophisticated	-0.111	0.901	-0.180
Relaxed	-0.811	0.557	-0.033
Unique	0.947	0.145	-0.025
Sporty	-0.544	0.675	-0.420

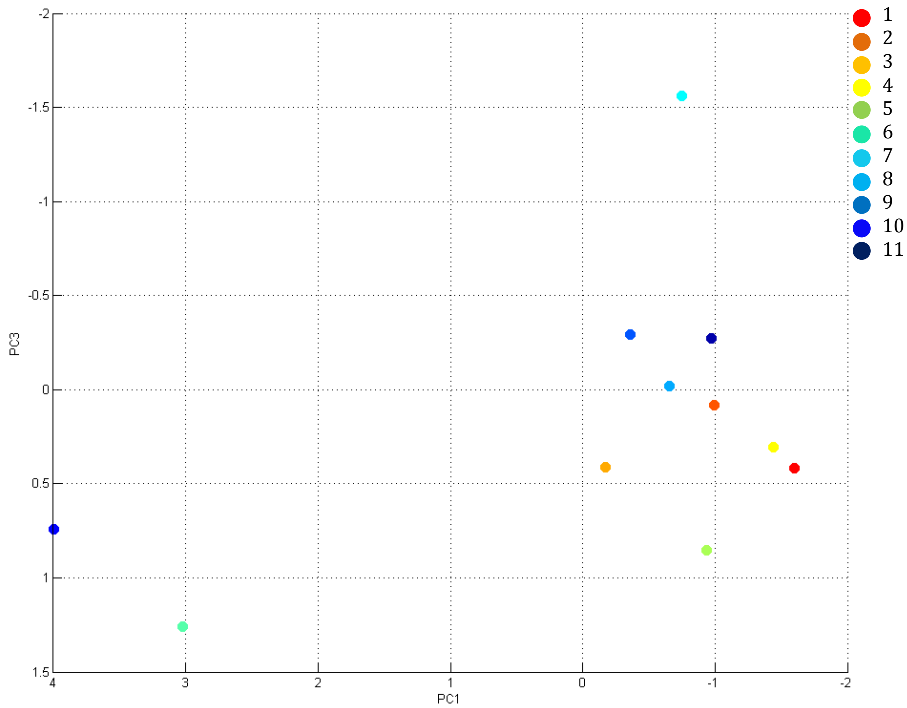
A



B



C



D

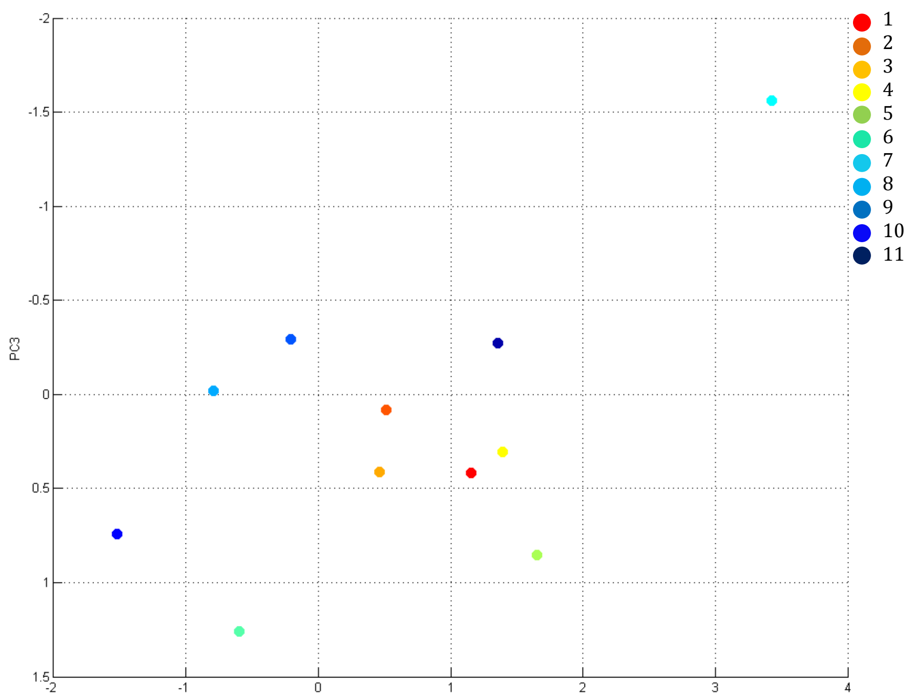
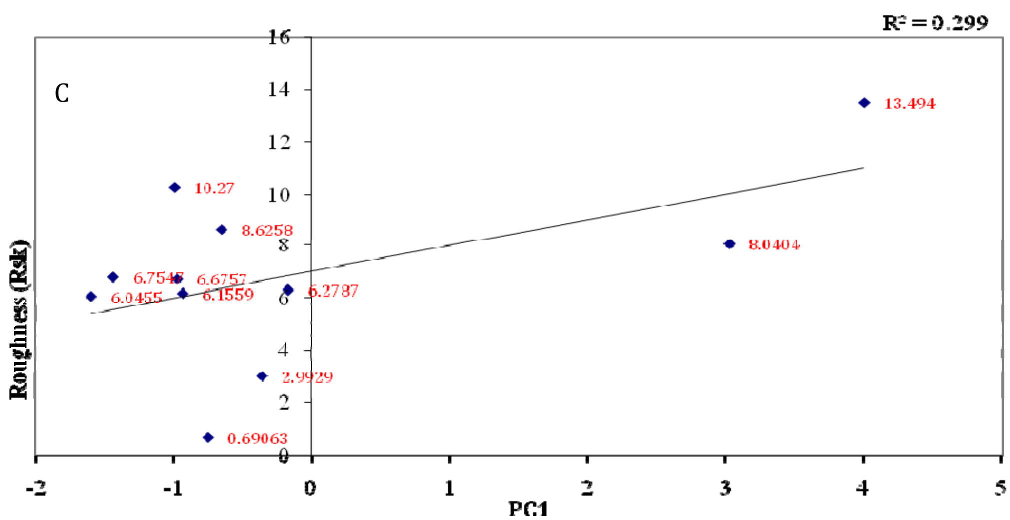
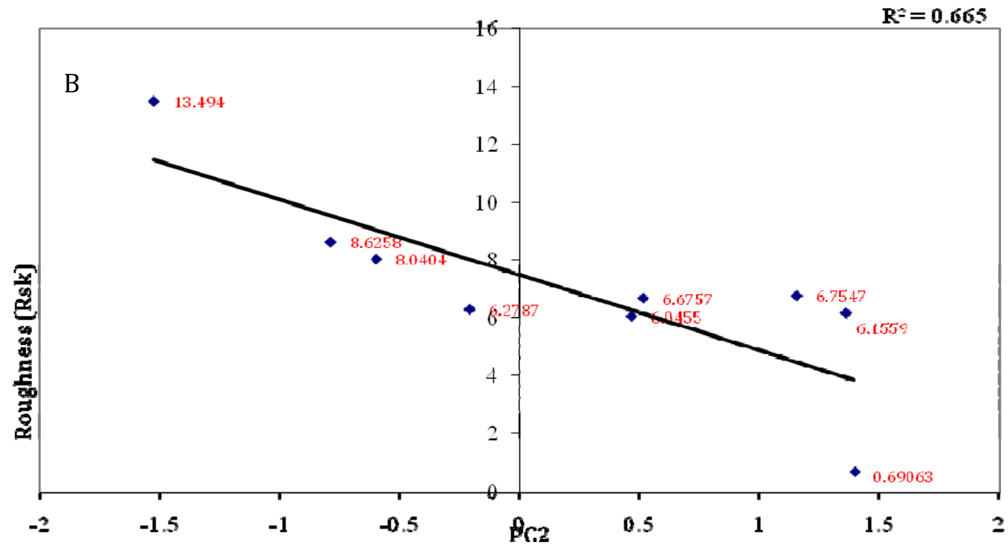


Figure 3.6 A-D A. 3D map of the stimuli. B. PC1 against PC2. C. PC1 against PC3. D. PC2 against PC3.

Table 3.4 shows the topographical properties of roughness, geometric structure and the peak spatial wavelength characteristics of each stimulus. For principal component 1 (*exciting* and *unique*), none of the topographical measurements were good predictors of stimulus ratings.

For principal component 2 (*quality* and *sophisticated*), roughness was a good predictor for stimulus rating because, with the exception of stimulus 3 and 10, as roughness decreased, the feeling of *quality* and *sophisticated* appeared to increase linearly, R^2=0.67 (Figure 3.7B). In terms of spatial wavelength magnitude, the stimuli with the highest values were rated on the extreme ends of the component. The low magnitude stimuli were clustered about the origin which suggested that the feelings of indifference to a stimulus against *quality* and *sophisticated* may be a function of low peak spatial wavelength magnitude. Furthermore, these stimuli also possessed similar roughness values and were isotropic. Peak spatial wavelength was not a linear correlate of stimulus ratings for *quality* and *sophisticated* (R^2=0.001).





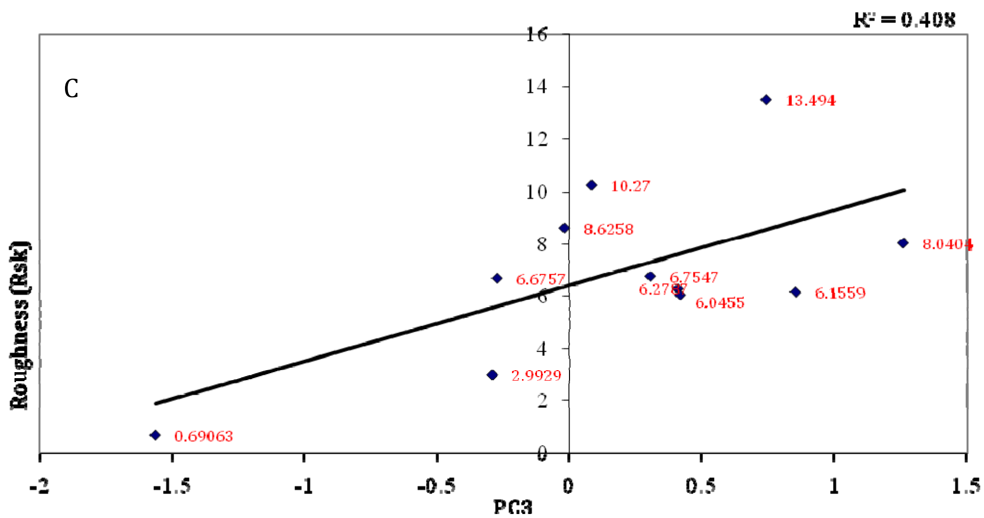


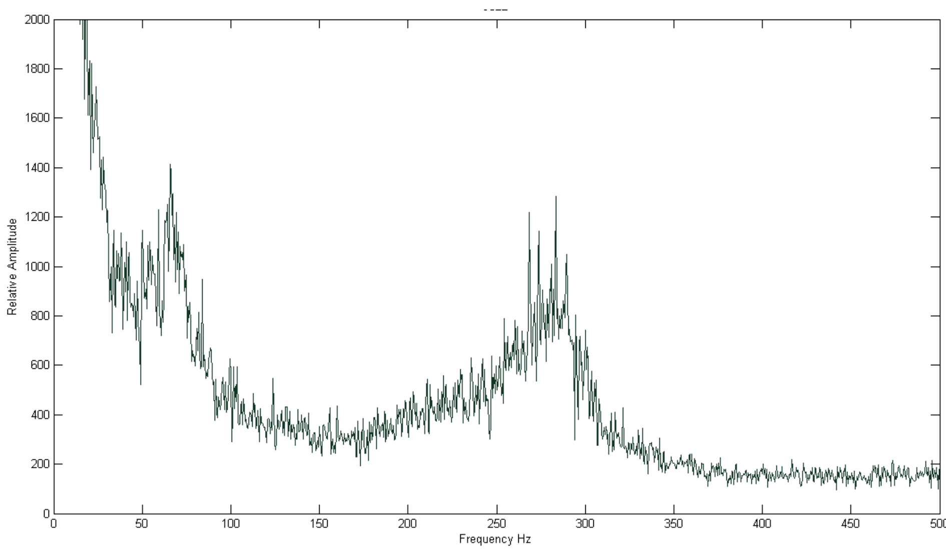
Figure 3.7A-C Roughness plotted against the component score for each stimulus.

Stimulus	Roughness (Rsk)	Geometric structure	Peak spatial wavelength (μm)	Relative magnitude for peak spatial wavelength -
1	6.67	Isotropic	0.896	12.4
2	13.5	Anisotropic	1.34	40.9
3	3.0	Anisotropic	8.08	9.73
4	8.63	Periodic	1.44	41.4
5	0.69	Anisotropic	1.01	10.7
6	8.04	Periodic	2.69	46.3
7	6.16	Periodic	5.04	45.3
8	6.75	Anisotropic	4.53	43.6
9	6.28	Isotropic	2.69	11.3
10	10.27	Periodic	0.73	16.6
11	6.05	Isotropic	4.03	16.6

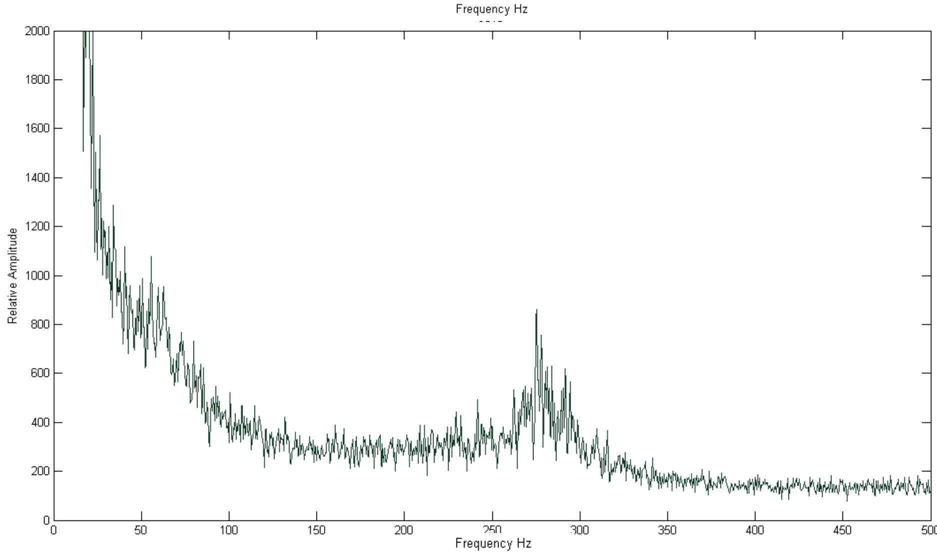
Table 3.3.4. Stimulus properties from the TalySurf profiling

Principal component 3, *warmth*, cannot be qualified by the stimulus roughness values, R^2=0.41 (Figure 3.6C) or peak frequency, R^2=0.03. The stimuli with the highest magnitude value for spatial wavelength were rated as more warm that those with lower magnitudes.

The Fast Fourier transform analysis of all the stimuli can be seen in Figure 3.8A-K and it can be seen that all except stimulus 5 (Figure 3.8E) have distinctive peaks over the 200-300Hz frequency band which vary in relative amplitude. The primary peak across the 50Hz to 80Hz band also varies in relative amplitude and shape across the stimuli. This relative amplitude, or spectral power, was not an indicator of subjective rating across any of the three components: R^2=0.07, R^2=0.007 and R^2=0.03 respectively. This was calculated by graphing the maximum relative amplitude value against the subjective ratings of each stimulus for each component.



A



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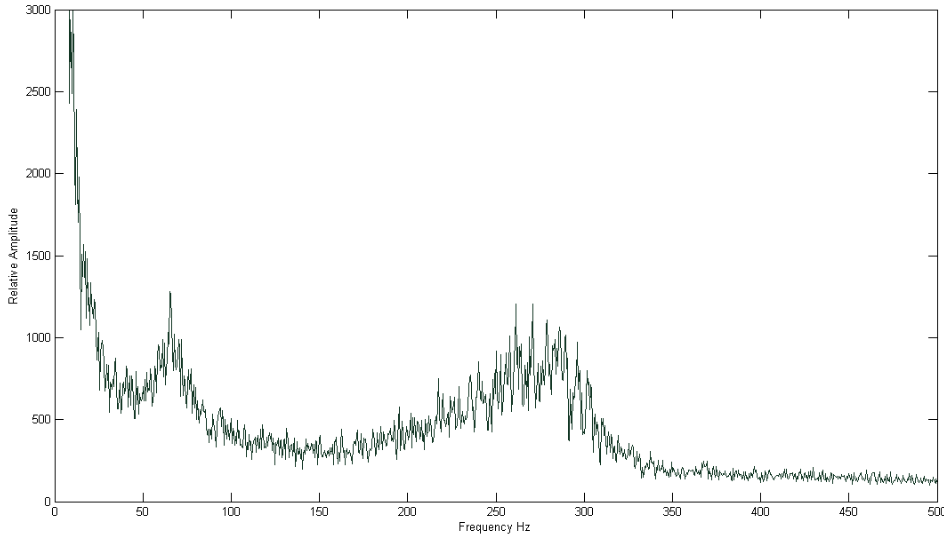
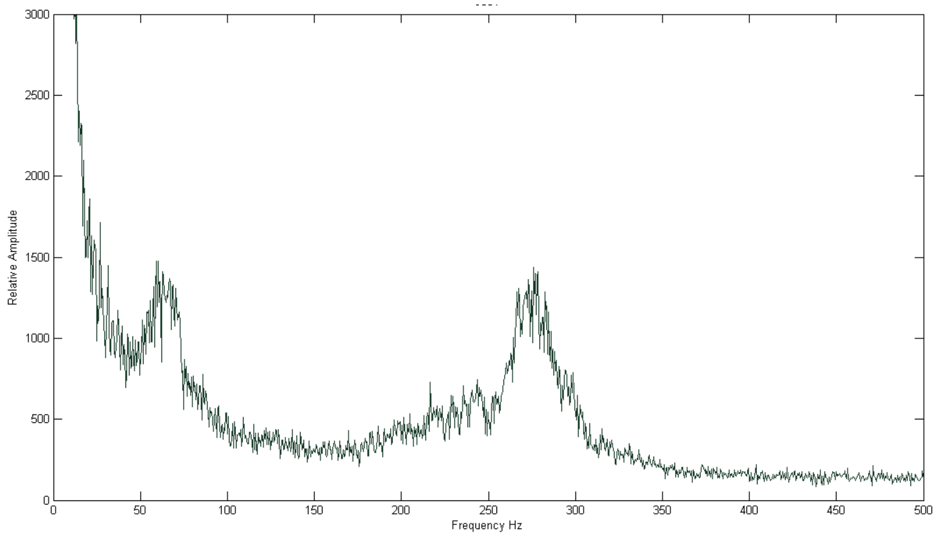
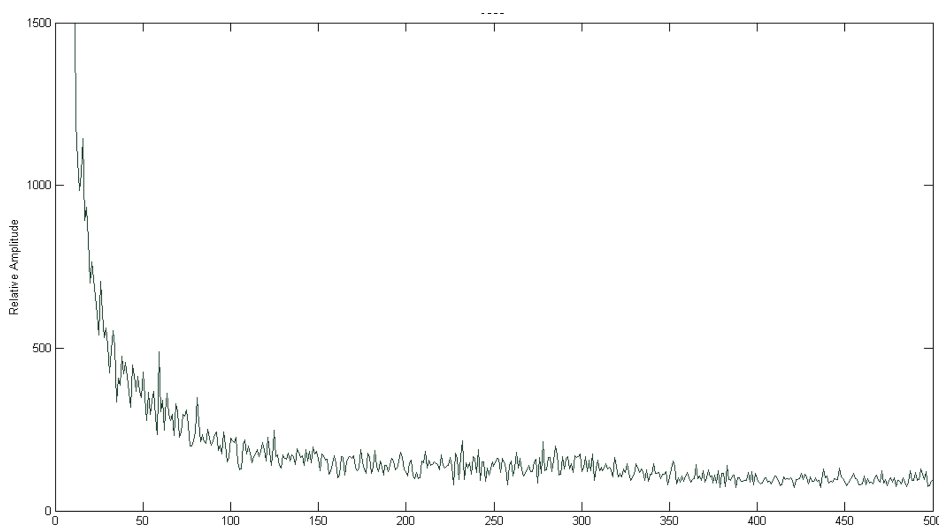

Relative Amplitude
Frequency Hz

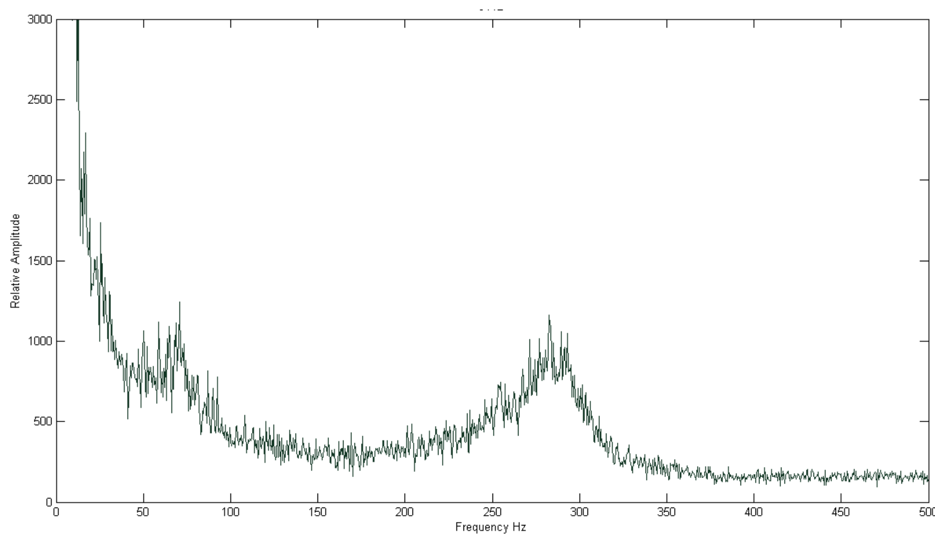
C


Relative Amplitude
Frequency Hz

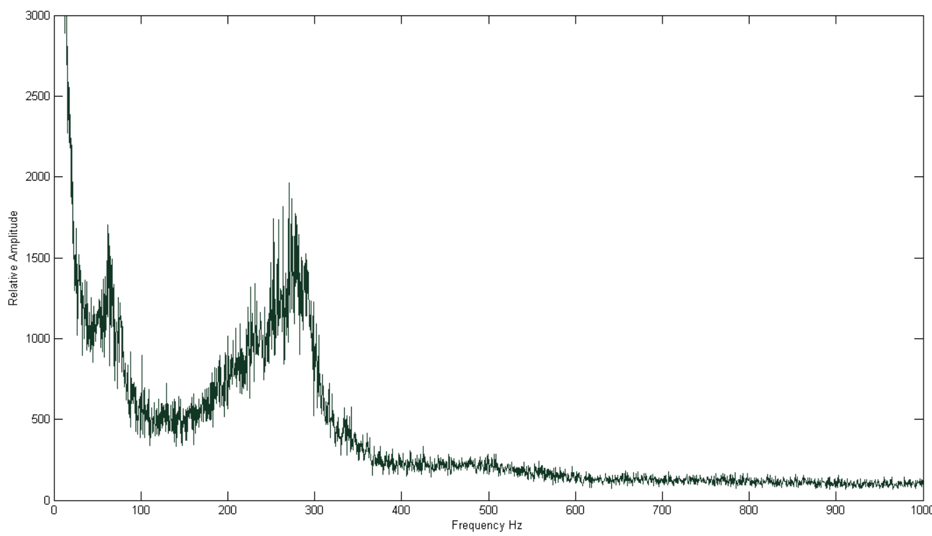
D


Relative Amplitude
Frequency Hz

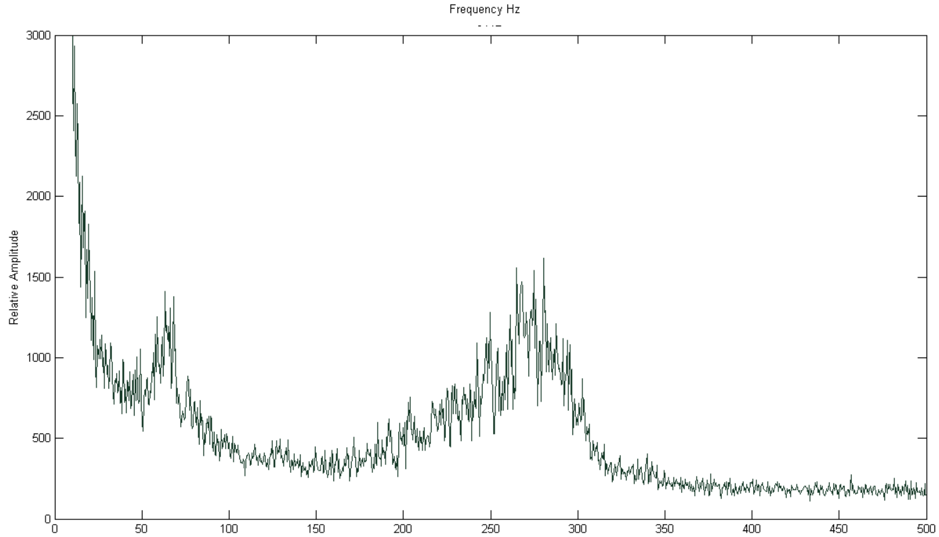
E


Relative Amplitude
Frequency Hz

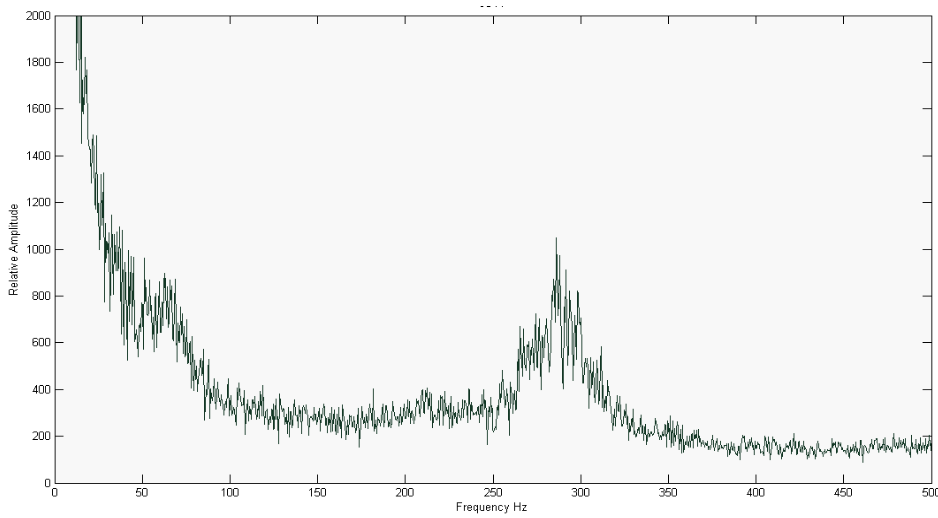
F


Relative Amplitude
Frequency Hz

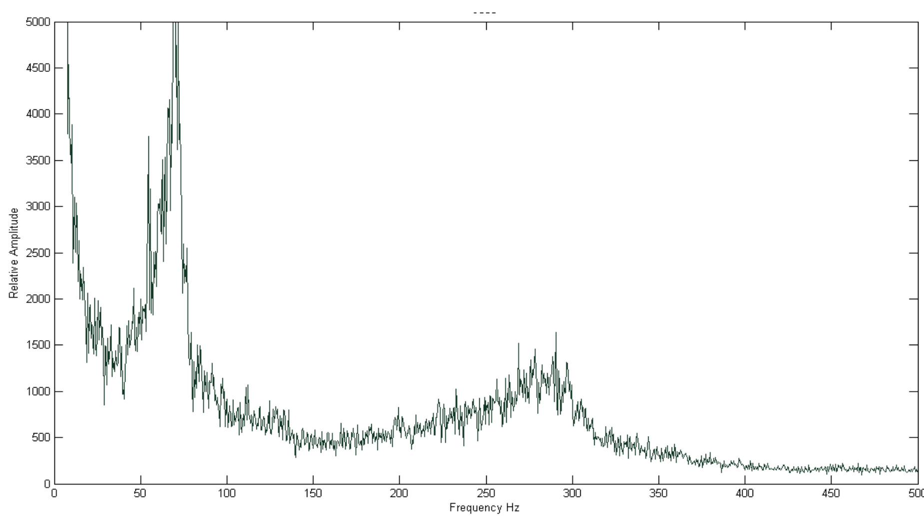
G


Relative Amplitude
Frequency Hz

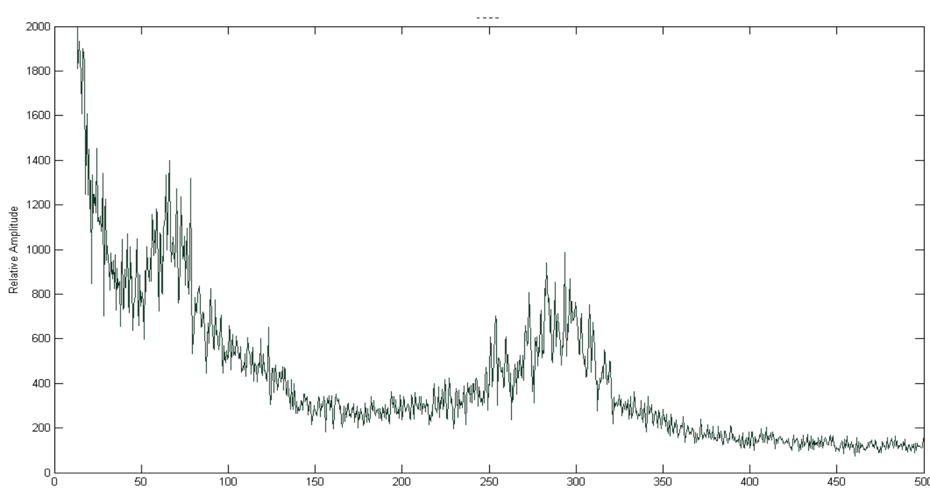
H



I



J



K

Figure 3.8A-K FFT spectra of stimuli 1 to 11.

3.4. General Discussion

There are several findings documented in this study. Firstly, that the moulded stimuli chosen for investigation in this chapter can be rated against affective adjectives, of which three components have emerged through principal component analysis. Secondly, from topographical measurement analysis, it was found that roughness was a good predictor of ratings against *exciting* and *unique* (PC2), and that the magnitude of the peak spatial wavelength contributed to both PC2 and *warmth* (PC3). Finally, vibration analysis from dynamic touch did not appear to be a contributor to stimulus ratings against any component. Why this may be the case will be discussed in this section.

Multi-dimensional scaling techniques have been used by Hollins *et al*. (1993; 2000) to define the dimensions of tactile perception such as roughness and softness. These landmark studies used everyday textures such as brick, sandpaper and scouring sponges to qualify which descriptors people used to describe the tactile experience. From Hollins *et al*.'s first study (1993), two textural dimensions were found; smooth-rough and soft-hard. Their second study revealed a third dimension of stick-slippery, which was not as salient because it was not entirely independent. This is thought to be because for three of the five participants, a slippery-sticky dimension did not manifest itself as independent; rather it was highly correlated with the rough-smooth dimension. This was also seen in the present study with the adjective *fashionable* with *sophisticated*.

Picard *et al*. (2003) examined everyday textures using three phases designed to systematically explore the semantic language associated with touch much in the same way described in this present study. However Picard *et al*. used car interior textiles as a context. They too identified a diverse language bank used by participants to describe the interactions including qualities such as soft and harsh, but also hedonic language. It was concluded by Picard *et al.* that dimensional importance of the touching experience relates to the type of material used, so the space determined for textiles would not correlate if plastics were used.

This present study shares some similarities to the recent researches of Chen *et al*. (2009a; 2009b) who also attempted to quantify affective responses to tactile textures by linking them to physical properties. Chen *et al*., however, used a variety of materials which introduced different thermal conductivities and compliance characteristics, whereas the present study used the same material for the stimulus set. They showed that ratings for *sophisticated* were linked to the physical roughness of the surface texture. In this present study, roughness was also found to be a good predictor of *sophisticated*. There are a lot of researches detailing the perception of roughness, most notably the works of Susan Lederman (1982) and Bensmaia and Hollins (2003; 2005) whose works revolve around a central duplex theory of touch perception. The duplex theory of touch (Hollins and Risner, 2000), originally derived from the work of David Katz (1925), explains that there are two clear classes of surface texture, those that are fine and those which are coarse. These two classes have been linked to spatial period; the spaces between the elements which make up a surface texture. Hollins and Risner (2000) stated that 'above 100μm, spatial mechanisms are progressively engaged and gradually become the dominant contributor to texture perception'. Bensmaia and Hollins (2003) concluded that a transitional measurement of 200μm spatial wavelength (or 100μm feature gap) constituted a fine texture whereby vibration is needed to determine the highly salient dimension of roughness. They conclude that roughness is linked to vibratory power for fine texture perception. Although vibration is present in the active touching of coarse textures, Lederman (1982) stated that vibration has no role in the perception of roughness for coarse surface textures.

Looking at the spatial wavelengths in Table 3.4, it is clear that these would constitute a coarse texture set, with the exception of stimulus 5 which means that the textures can be deemed coarse. The magnitude of the peak spatial wavelength was found to be a good indicator of component 2 and 3 which tenuously mirrors the power theory of Bensmaia and Hollins (2003; 2005) for fine texture roughness perception. When converted to frequency (Hz) using the formula:

$$f=s/\lambda \tag{3.1}$$

where f is the frequency (Hz), s is scanning speed (mms^{-1}) and λ is spatial wavelength (μm), then the peak frequency components for each stimulus range from 6.2 to 68.5Hz. These findings may shed more light on the importance of low frequency vibration in the affective rating of stimuli.

The results from the vibration analysis of each stimulus with the Hall Effect transducer did not show any clear indications of being implicated in affective rating, although distinctive peaks were found in the spectra, especially between 200Hz and 300Hz. One possible explanation for this could be due to human finger resonance. It has been shown that the finger resonates between 100 and 350Hz (Welcome *et al.*, 2008) which may explain why all stimuli (except stimulus 5) included a peak over this frequency range. It was also observed that most textures elicited vibrations above 200Hz which is unexpected based on the dominance of large spatial wavelengths. Using the same formula, in order to achieve a vibration based on wavelength, values of between 0.16 and 0.25μm would be required. These were not observed in the topographical analyses of the stimuli recorded from the 2μm diameter stylus. Another key limitation in this method of vibration recording is inaccuracy due to the damping properties of the skin on travelling waves. By this, it is meant that the magnet does not sit at the point of finger-texture contact, so the travelling wave to the magnet may lose magnitude. A further limitation to this method is the resolution of frequencies below approximately 50Hz caused by 1/f noise. When compared with the data acquired by the profilometer, approximations of the lower frequencies components can be made which as discussed, ranged from 6.2 to 68.5Hz. It is acknowledged that touching with a probe (Talysurf) and with the finger may produce different spectra, but it has been shown by Bensmaia and Hollins (2003) that if the spatial wavelength is known, the frequency detected by the finger will be approximated based on the scanning speed.

3.5. Summary

This present study explored the affective properties of tactile surface textures. Adjectives and stimuli were chosen in a series of experiments within the context of car interiors. Principal component analysis revealed that the eleven moulded plastic stimuli could be successfully rated against the three affective components: *exciting* and *unique*, *quality* and *sophisticated*, and *warmth*. Topographical and texture elicited vibration analyses were conducted to investigate which physical properties of the stimuli were good predictors for stimulus placing against the components. The magnitudes of peak spatial wavelength were good indicators to how these stimuli were rated along the principal component 3, and for component 2 with the addition of topographical roughness. There were no clear predictors for component 1, *exciting* and *unique*.

Low frequency vibrations that were calculated from spatial wavelengths could be involved in affective adjective rating. High frequency investigation in this present study with the Hall Effect transducer did not reveal clear data to explain stimulus ratings against the components. Finger resonance, dampening of travelling waves and 1/f noise were highlighted as key limitation to the method used. Although current literature suggests that only fine texture perception is driven by vibratory cues, the results presented here suggest that vibrations which predominantly occupy lower frequency bands could be good predictors of affective responses. To test this theory and further investigate the role of vibration in texture processing, the effect of amplitude and frequency on perceptual and affective judgements needs to be explored without spatial cues. Using pure vibrations applied to a smooth plate for example, would remove any coarse spatial cues and systematic investigation into the effect of amplitude and frequency on affective evaluation could be undertaken. Using pure vibratory stimulation also permits the investigation of whether pure vibration can convey perceptual information such as roughness and softness without spatial cues. Furthermore, investigation of how imposed vibration affects perception in the static and dynamic finger scanning modes will establish whether imposed vibration is an effective way to generate new surface texture specifications as outlined in research objective three in this thesis. The next chapter will investigate these key points.

Chapter 4

Subjective rating of vibratory stimuli in static and dynamic touch

4.1. Experiment rationale

The results in Chapter 3 identified that vibratory cues from texture exploration were a good predictor of affective responses for the eleven test stimuli. Specifically, the magnitude of the peak spatial wavelength was related to the ratings of each stimulus against the components of *quality* and *sophisticated*, and *warmth*. The study reported in this chapter was therefore designed to investigate the role of vibratory amplitude on tactile perception. It has been shown that for fine textures, which elicit high frequency vibrations, it is spectral power (associated with amplitude) that is responsible for the perception of roughness (Bensmaia and Hollins 2003; 2005). Although it is generally acknowledged that low frequency vibrations are generated in the dynamic exploration of coarse textures, it has been hypothesised that neither amplitude nor frequency are dominant in discrimination of roughness judgements (Taylor and Lederman, 1975; Lederman, 1982, p.142). However, ratings in Chapter 3 indicated that the magnitude of low frequency vibrations could be linked to affective texture discrimination.

The goal of this series of experiments is to test the efficacy of an alternative method of vibrotactile stimulation using a piezo-mounted platform. The specific aims are (1) to determine whether parallels can be drawn between this method and those employed in the literature (Section 2.4.1), (2) whether textural adjectives can be rated purely as a function of vibratory amplitude with the elimination of the spatial cues and (3) to compare static stimulation, where the finger pad is placed on the platform with no lateral movement permitted, and dynamic exploration of the platform. These aims will inform the thesis objective which outlines the investigation of whether textural descriptors could be assessed solely through vibration. Literature shows that vibration plays a role in fine texture discrimination (Bensmaia and Hollins, 2003; 2005), so broadly, this chapter aims to understand whether this can be extended across a wider range of amplitudes and frequencies that may not be experienced with fine texture scanning.

4.2. Experiment 1: Adjective selection and methodology testing

The aim of Experiment 1 was to establish whether participants were able to detect and rate vibratory stimuli against *stickiness, roughness, softness* and *bumpiness* which have, with the exception of *bumpiness* which is a textural adjective from Gescheider *et al*. (2005) been attributed to vibration in literature (see Chapter 2, Section 2.5).

4.2.1. Method

4.2.1.1. Participants

Ten male participants from the School of Mechanical Engineering, aged between 21 and 30 took part in the experiment. All were naïve to the experimental objectives, but were informed that they would be touching a vibrating plate mounted on a piezo electric actuator. They were also shown the positioning of the apparatus prior to the start of each experimental run. The participants were compensated by a small cash gift for their involvement in the investigation.

4.2.1.2. Apparatus

A circular ABS tile of 60mm diameter with no discernable macro patterning was vibrated using a variety of sine waves by a piezo-electric actuator (PSt 150/5/100 VS10, Piezomechanik). The actuator was controlled by a Labview (National Instruments) program which sent the signal through an amplifier at ten times gain to produce a maximum displacement of 100μm peak-to-peak on the actuator. The program set a 3V offset on the signal sent to the actuator to reduce negative displacement.

Pink noise was played through headphones to the participants to mask any noise produced by the actuator. This eliminated the possibility of participants using auditory cues in the subjective rating task.

4.2.1.3. Stimuli

The vibratory stimuli for this investigation were sinusoidal waveforms. In total, 27 different waveforms were produced using amplitudes in the range of 40μm to 130μm peak-to-peak and frequencies of 30Hz, 90Hz and 225Hz. As the objective of this preliminary experiment was to test that the chosen adjectives could be rated by the participants, different frequency and amplitude values were chosen to the main study. The amplitudes were primarily chosen to be above detection threshold for both the PC and RA afferents, and the frequencies chosen to span the PC and RA afferent's operating range.

4.2.1.4. Procedure

The participants were asked to read an experiment protocol before entering the laboratory which detailed the task involved in the investigation and their expected scanning speed and motion. Magnitude estimation was used to record the participants' responses to the stimuli (Zwislocki and Goodman, 1980). The instructions given to the participants concerning how to use magnitude estimation is documented in Appendix A.

The participants were seated at a desk behind a curtain, so that they could not see the stimuli or the experimenter. On their side of the desk were a set of headphones and a clipboard to which a sheet of paper showing 27 rows of empty boxes each with headed with a different adjective. These adjectives were *stickiness*, *roughness, bumpiness* and *softness*.

On the experimenter's side of the desk was the actuator which protruded 10mm from the surface of the desk in which a whole had been cut (figure 4.1). Participants were asked to reach under the curtain and feel the surface with their dominant hand, numerically rate the vibration for each of the four adjectives and write these in the designated boxes. Five participants were recruited to use static touch, the other five for dynamic touch. Before the start of the study a second example of using magnitude estimation was given using the brightness of the strip light in the room. Once explained again, participants were asked to give verbal confirmation of their understanding. Simple hand motions were exchanged between the participants and the experimenter to signify that the next stimulus was ready for evaluation or that the participant had finished rating. Each stimulus was presented once.

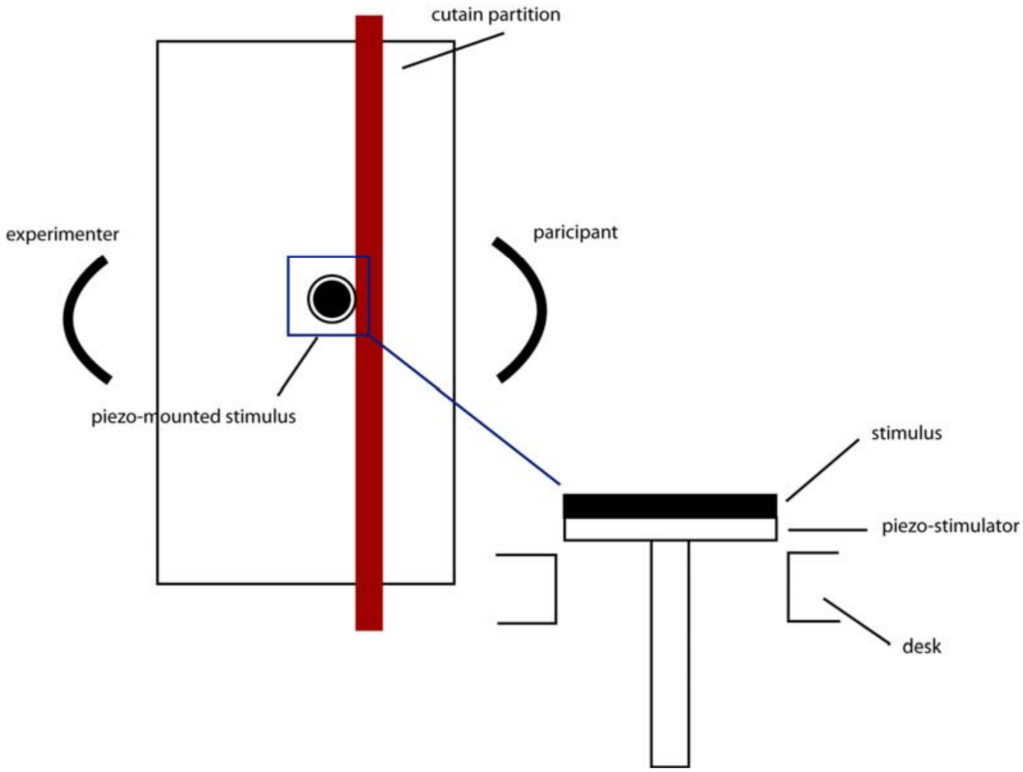


Figure 4.1 Experiment set-up

4.2.2. Results and Discussion

No subjective results were analysed from the preliminary experiment. The purpose was to establish whether participants were able to use this approach to rate a vibratory stimulus and to use it as a training exercise. It was noted by all participants that it was difficult to write down their decisions whilst feeling the stimulus because most preferred to feel and write with their dominant hand. It was also apparent that some of the words were difficult to quantify. *Bumpiness* was regarded as the same as *roughness*, and *stickiness* was difficult to rate in the static touch mode. Taking these notes into consideration, the protocol was revised for the main experiment and is documented in section 4.3.1.4.

4.3. Experiment 2: Perceptual rating of *intensity, roughness* and *softness* for static and dynamic touch

The aim of Experiment 2 was to establish whether participants were able to detect and rate vibratory stimuli against *intensity, roughness* and *softness*.

4.3.1. Method

4.3.1.1. Participants

The same ten male participants from the preliminary experiment were recruited. All were familiar with the experimental protocol and were informed that they would be touching a vibrating plate. They were all compensated with a small cash gift for their time.

4.3.1.2. Apparatus

The apparatus used in this experiment was identical to that used in the preliminary experiment (see Section 4.2.1.2.)

4.3.1.3. Stimuli

Using the same stimulus generation methodology as Section 4.2.1.3, sixty vibratory stimuli were generated. A wide range of amplitudes were chosen for the frequencies of 35Hz, 100Hz, 200Hz, 250Hz and 400Hz and are displayed in Table 4.1. The frequencies were again, selected to excited both the PC and the RA afferents. The 35Hz and 100Hz frequencies were selected to target the RA afferents and the remaining to target the PC afferents at different sensitivity levels according the threshold curves of Bolanowski *et al*. (1988). Maximum sensitivity for the PCs is at 250Hz, so it is hypothesised that there will be a difference in ratings between the 250Hz and both the 200Hz and 400Hz vibrations.

As this study has not been designed to block receptor function or afferent recruitment in a neurophysiological sense, vibration thresholds have not been calculated for each participant. The vibratory amplitudes chosen for each of the frequencies are hypothesised to sit above threshold levels based on the published levels of Morley and

Rowe (1980) who showed that at the least sensitive end of the stimulus detection spectrum (dominated by low frequencies) 8μm peak-to-peak amplitude was detectable.

4.3.1.4. Procedure

The protocol of the main experiment was similar to that in Section 4.2.1.4, except for the adjectives used and the data collection method. The words selected for this experiment were *intensity, roughness* and *softness*. As participants from the preliminary experiment could rate *roughness* and *softness*, these were included. In order to benchmark these results against published literature, *intensity* was chosen. Instead of requiring the participants to write their magnitude estimations down, they were asked to say them aloud for each adjective clearly, with a 2 second gap between responses. The responses were documented by an assistant.

Table 4.1 Sixty vibratory stimuli were derived from five frequencies and twelve amplitudes (all values are peak-to-peak)

Frequency (Hz)	Amplitude, peak-to-peak (μm)
35	15.3
100	28.3
200	30.6
250	36.9
400	39.9
	50.5
	56.5
	73.9
	79.9

93.4
121.9
131.5

Each participant was required to complete three runs of the same experiment on three different days; therefore three estimations were given for each stimulus in total. The adjectives and waveforms remained the same throughout, only the order in which the stimuli were presented differed and this was randomised.

Of the ten participants recruited, five took part in the dynamic touch experiment whereby they were asked to maintain a constant pressure and run their finger across the surface of the plate at $50 mms^{-1}$. The remaining five participants followed the same experimental protocol as those in the dynamic touch group, but were asked to place their finger on the plate and to make no lateral movements and maintain a constant pressure. An assistant was recruited to record these values in a spreadsheet for both the dynamic and the static groups.

4.3.1.5. Analysis

As the magnitude estimation method was used, in which each participant used their own numerical scales, the data needed to be normalized before they could be analysed (McGee, 2003). The data was firstly converted to log10 values, and the mean for each participant's new score was calculated. Next, the offset was calculated by subtracting each participant's overall log mean from the overall mean (from all participants). Finally, each participant's offset was added to the individual log scores, and the antilog was calculated. The Kolmogorov-Smirnov test was used to check the data for normal distribution and revealed that normality was not present. This is done by standardising all of the scores in the data set, and comparing these values against normal distribution values. Friedman ANOVA, a non-parametric test which looks at the way repeated evaluations of a stimulus is treated, was therefore used to analyse main effects, firstly for the effect of amplitude scoring within each frequency on participant's scoring for each adjective, then the effect of frequency for each amplitude also. Full significance values for Section 4.4 are reported in Appendix B.

4.3.2. Results

4.3.2.1. Static touch

Friedman ANOVA revealed that for *intensity* ratings against 35Hz (X^2=48.090, df=11, p< .001), 100Hz (X^2=44.874, df=11, p< .001), 200Hz (X^2=47.730, df=11, p< .001) and 250Hz (X^2=38.263, df=11, p< .001) the amplitude of the waveforms were scored differently. For the vibratory condition of 400Hz, amplitude was not significant (X^2=17.691, df=11, p= .098). This can be seen in Figure 4.2. For each frequency of the vibratory conditions, all ratings for *intensity* were significantly different at p< .005 across all amplitudes with the exception of 79.7µm and 93.4µm.

For *roughness* (Figure 4.3), the subjective ratings across the different amplitudes were significant for 35Hz (X^2=48.885, df=11, p< .001), 100Hz (X^2=45.360, df=11, p< .001), 200Hz (X^2=35.892, df=11, p< .001) and 250Hz (X^2=26.24, df=11, p< .005). For 400Hz (X^2=8.716, df=11, p< .648), no effect was found across the amplitudes for *roughness*.

When looking at the ratings of *roughness* and frequency, for certain amplitudes, ratings were significant. These were: 15.3µm (X^2=9.737, df=4, p< .05), 28.3 µm (X^2=13.113, df=4, p< .05), 30.6µm (X^2=15.265, df=4, p< .005), 36.9µm (X^2=13.004, df=4, p< .001), 56.6µm (X^2=15.292, df=4, p< .001) and 122.0µm (X^2=10.766, df=4, p< .05).

For the perception of *softness* (Figure 4.4) for 35Hz (X^2=22.140, df=11, p< .05), 100Hz (X^2=23.597, df=11, p< .05), 200Hz (X^2=28.281, df=11, p< .005) and 250Hz (X^2=36.292, df=11, p< .001) ratings were different across the amplitudes. When analysing the effect of frequency across all amplitudes, frequency significantly altered the ratings of *softness*. These were 15.3µm (X^2=16.667, df=4, p< .005), 30.6µm (X^2=13.778, df=4, p< .01), 36.9µm (X^2=15.702, df=4, p< .005), 56.6µm (X^2=15.125, df=4, p< .005), 73.9µm (X^2=16.215, df=4, p< .005) and 131.5µm (X^2=15.429, df=4, p< .005).

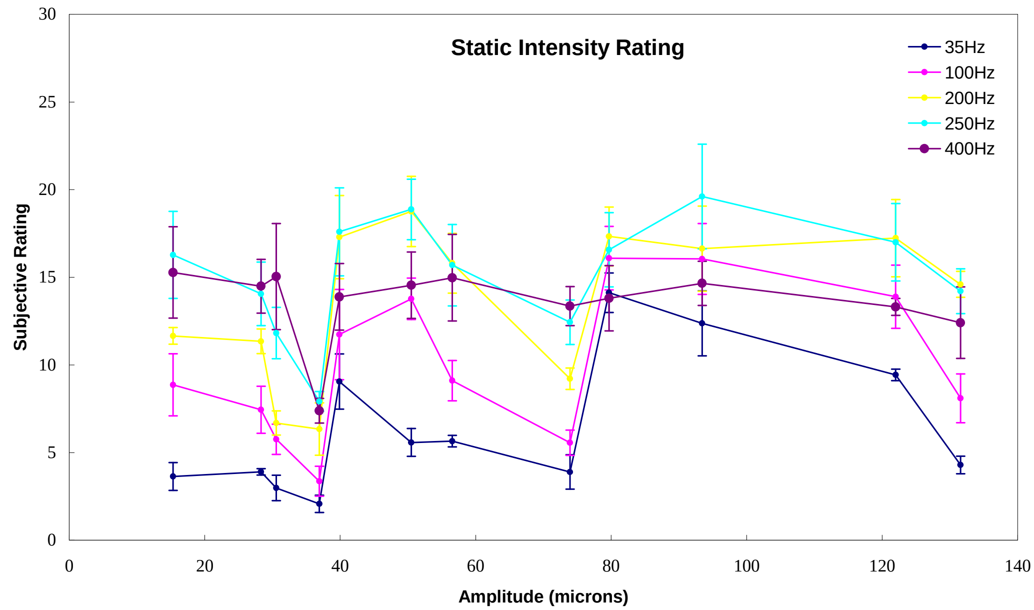


Figure 4.2 Static subjective ratings of *intensity*.

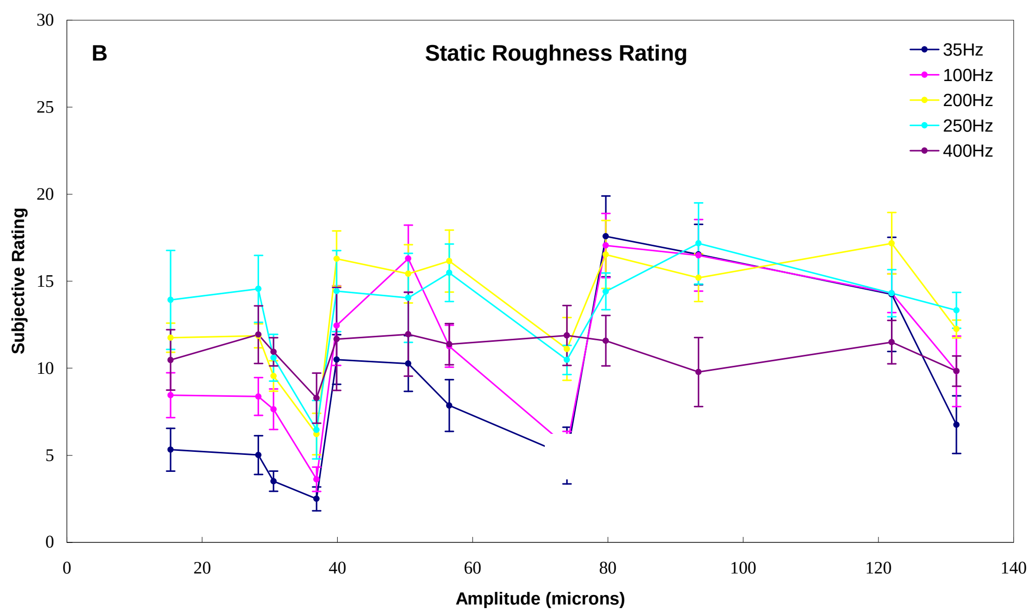


Figure 4.3 Static subjective ratings of *roughness*.

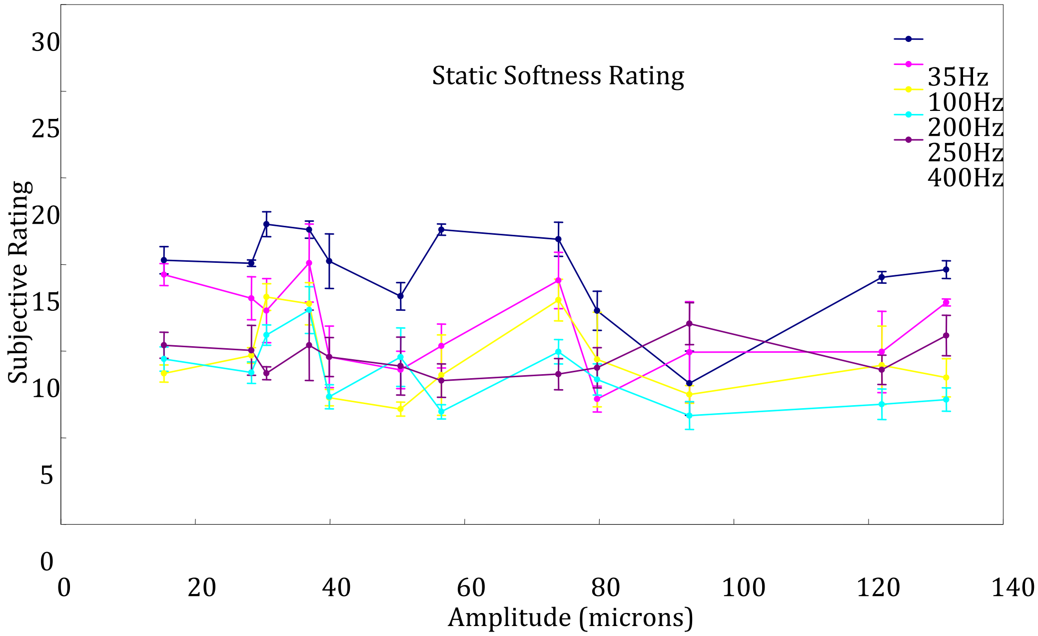


Figure 4.4 Static subjective ratings of *softness*.

4.3.2.2. Dynamic touch

Intensity ratings appeared to be a function of both amplitude and frequency as shown by Friedman ANOVA. For each frequency, there were significant differences in the participants ratings depending on the amplitude that was applied – 35Hz (X^2=50.355, df=11, p< .001), 100Hz (X^2=49.543, df=11, p< .001), 200Hz (X^2=40.822, df=11, p< .001), 250Hz (X^2=33.825, df=11, p< .001) and 400Hz (X^2=49.543, df=11, p< .001). The effect of frequency was also significant in changing the ratings of *intensity*, with all values significant at p< .05.

Roughness ratings were also affected significantly by both frequency and amplitude. When looking at the ratings for amplitudes across all frequencies, ratings by participants were significantly different for all but 400Hz– 35Hz (X^2=39.519, df=11, p< .001), 100Hz (X^2=40.437, df=11, p< .001), 200Hz (X^2=36.200, df=11, p< .001) and 250Hz (X^2=32.477, df=11, p< .001). For the frequencies across each of the amplitudes, all were significant at p< .05. These are shown in Figure 4.6.

For the subjective ratings for *softness*, participants ratings were significantly different across the amplitudes for 100Hz (X^2=35.731, df=11, p< .001), 200Hz (X^2=25.394, df=11, p< .001) and 250Hz (X^2=25.048, df=11, p< .001). For each of the frequencies across each amplitude, only three conditions showed significant differences in scoring. These were 28.3µm (X^2=10.384, df=4, p< .05), 30.6µm (X^2=16.426, df=4, p< .01) and 73.9µm (X^2=12.426, df=4, p< .05).

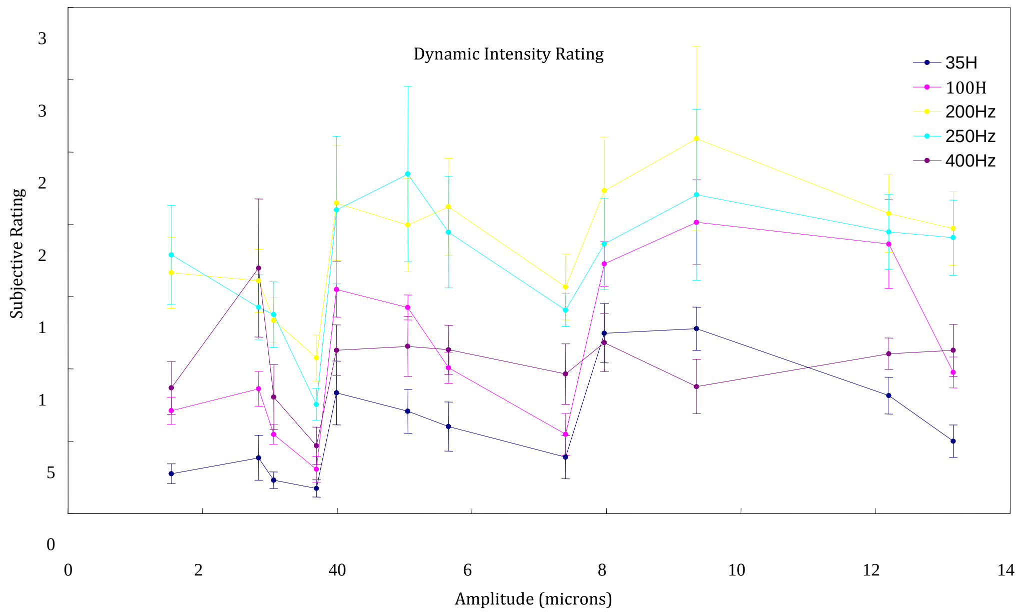


Figure 4.5 Dynamic touch subjective ratings for *intensity*

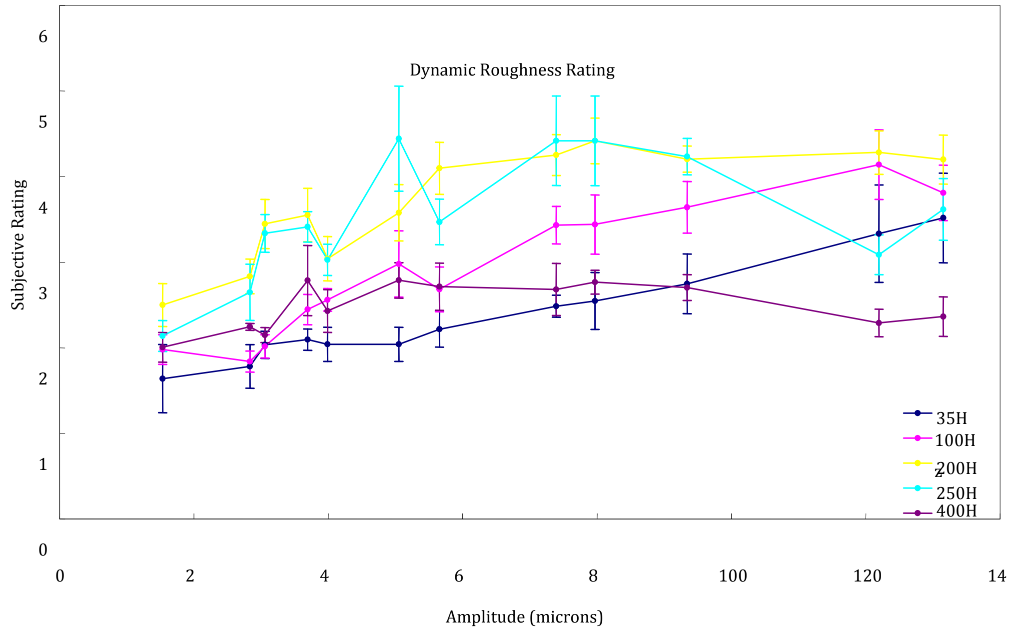


Figure 4.6 Dynamic subjective ratings of *roughness*

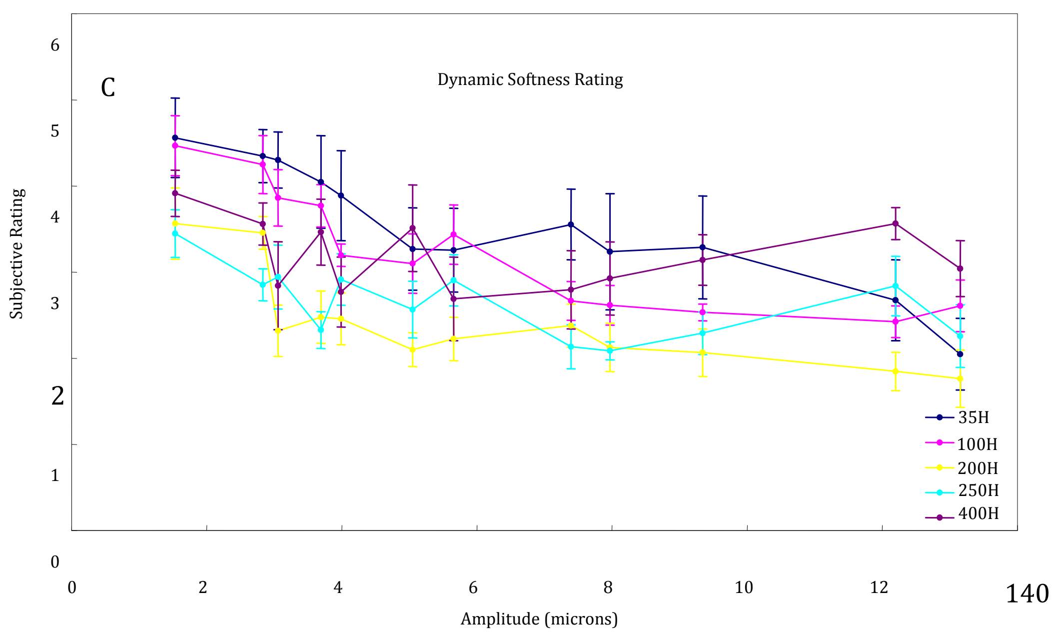


Figure 4.7 Dynamic subjective ratings of *softness*

4.3.3. Discussion

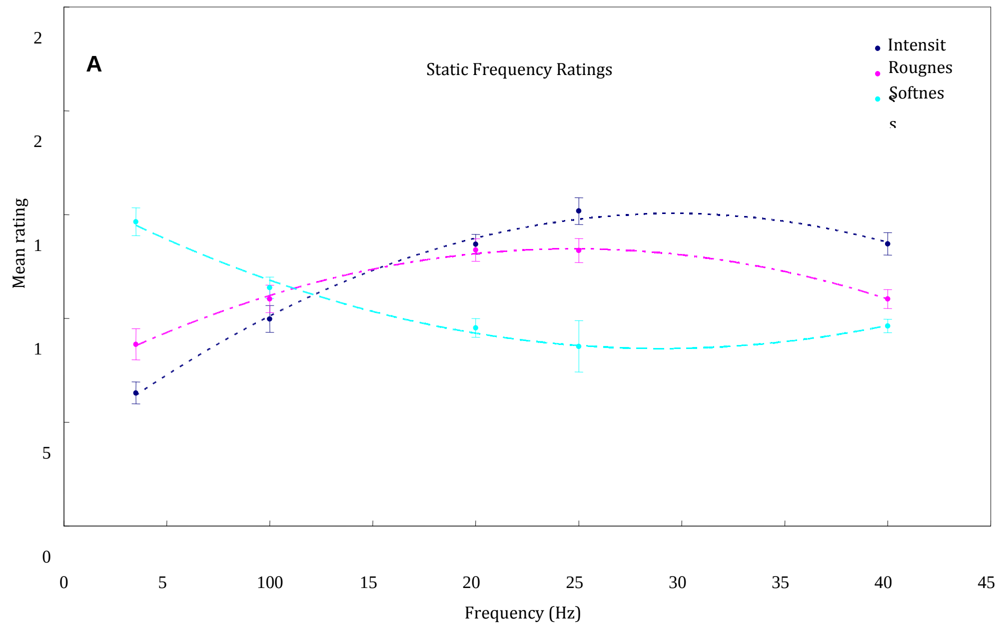
Most vibrotactile studies have been designed to characterise the function and operating bandwidths of the four mechanoreceptors recruited in touch perception, and to generate sensitivity threshold models (Bolanowski *et al*., 1988; Gescheider *et al*., 2001). These studies have used contact probes of varying sizes and have been applied to different places on the finger pad of human subjects to activate these afferent populations. Johansson and Vallbo (1979) showed that RA afferents have lower thresholds at the tip of the finger and that sensitivity was not a function of stimulator size, whereas Pacinian corpuscles are affected by size but not location (P Channel is known to use spatial summation). This was confirmed in later publications (Gescheider *et al*., 2001; Whitehouse *et al*., 2006). Taking this into consideration, the present study used a piezo electric actuator which was able to stimulate the whole finger pad, and therefore could have increased the PC and RA's sensitivity to vibratory stimulation.

A small number of studies have investigated how vibratory stimulation can convey more than threshold data. Hollins and Roy (1996) investigated the perceived intensity of vibrations and showed that it to be a function of amplitude. Hollins *et al*. (2000) explored the contribution of the vibratory mediated channels in the perception of smoothness. Limitations in knowledge exist still, as no known study has considered how people perceive a vibrating stimulus when the finger is run across it. Also, whether perception of factors such as *intensity* alter with active dynamic touch.

The results from this present study, show clear links to published psychophysical data concerning vibrotactile stimulation and perception. Intensity ratings in the static mode against the different frequencies display a strong correlation to the threshold curves of vibrotactile sensitivity shown by Bolanowski and colleagues (1988; 2001). Bolanowski and colleagues state that sensitivity threshold, particularly for the Pacinian (P) channel which is u-shaped, has a maximum sensitivity of approximately 250Hz after which point the threshold increased again. In accordance then with the model, the inference is that for any given amplitude component of a waveform, a higher intensity rating would be obtained for 250Hz over any other frequency. In the present study, this is seen in Figure 4.8A. Static vibration perception shows that the highest rating for *intensity*, and indeed *roughness* and *softness*, was at 250Hz. In dynamic touch, the curvature of the trend is much more pronounced than the static touch mode

(Figure 4.9A). Although this curve is still centred on the 250Hz vibration condition, it implies that the two modes of touch are perceived differently for frequencies around the maximum sensitivity marker of the P channel. Ratings were perceptually similar for the 200Hz and 250Hz frequencies. It was also seen that with the exception of *intensity* for dynamic touch, there was no significant differences in the ratings against each of the amplitudes. This suggests that changes in amplitude at higher frequencies are more difficult to detect, a hypothesis that is supported by Pongrac (2007).

The effect of amplitude remained similar in dynamic touch to the static mode (Figure 4.8B), in that three functions between low, medium and high amplitudes exist. In Figures 4.8B and 4.9B, roughness perception behaves in a similar way to intensity ratings which appears to contain three separate functions of low, medium and high amplitudes where there is a decline in *roughness* and *intensity* perception from the first amplitude of each separate function. Vibration analysis for *roughness* has only been explored in fine texture perception (Bensmaia and Hollins 2003, 2005; Yoshioka *et al* 2007). Current theories in *roughness* perception have shown it to be an intensive code; that *roughness* is a function of the spectral power of complex vibrations, and not the dominant frequency (which is dependent on scanning speed). The Friedman ANOVA in this present study showed that this was not the case as most specifically in dynamic touch, frequency elicited different ratings across the amplitudes. Bensmaia and Hollins (2003) reported a logarithmic relationship between spectral power and roughness ratings. This was not observed in the present study. However, as spectral power does not change for the different frequencies employed in this present study, and as analysis has shown that frequency also has an effect, the Bensmaia and Hollins (2003) theory does not give a definitive explanation of *roughness* encoding in the somatosensory system for pure vibratory stimuli. As the waveforms investigated by Bensmaia and Hollins (2003) are complex a direct comparison may not be possible. Also, their intensive theory model only accounted for 72% of the variance in the data, which leaves 28% unaccounted for. Bensmaia and Hollins (2005) expressed that although *roughness* perception can be accounted for in the most part by the intensity of texture-elicited vibrations, their textures had 'salient temporal' characteristics. In other words, frequency information is also needed to form a perception. In the case of this present experiment, frequency, or temporal characteristics, has been shown to be statistically significant in forming not only the *roughness*, but also the *intensity* and *softness* percepts for various amplitudes.



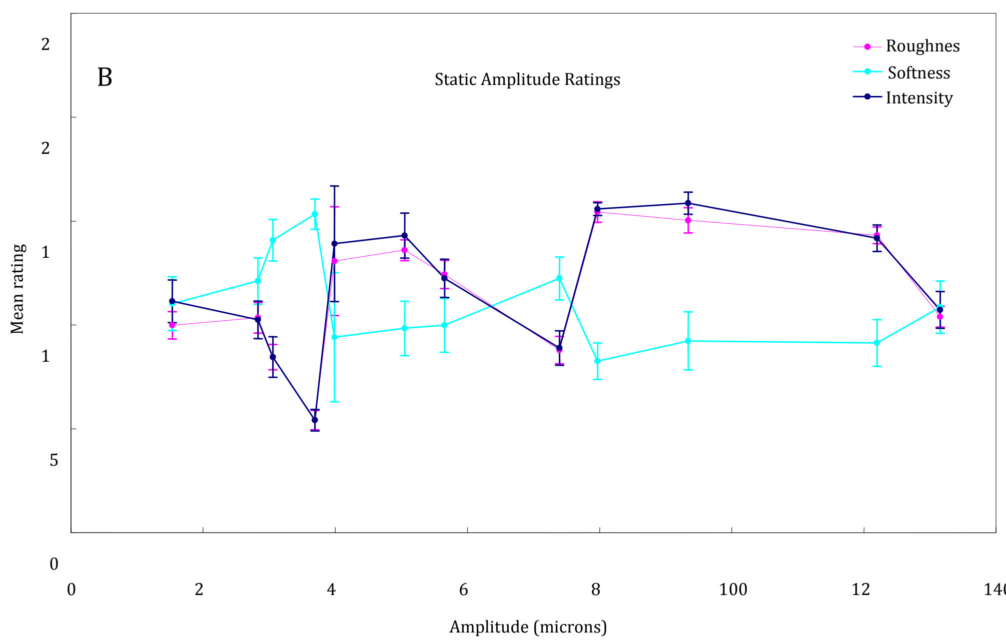


Figure 4.8 A-B Static touch subjective ratings as a function of (A) frequency and (B) amplitude.

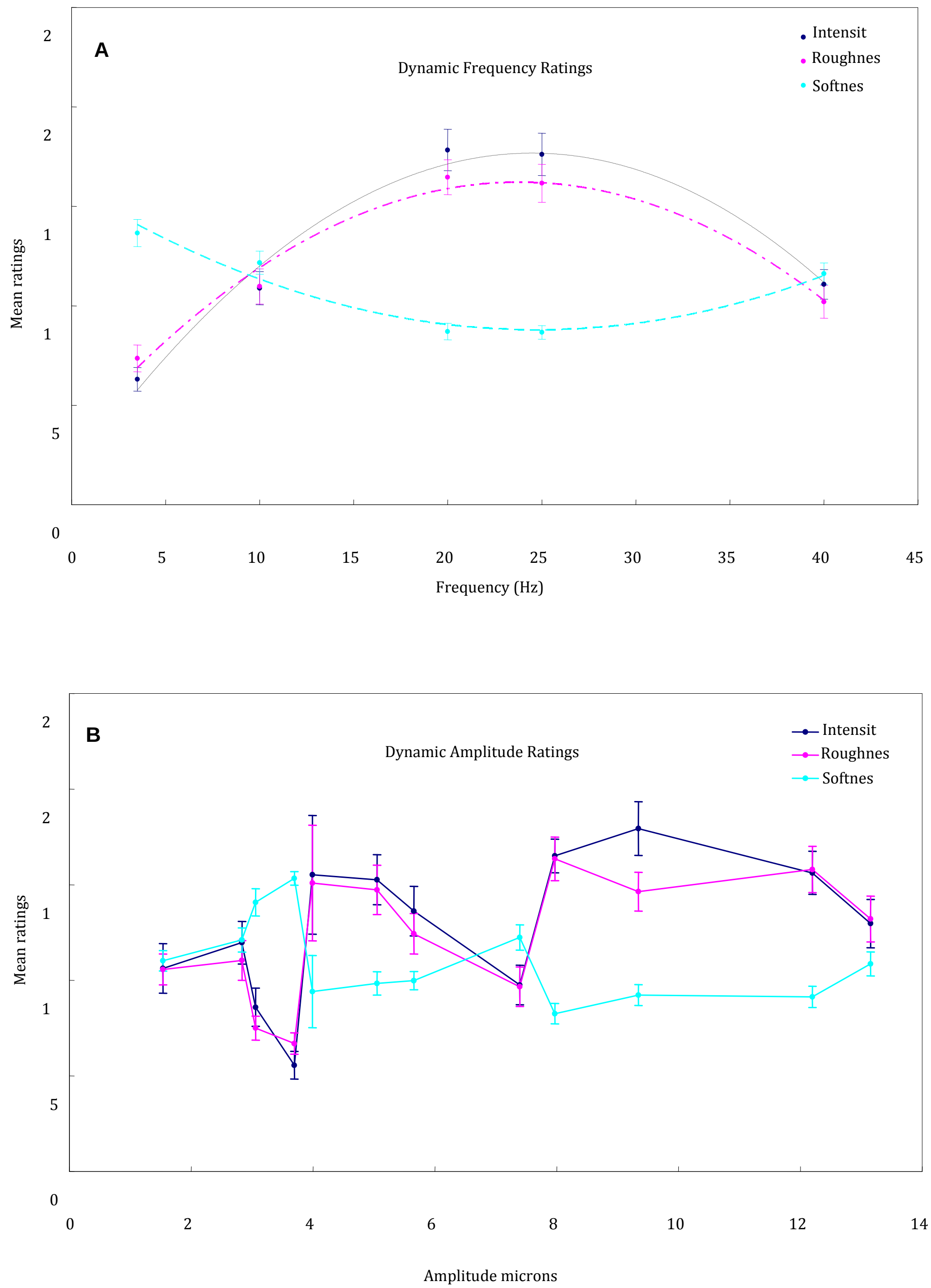


Figure 4.9 A-B Dynamic touch subjective ratings as a function of (A) frequency and (B) amplitude.

Softness perception, although considered to be a perceptual correlate of compliance (Chen *et al*., 2009a, 2009b; Srinivasan and LaMotte, 1995) in this present study results showed different levels of perceptual *softness* as a function of vibration. Friedman *et al*. (2008) employed a variety of experimental procedures to quantify the perception of *softness*. With direct touch, force and deformation of the finger pad with the surface texture was a good indicator of *softness* in static touch. Evidence in indirect touch, where spatial cues on the skin are absent, it has shown that vibratory stimulation could carry softness cues (Yoshioka *et al*., 2008) for synthesising softness on a hard surface. Whether vibration-linked *softness* is directly attributed to mechanoreceptor activation induced through tapping the stimulus for example, or the associated sensory signals from muscles and joints remains to be seen. Nevertheless, in this present study, subjective ratings for *softness* changed as a function of amplitude and frequency and this trend was observed across both touch modes. As a caution though, it must also be considered that, as *softness* ratings were inverse to those of *intensity* and *roughness*, ratings could be attributed to participants assessing the antonym of *roughness*.

4.4. Summary

This present study shows that vibration can convey *intensity, roughness* and *softness* data when spatial cues are absent. It can also be concluded that a piezo-actuator is an efficacious method of producing vibrotactile stimulation as results are consistent with literature concerning threshold models and intensity perception. It should be taken into consideration though that there are differences in the graphed functions for static and dynamic vibration processing. As the only difference in the procedures between the two experimental procedures is finger scanning, it can be inferred that the introduction of scanning motion alters the perception of vibratory frequency. The ratings in relation to amplitude however, remain similar between the modes. The next research question then, is are the vibrations in this present study comparable to those generated by the scanning of the fingerpad across a surface texture such as those experienced in Chapter 3? Are spatial wavelength and vibratory frequency, and texture feature depth and vibratory amplitude perceptually similar? This is explored in Chapter 5.

Chapter 5

Sensation matching between imposed and texture-elicited vibrations

5.1. Experiment rationale

The aim of this study was to investigate to what extent imposed vibrations are perceptually similar to those elicited by a surface texture. It was shown in Chapter 4 that the vibration generation method of a piezo-vibrated touch platform was able to produce results compatible with psychophysical literature for the perception of intensity specifically. Importantly, the results for both static and dynamic touch of this platform were closely related. This current study therefore used the same vibration generation method and asked participants to match imposed vibrations to those elicited by a grated surface texture.

The specific objectives of this study were to establish whether parallels could be drawn between (1) vibratory amplitude and texture feature depth, and (2) vibratory frequency with texture spatial period. These objectives were investigated in a series of experiments using square waveform vibratory stimuli and square wave gratings in three sensation matching experiments.

5.2. Sensation matching experiments

5.2.1. Method

5.2.1.1. Participants

Four male participants were recruited for this series of experiments from the School of Mechanical Engineering and were aged between 22 and 28 years. All were informed of the experimental procedures before agreeing to participate, and compensated by a small cash gift for their involvement.

5.2.1.2. Stimuli

The stimuli consisted of four Acrylonitrile Butadiene Styrene (ABS) circular gratings, each measuring 50mm in diameter. Two of these were from the Standex engraved range as used in Chapter 3. The engraved tiles had or spatial periods wavelengths of 1540μm and 650μm and respective feature depths of 92μm and 64μm. In order to explore the intermediary range between these gratings, two further stimuli were manufactured, also from ABS, with spatial wavelengths of 1000μm and 800μm. The feature depths of these manufactured tiles were 98μm and 100μm. The wavelengths of the stimuli were verified using a surface profilometry Talysurf 120L machine. The fifth tile, also ABS, had no discernable macro-patterning and was also from the Standex range. The stimuli are listed in Table 5.1.

Figure 5.1 Example of the grated stimuli used in the study

Table 5.1 Stimulus specifications and predicted frequencies calculated at 50mms^{-1} scanning seed.

Stimulus	Production method	Spatial wavelength	Feature depth	Predicted frequency
1	Engraved	1540µm	92µm	32.5Hz
2	Machined	996µm	98µm	50.2Hz
3	Machined	801µm	100µm	64.2Hz
4	Engraved	650µm	64µm	76.9Hz
5	-	NA	NA	NA

5.2.1.3. Apparatus

A purpose built electronic circuit comprising ten red light emitting diodes spanning 50mm, was programmed to flash sequentially in 1 second is shown in Figure 5.1A. This was used to train participant scanning speed. A PIC 16F685 microcontroller was programmed using Flowcode (Matrix Multimedia) to generate a 'running lights' C program code. The circuit board was housed in a vacuum formed acrylic casing with a designated finger scanning platform running in parallel to the ten LED's. The unit was powered by a 9V source, and used an LM705 voltage regulator to step the power down to the operating voltage of the PIC (5V).

The smooth tile described in Section 5.2.2, was mounted on a circular steel platform which was screwed on to the piezo electric actuator (See Chapter 4 for specification). The square waveforms delivered to the actuator, were controlled by a specifically designed Labview (National Instruments) program which allowed for dynamic adjustments via the onscreen command window. A voltage amplifier (EPA – 104, Piezo Systems) was used at 10 times gain to produce a signal operating range of ±5V (or ±50µm displacement) to the actuator which had a 3V offset to reduce negative compression.

A 2-dial control box (Fig. 5.2B) was produced which allowed the participants to adjust either the amplitude, dial A, or the frequency, dial B which the experimenter could view onscreen. Ranges were set accordingly and discussed in the intensity matching procedures.

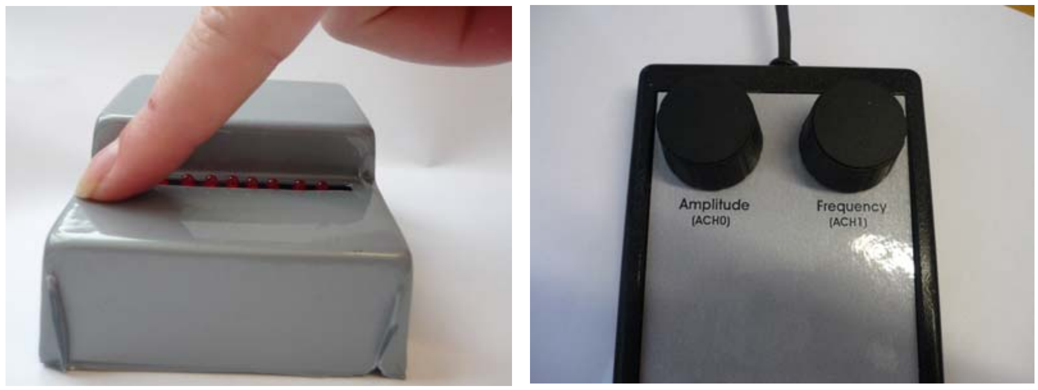


Figure 5.2 A-B (A) Running light box to train participant scanning speed. (B) 2-dial control box for adjusting vibratory frequency and amplitude.

An 8-port DAC card (PCI 504E, National Instruments) was used to mediate signals from the computer to the actuator, and the control box back to the computer. Slight time delays, in the region of 1 second were present during the conversion stage, so the experiment was calibrated accordingly to consider this delay.

In addition to the apparatus described for the psychophysical experimental series, a Hall Effect transducer was mounted to the finger and scanned across the grated stimuli. The same method described in Chapter 3 was employed.

5.2.1.4. Scanning speed procedure

In order to minimise scanning speed variations across participants, an exercise was devised to train stimuli scanning velocity. Using the scanning speed training device described in Section 5.2.3, participants were required to learn a specific scanning speed. This was achieved by running the finger along the scanning platform at a speed which matched the transition of the flashing LED's. This was performed a minimum of twenty times, or until the experimenter deemed the speed sufficiently learned. Participants were informed that this was the speed they were required to scan both the gratings and piezo-mounted stimulus. Visual monitoring was employed by the experimenter to ensure consistent results and if the participants deviated from the prescribed scanning speed, they were asked to correct their movement.

5.2.1.5. Sensation matching procedure

The study was divided into three sensation matching experiments. Experiment 1, asked participants to sensation match between vibratory amplitude and texture feature depth. In experiment 2, sensation matching between vibratory frequency and texture spatial wavelength was conducted and in experiment 3 participants were asked to match both vibratory parameters to the grated stimulus. All experiments required participants to make of sixteen judgements in total; four for each stimulus. Two experimental runs were conducted. At the beginning of each run, the participants were informed of the experimental format, that there were three separate experiments in which they were required to make sensation matching judgements across two stimuli at any given time and that of these two stimuli, the grated stimulus would always be stationary and the smooth stimulus would vibrate.

The participants were informed that they would be in control of the vibrations delivered to the piezo-mounted stimulus by adjusting either dial A, B or both depending on the experiment. Participants were made aware that the smooth stimulus would be vibrating and that the surface texture would not be changed during the course of the session. This was fully understood by the participants. They were not informed how many different stationary stimuli they would be touching in total, only that there would be sixteen judgements required in each experiment.

For each experiment, the apparatus set-up and procedure was similar. Behind a curtain, which eliminated visual cues concerning the stimuli and apparatus, the actuator mounted stimulus and the grated stimulus were placed side by side (approximately 200mm apart centre point to centre point). The grated stimulus was fixed to the table with double-sided tape so it would be sufficiently secured for stimulus exploration, but easy enough to remove and replace with the next stimulus. On their side of the curtain was the control box with 2 dials labelled A and B.

Each participant was instructed to reach underneath the curtain to run their finger across the grating. They were instructed to conform to a specific mode of movement – a speed of 50mm/s which was learned in the pre-experiment phase, a constant pressure and trajectory, and finally, clear defined strokes from left to right, lifting their finger at the end of the stimulus and returning to the left to begin a new stroke as many times as was sufficient to explore the grating. The grating ridges ran perpendicular to the scanning direction. The same scanning action was then repeated with the piezo-mounted stimuli, however, adjusting dial A, B or dials A and B until the square waveform delivered to the actuator matched the sensation of running the finger across the stationary gratings.

Participants were encouraged to test the ranges of the dials before being presented with any of the stimuli which would enable a reference plane for sensation matching to be established. Unlike the experimental procedure described in Chapter 4, only visual cues and not audible, were eliminated. As no subjective data was collected in this study which concerned either affect or the perception continua with numeric indicators, the noise generated by the actuator was regarded as negligible to the sensation matching exercise outlined in this study.

Once the participant had decided upon a final vibration setting for the actuator which was perceived to match the sensation of the stationary grating, they were instructed to give oral confirmation so that the experimenter could record the final value and proceed to set up the next stimulus. The movement of the dials could be seen in real-time on the computer screen by the experimenter. This data was captured and saved to file.

In experiment 1 (amplitude/feature depth matching), dial A which controlled the amplitude function of the square waveform, was adjusted by the participant. The experimenter set the upper limit of the dial to 5 Volts (which drives a maximum 100μm peak-to-peak displacement). For each grating, the frequency was set to that of the calculated wavelength for 50mm/s scanning speed (see Table 5.1) using the following equation:

$$f = \frac{s}{\lambda} \tag{5.1}$$

where s is the scanning speed and λ is spatial wavelength. This was input for the lower and upper bounds which rendered dial B, which controlled frequency adjustment, disabled, safeguarding against accidental use during task A.

For experiment 2, (vibratory frequency and texture spatial wavelength matching), followed a similar format to experiment 1, except dial B was used to adjust the frequency of the square waveform with an upper bound of 400Hz. Dial A was disabled and set at the feature depth values as given in Table 5.1.

The final experiment allowed the participants to change both dial A and B with the lower and upper bounds described above to adjust both vibratory amplitude and frequency.

5.2.1.6. Analysis

The sensation matching values for all participants and experiments were collated. For experiments 1 and 2, descriptive analysis was performed. Mean values were reported to calculate the relationship factors between the stimuli amplitudes and frequencies to those chosen with the actuator. Experiment 3 was graphed to determine if when both dials are adjusted, similar trends to the former experiments were found.

5.2.2. Results

5.2.2.1. Experiment 1: amplitude sensation matching

In order to establish whether the surface feature depths of the stationary gratings could be identified and matched to the amplitude of the vibration delivered to the actuator, all judgement values chosen by the participants on both runs are plotted in Figure 5.2. No outliers were removed, or standardised values computed. The mean, standard deviation and multiplication factors are tabulated for the perceived amplitudes against the actual values in Table 5.2. Figure 5.3 shows that the perceived vibratory amplitude did not follow the relationship expected as shown by the linearity of feature depth (pink squares).

Table 5.2 Experiment 1 results

Stimulus	Actual feature depth (µm)	Mean perceived amplitude (µm)	Standard deviation	Multiplication factor
1	92	51.5	3.3	1.79
2	98	16.7	1.56	5.87
3	100	14.5	1.32	6.91
4	64	21.0	1.94	3.01

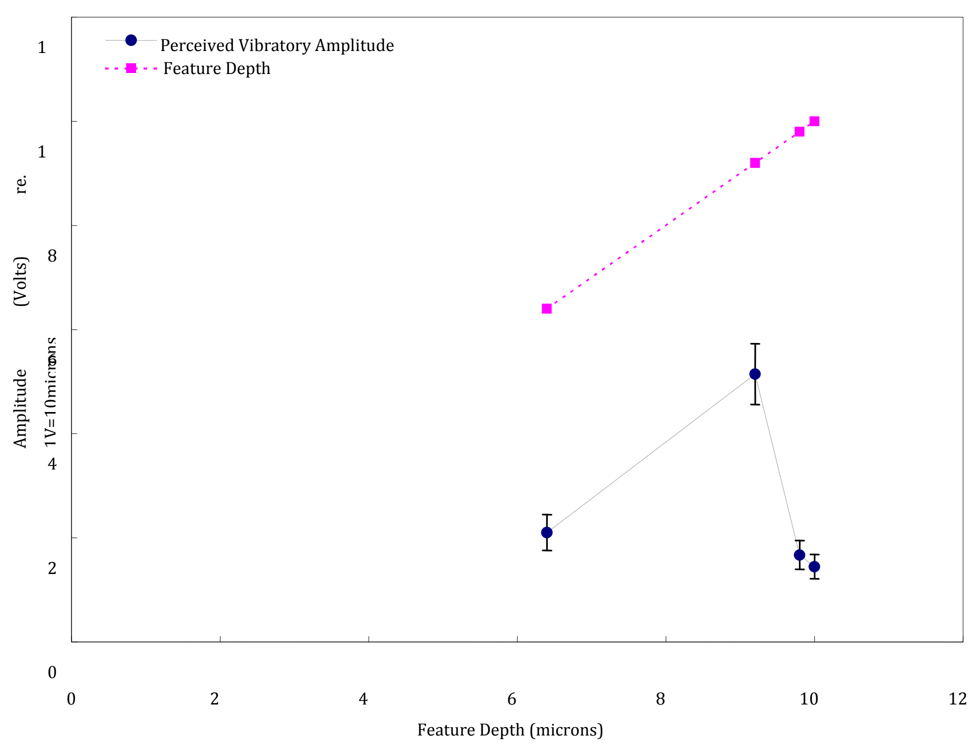


Figure 5.3 Perceived vibratory amplitude in Volts against the actual feature depth in microns. Standard errors for the feature depths of 64, 92, 98 and 100µm are 0.34, 0.58, 0.27 and 0.23 respectively.

5.2.2.2. Experiment 2: frequency sensation matching

In order to establish whether the spatial wavelengths of the stationary gratings could be matched to the frequency of the vibration delivered to the actuator, the perceived and actual frequencies were plotted against each other in Figure 5.3. No outliers were removed. The mean, standard deviation and multiplication factors are displayed Table 5.3. Figure 5.4 shows that the relationship between perceived vibratory frequency of the vibrating plate (blue diamonds), and the actual frequency of the grated stimuli (pink squares), as projected by equation 5.1, is more complex that anticipated.

Table 5.3 Experiment 2 results

Stimulus	Spatial wavelength (μm)	Mean perceived frequency (Hz)	Standard deviation	Multiplication factor
1	1540	150.7	78.8	4.6
2	996	236.1	84.3	4.3
3	801	260.0	66.3	4.2
4	650	233.2	88.5	3.0

5.2.2.3. Experiment three: amplitude and frequency sensation matching

Amplitude was plotted against frequency for each of the stimuli (Figure 5.5) using microns for the amplitude and feature depth values, and frequency for the vibratory stimuli and the spatial wavelengths of the stimuli.

The correlation coefficients for each of the stimuli showed that there were no relationships in the results across participants (stimulus 1, r=0.5549; stimulus 2, r=0.0152; stimulus 3, r=0.0426 and stimulus 4, r=0.0521) in choosing a particular frequency band or amplitude range.

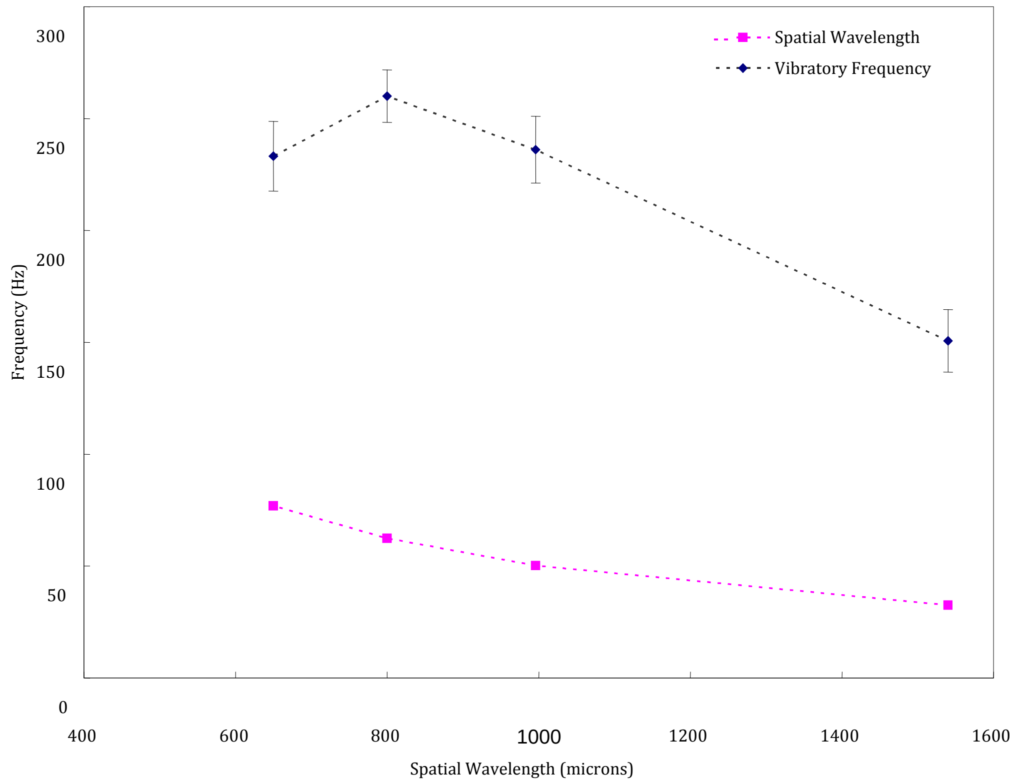


Figure 5.4 Perceived vibratory frequency in Hertz against the spatial wavelength in microns. Standard errors for 640, 801, 996 and 1540μm wavelengths are 13.9, 14.9, 11.7 and 15.6 respectively.

5.3. General Discussion

Analysis of the sensation matching data has shown that participants were only able to match frequency as shown in experiment 2, but this did not follow the simple relationship described in equation 5.1. Experiments 1 and 3 did not result in any correlations with amplitude or wavelength. A potential reason for these results could be due to the different neural mechanisms engaged by the two distinct modes of vibration, those of imposed and naturally generated vibrations through touching textures.

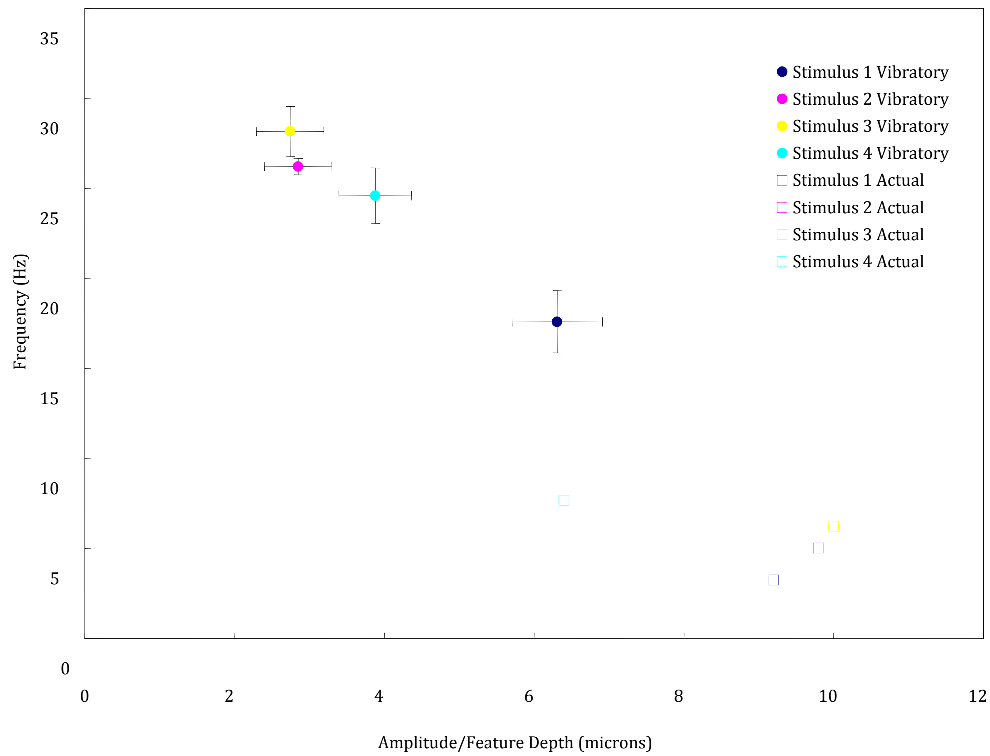


Figure 5.5 Perceived vibratory equivalent of the physical stimuli. Closed circles depict the vibratory estimations and the open squares show the physical stimuli values. Standard errors for the amplitude for stimulus 1-4 are 6.0, 4.5, 4.5 and 4.8, and for frequency are 17.3, 14.3, 13.8 and 15.3 respectively.

High frequency vibrations, namely in the range of 40Hz to 400Hz are mediated by the PC system (Bolanowski *et al*, 1988) which are either generated by movement across a fine textured surface with a spatial period of less than 200µm (Bensmaia and Hollins, 2003) or by stimulating the corpuscles with a vibrating contactor (see section 2.4.1.). For stimulus 1, which had the lowest predicted frequency, there was an observed divide in the data between the four participants (Figure. 5.6). Taking this range into consideration, the vibrations generated by the finger across stimulus 1, which was calculated to be 32.5Hz, did not sit in the PC receptive field and may explain the divided judgement frequency values. It is speculated that participants 1 and 2, who selected higher values, may have employed a slightly faster scanning speed or that their thresholds for vibration sensitivity may be different. Morley and Rowe (1980) reported much larger differences in their participant's thresholds for lower frequencies in comparison to higher frequencies.

The RA system, which is responsible for localised movement, processes vibratory stimulation between 4-40Hz (Bolanowski *et al*, 1988). It could also be suggested that the responses for stimulus 1 may have been more strongly mediated by this system for participants 3 and 4 who selected much lower frequencies. More recent documentation (Johnson *et al*., 2000; Johnson, 2002) suggest that the RA system is more suited to the detection of slip between an objects and the hand, therefore providing feedback grip. Nevertheless, low frequency vibrations would be generated, therefore mediated by the rapid adapting corpuscles.

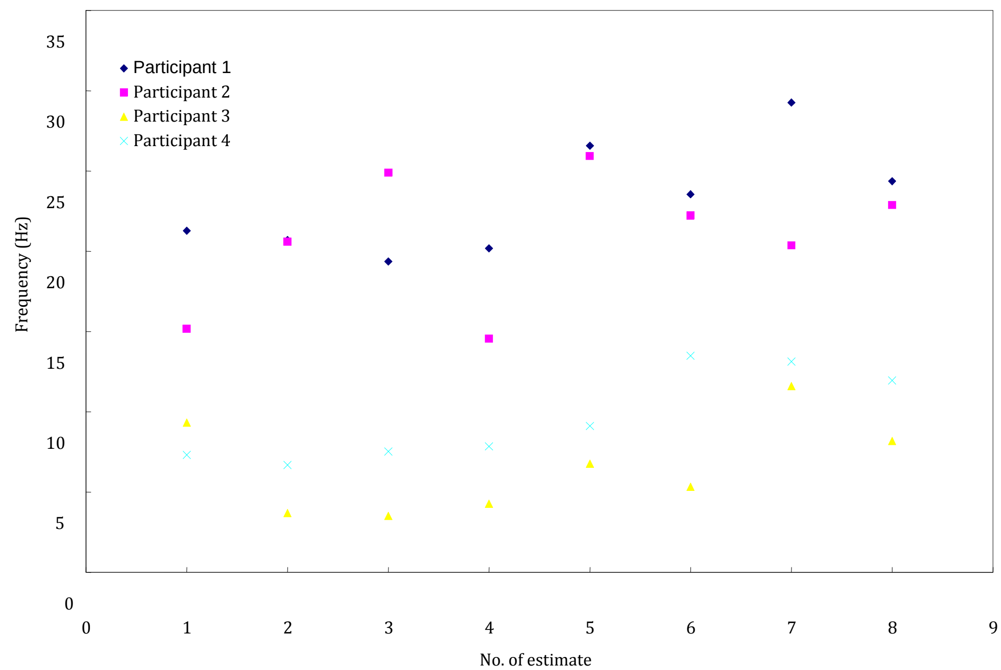


Figure 5.6. Results from Experiment 1: frequency sensation matching for stimulus 1, which shows the difference in frequency estimation between participants 1 and 2, and 3 and 4 who's mean chosen frequencies were 231.6Hz, 208.3Hz, 65.9Hz and 96.3Hz respectively.

The PC and RA mechanoreceptive systems would have been operational in both scanning the grated stimuli and the piezo mounted surface. There is, however, a third afferent system which is activated during the dynamic touch of a surface texture. The SA I system is responsible for the spatial perception of coarse texture and for force distribution on the fingertip (see section 2.3.2.). In this present study, the participants were asked to run their finger across a grated stimulus, which would include the SA I afferents, whereas it is reasonable to say that the imposed vibrations most probably did not. It is acknowledged that these spatial mechanisms are dominant in texture discrimination which is evident in the results of this present study by how the matching frequencies for each texture stimulus varied with spatial wavelength, albeit at a four-fold increase.

It could also be concluded that this four-fold increase in frequency judgements in experiment 2 is simply due to the way the vibrations are generated. Stationary stimuli vibrations are produced by tangential and normal forces whereas the actuator produces a vibration in the z-direction, to which the finger scans laterally which consequently adds another frequency element – the scanning speed. The scanning speed could account for the mean four-fold increase in frequency perception. The differences could also be because of the way the finger experiences the vibration. When the finger is run across a surface, vibration patterns are produced across the fingerpad at different times. When the fingerpad experiences the imposed vibration, the same vibration pattern is experienced across the entire surface at the same time. This difference may also account for the differences in perceived frequency.

A key point raised in conversation after completion of all experimental runs was how the participants were making their sensation judgements. All participants reported a similar method which related directly to one of the established continua of touch perception; roughness (Hollins *et al*, 1993). Participants reported that in experiment 1, they increased the amplitude in accordance with a higher perception of roughness. In experiment 3, the dial was moved to follow a reduction in frequency as *roughness* increased, and applied a mixed method for experiment 3. A large body of research has been conducted in the field of *roughness* perception. In summary of these investigations, the most notable fundamental conclusions drawn by Lederman and Taylor (1974) show that with grated stimuli, subjective *roughness* and spatial period share an almost linear relationship. In other words, as spatial period increases, so to does subjective *roughness*. To this end, frequency is inversely proportional to *roughness* perception; therefore results obtained in experiment 2 of this present study are consistent with this theory.

Further to this hypothesis, Lederman (1974) shows that contact force provoked an increase in *roughness* perception. She also documents that in natural scanning mode, most subjects employ a force of approximately 1N. It can be surmised then that the possibly variations in contact force used by the participants in experiment 1 could explain the degree of variability in their chosen amplitude settings. Green *et al*. (1979) discuss the concept of 'bottoming out' which refers to the finger being able to feel the bottom of the valleys between textural elements. No known published data gives any physical measurements or parameters for this.

To investigate this theory further and to attempt to understand the variability in the amplitude matching experiment, a finite element model was used to evaluate skin penetration into the stimulus grooves. A finite element model of the human finger was pressed against each of the grated surfaces with an arbitrary depth (Figure 5.7) and revealed that the maximum finger penetration of the skin with a 2mm compression of the tissue (or approximately 1.5N normal force) would not allow the participants finger to fully feel the bottom of the valleys. Table 5.4 shows these values.

Table 5.4. Finite element modelling predictions against the actual stimuli values used in this present study.

Stimulus	Feature spacing (μm)	Feature depth (μm)	Predicted penetration depth (μm)
1	770	92	90
2	498	98	74
3	400	100	73
4	325	64	64

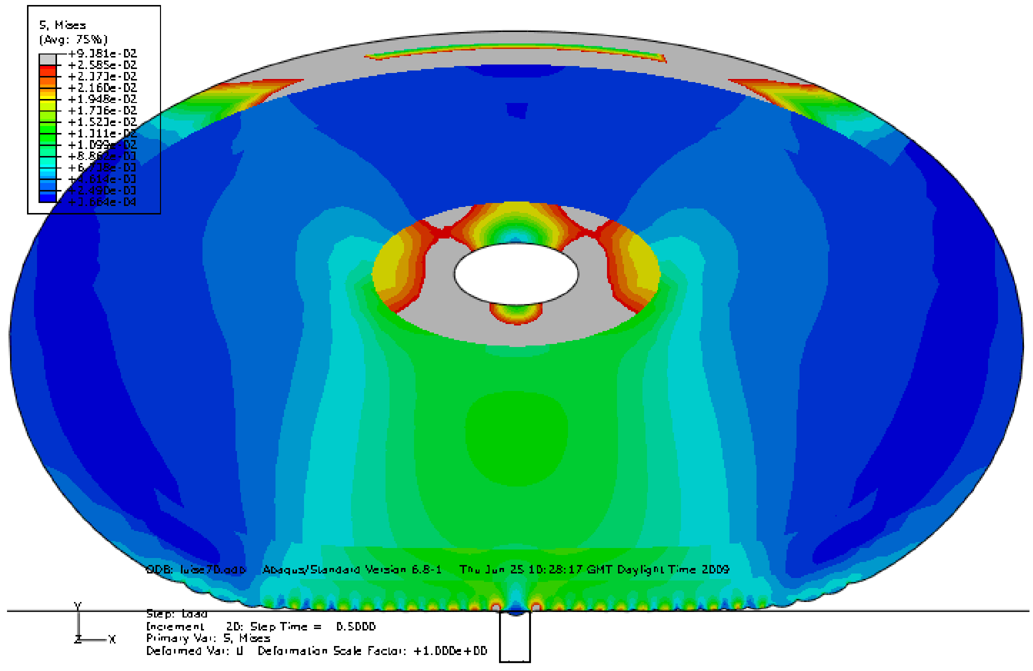


Figure 5.7. Finite element model of the finger being pushed at a 1.5N force against a grated stimulus. The legend denotes stresses in the fingertip. These are not necessary in this present study. Courtesy of Dr. Fei Shao of the University of Leeds. Finite element model is described in Shao, Childs, Barnes and Henson (2010).

Smith *et al* (2002), reports the role of friction and tangential forces in subjective *roughness* judgements and found that these factors, taken alone, do not correlate with subjective *roughness*. Kinetic friction did prove to yield moderate correlations (0.64) but this value was only true for half of the participants which render the hypothesis inconclusive. However, Smith *et al*'s analysis of the rate of change of tangential force (associated with kinetic friction), correlates much more robustly with *roughness* judgments. The coefficient is reported to be 0.88 for all participants, who all use different scanning forces which add to the efficacy of the prediction model of the subjective scaling of *roughness*. Given that the spatial periods here start from 1500µm, this model may not be applicable to the results reported for amplitude in experiment 1, especially as Smith *et al.*'s subjects were able to feel to the bottom of the texture valleys.

This does lead to questioning of the role of normal and tangential forces employed by the participants to explain the results of experiment 1. Nefs *et al.* (2002) report that in their experiment for line frequency discrimination, subjects apply different normal forces which increases with line frequency as a way for further discriminating the differences between stimuli. As participants were asked in the intensity matching tasks to maintain a constant pressure, it is further concluded that they were unable to distinguish between the different grating feature depths.

5.4. Summary

The results reported for all sensation matching experiments show that it is possible although to a limited extent, to relate vibration generated by dynamic touch of stationary gratings and those imposed mechanically by an actuator. There was no reported relationship between the amplitudes. It is hypothesised that the missing spatial processing aspects of touch in the actuator vibrations and the participants' inability to feel the bottom of the feature valleys may be the reason for this. Frequency displayed a strong, yet complex, relationship across the vibration types. It is speculated that this could be by large due to scanning speed and possibly the way in which the vibrations stimulate the fingertip. Both amplitude and frequency adjustment strategies employed by the participants appeared to rely largely on their perception of *roughness*. This is key finding in this experiment that without being asked to form a textural assessment of the task, participants uniformly chose to use *roughness* to perform the task. Finally, no correlations were found when both components of vibration were adjusted by the participants.

These results indicate that the relationship between how imposed vibration and those generated by active touch of a grated surface texture are processed is complex. It is hypothesised that not only are the physical mechanisms different such as the involvement of SA I type afferents, but also the temporal processing element which is related to how the vibration is received on the finger pad. By this it is meant that in texture scanning, vibrations tend to travel across the wave as the skin interacts with the texture features, whereas imposed vibration happens in the same way across the whole fingerpad at the same time. It is these differences that need to be taken into consideration when applying a vibration to surface texture. Furthermore, this experiment showed that there are differences in response across subjects. This was specifically highlighted by in experiment 2 and the frequency matching of stimulus 1 to a vibratory frequency. The divide discussed, centred on the assumption that 40Hz is the frequency at which Pacinian corpuscles become more dominant in perception. It could be concluded by the results that this may not be as clear a divide in humans and they way their mechanoreceptors and tuned. There may be a larger window of receptor dominance transition than indicated by the literature.

Chapter 6

Affective responses to vibrating tactile textures

6.1. Experiment rationale

In Chapter 3, it was hypothesised that vibration could communicate affect through textured surfaces, specifically the magnitude of the vibration. Low frequency vibrations proved to be a strong candidate for the perception of *warmth*, *good quality* and *sophisticated*, but predictions about high frequencies could not be made. Chapters 4 and 5 investigated the effect of applying vibration to the finger with a piezo actuator. In Chapter 4, a broad range of frequencies were used (35-400Hz), and it was established that the perceptual dimensions of *softness* and *roughness* could be communicated through vibration, as well as establishing that the piezo actuator was a successful way to impose vibration to the whole fingerpad. To investigate whether vibratory and texture elicited vibration are perceived similarly, a sensation matching task was undertaken in Chapter 5. Results showed that although texture feature depth and vibratory amplitude could not be matched, spatial wavelength and vibratory frequency could be matched, albeit with a four-fold difference.

Hollins *et al*. (2000a) considered applied vibration with dynamic touch and textural perception. Hollins *et al*.'s exploration into the hypothesis that if vibration is central to texture perception (then perceptual manipulation is possible) resulted in two findings. Firstly, that increasing the amplitude of the imposed sinusoidal waveform to a grooved stimulus decreased subjective smoothness compared to the stationary condition. Secondly, that regardless of frequency the vibrating stimulus was rougher in comparison to no vibration at all. Very little subjective difference between the frequencies and smoothness perception was reported. Hollins *et al*. demonstrate the efficacy of the application of vibration to influence texture perception by means of an intensity code determined by the amplitude component of a waveform. The study, however, did not explore the effect an imposed vibration had on the vibratory spectrum of the grooved stimulus, or how imposed vibration contributes to the other perceptual continua or affective and hedonic properties.

Taking this into consideration, this present study aimed to establish whether applied vibration could affect participants' responses to different surface textures. Specifically, this study aimed to elucidate (1) whether imposed vibrations can change the perception of the psychophysical textural dimensions of *warmth*, *roughness* and *stickiness*, and (2) if this is possible for the affective adjectives of *good quality*, *sophisticated*, *exciting*, *unique* and *warmth* explored in Chapter 3. To this end, 35Hz and 200Hz vibrations with three different zero-to-peak amplitudes (10μm, 30μm and 43μm) with the addition of a stationary condition were applied to four textured surfaces.

6.2. Experiment 1: Effect of imposed vibrations on perception of *warmth, roughness* and *stickiness.*

The aim of this first experiment was to test the methodology used here against the results of Chapter 3, which found that perception of smoothness was related to amplitude of imposed vibrations. In this present study, participants were required to make subjective magnitude estimations (Zwislocki and Goodman, 1980) to test stimuli against the perception of *warmth*, *roughness* and *stickiness*. The percept of hardness was not considered, because all stimuli were made of the same material, and it was assumed that the hardness of the stimuli would be perceived as being the same.

6.2.1. Method

6.2.1.1. Participants

Eleven male undergraduate and postgraduate students, between 18 and 24 years old, were recruited through an email advertisement to participate in all three experiments. Participants were given a small cash gift to compensate them for their time.

6.2.1.2. Stimuli

The stimuli consisted of four 60mm diameter black ABS plastic plaques which were selected from Chapter 3. These stimuli were chosen because they displayed sufficient differences in texture and profile structure for analysis (Figure 6.1). Stimulus 1 (smooth) was chosen as an example of a microstructure texture which, visually, has little discernable patterning. Stimuli 2 (circle) and 3 (square) had homogeneous textural characteristics in both feature depth and spacing, whereas Stimulus 4 (rough) displayed no consistency in either depth or spacing, thus being a stimulus with heterogeneous characteristics.

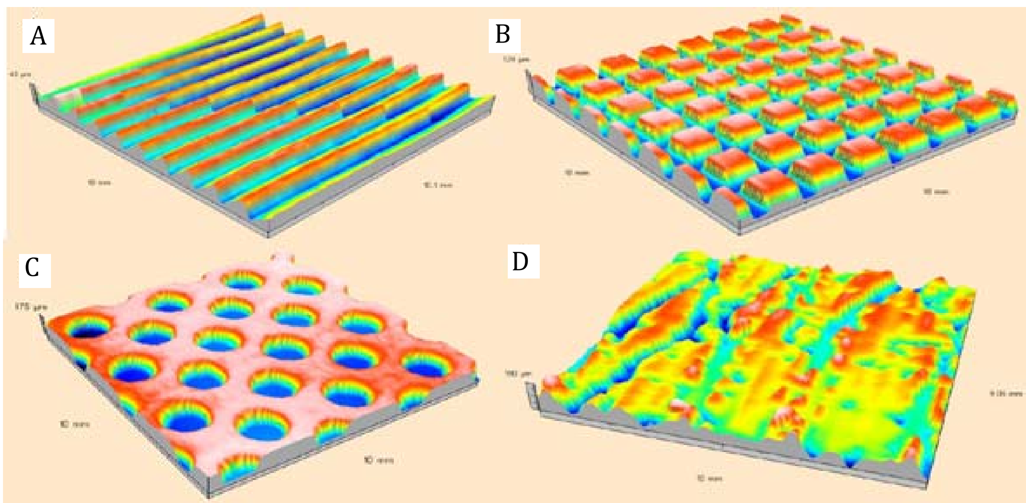


Figure 6.1 Three-Dimensional representations of test Stimulus 1 (smooth), Stimulus 2 (circle), Stimulus 3 (square) and Stimulus 4 (rough). Traces were taken using a commercial stylus surface profilometer (RTH Form Talysurf 120L) from a 10x10mm section of each stimulus. The scale is not the same for each of these images.

Two sinusoidal test frequencies were chosen. As little is known about vibration and tactile texture perception below 150Hz, 35Hz was chosen as the first test frequency, and 200Hz the second based on the knowledge that these two frequencies are mediated by different receptor afferents, the RA and PC channels. Previous research suggests that amplitude influences the perception of *roughness* (Hollins, Fox and Bishop, 2000; Hollins and Bensmaia, 2003); therefore three amplitudes were chosen for the investigation. These were selected from the test stimuli's peak-to-valley heights. The amplitudes chosen were 20, 60 and 86μm peak-to-peak displacements, the same as Chapter 4. These values came from the average feature depth value of

Stimulus 2-4 in this present study. The seven conditions of amplitude and frequency for the experiment can be found in Table 6.1.

6.2.1.3. Apparatus

Each of the stimuli was mounted on circular steel bases which were screwed onto a piezoelectric actuator (Piezomechanik PSt 150/5/100VS10 VAg with position detection). The sinusoidal waveforms were generated by a Labview (National Instruments) program and were delivered to a voltage amplifier via an 8-port DAC card (National Instruments PCI 504E). The voltage amplifier (Piezo Systems EPA – 104) was used at a gain of 10 to produce a signal operating range of ±5V (or ±50μm amplitude) to drive the piezoelectric actuator with a 3V offset. A slight time delay, of approximately 1 second, was present during the conversion stage. Each exploration of the stimulus was therefore not started until 5 seconds after each condition had been initiated.

The piezoelectric actuator was mounted below the surface of a table, in a 70mm diameter hole, so that each stimulus sat approximately 10mm above the surface of the table.

6.2.1.4. Procedure

Before entering the laboratory, the experimenter explained to participants what was to be expected during the session, what they were going to see in the room, and instructions regarding their task. A description of absolute magnitude estimation was given. The participants were informed that they could use whole numbers, fractions or decimals, but were restricted to the use of positive numbers and to avoid zero. The example of two lines was used to illustrate the scaling method (Zwislocki & Goodman, 1980). Participants were not informed that vibration would be applied to the textured stimuli and so were naïve to the objectives of the experiment.

On entering the laboratory, each participant was asked to sit on a chair that faced the experimenter. The experimenter sat behind a curtain to ensure that participants could not see the stimuli and the experimenter. In front of the participants was a folder in which the documents for the experiment could be found. On each of the three sheets was a table; the column headings of which were the adjectives (*warmth*, *roughness* and *stickiness*), and the rows indicated the number of the stimulus. Participants were instructed to wear headphones for the 40 minute duration of the experiment, through which pink noise was played to mask the sound of the piezo-actuator.

Table 6.1 Conditions of vibration applied to each stimulus. Condition 7 represents the stationary condition where no vibration was applied.

Condition of Vibration	Amplitude(zero-to-peak, μm)	Frequency (Hz)
1	20	35
2	60	35
3	86	35
4	20	200
5	60	200
6	86	200
7	-	-

The participants were instructed to reach under the curtain and touch the stimulus. They were then required to evaluate each stimulus against the adjectives on the sheets using magnitude estimation. There were only two restrictions placed on the touching process: that the participants were not to leave their finger stationary on the stimulus at anytime, and to maintain a constant scanning speed. They were permitted to use any finger and scanning pattern to encourage their natural method of touch. The participants were instructed to remove their hand from the table completely when they had finished their exploration of the stimuli.

Each run consisted of three blocks. The first block was a practice block for the participant to use magnitude estimation using the same conditions as the actual test. The further two contained 28 test conditions each in a random order, generated by a VBA macro in Excel (Microsoft, 2003), and were used for data analysis.

6.2.1.5. Analysis

The magnitude estimation method of scaling was used in this experiment. Each participant used their own numerical scales, which meant that the data for each participant needed to undergo a normalisation procedure before statistical analysis could be conducted, similar to that described in Section 4.1.3.5. The data was firstly converted to log values; the offset was calculated by subtracting each participant's overall log mean from the overall mean (from all participants). Then, each participant's offset was added to the individual log scores, and the antilog was calculated. The Kolmogorov-Smirnov test was used to check for normal distribution in the data and revealed that it was not present in this experimental dataset. Friedman ANOVA was therefore used to determine if applied vibration could sufficiently manipulate participants' perception of each of the four surface textures.

6.2.2. Results

Friedman ANOVA reported no significant differences in participant ratings for each of the four textured stimuli – smooth (χ^2=2.587, df=6, p=.859), circle (χ^2=7.895, df=6, p=.246), square (χ^2=8.208, df=6, p=.223), and rough(χ^2=4.269, df=6, p=.640) – when a vibration was applied for the perception of *roughness* (Figure 6.2).

For the perception of *warmth*, shown in Figure 6.3, for smooth (χ^2=4.511, df=6, p= .608), circle (χ^2=6.092, df=6, p= .413) and square (χ^2=2.663, df=6, p= .850) there were no significant changes in ratings with applied vibration. However, for the rough stimulus, there was a significant difference in ratings with applied vibration (χ^2=12.552, df=6, p< .05). Wilcoxon signed rank analysis was used to conduct pairwise comparison to show specific differences between the vibratory conditions. With a significance level of p< .007 (which is the regular p< .05 divided by the number of conditions, 7), pairwise comparisons revealed that the vibration 3 (43µm and 35Hz) and vibration 6 (43µm and 200Hz) were the most different (Z=-2.521, n=11, p= 0.004, two-tailed).

Finally, for the perception of *stickiness* (Figure 6.4), no significant differences with the application of vibration were found in participant ratings for each stimulus – smooth (χ^2=11.009, df=6, p= .088), circle (χ^2=5.906, df=6, p= .434), square (χ^2=2.091, df=6, p= .911) and rough (χ^2=4.191, df=6, p= .554).

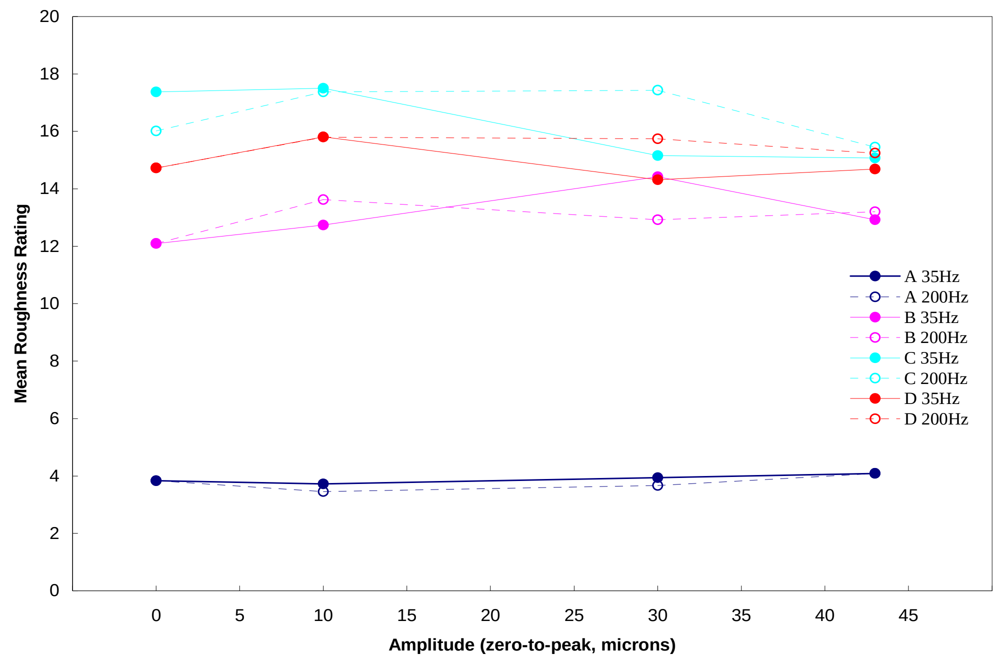


Figure 6.2 ***Roughness*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

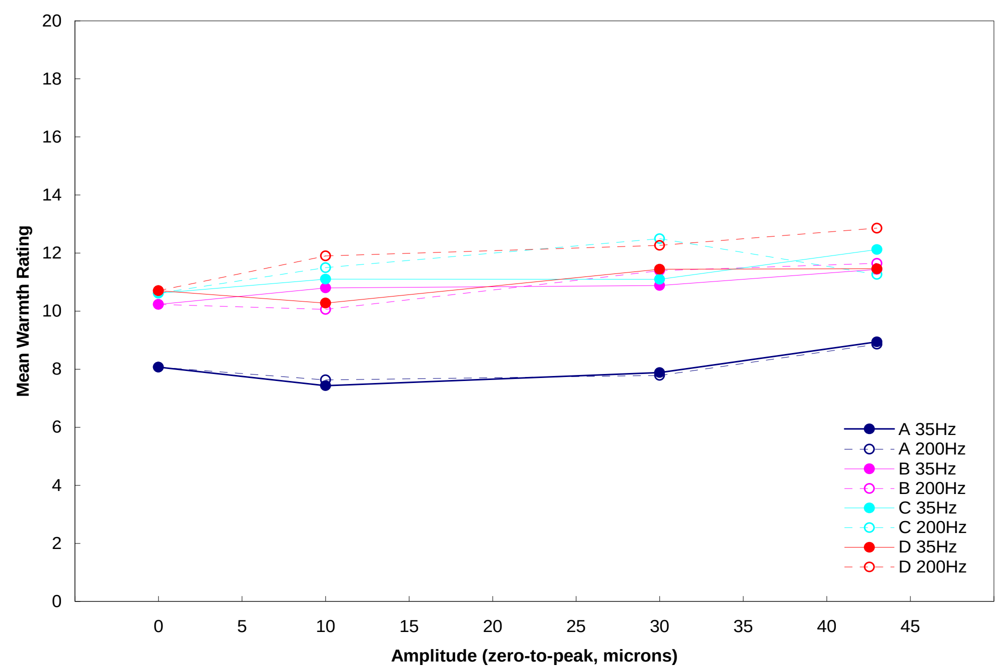


Figure 6.3 ***Warmth*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

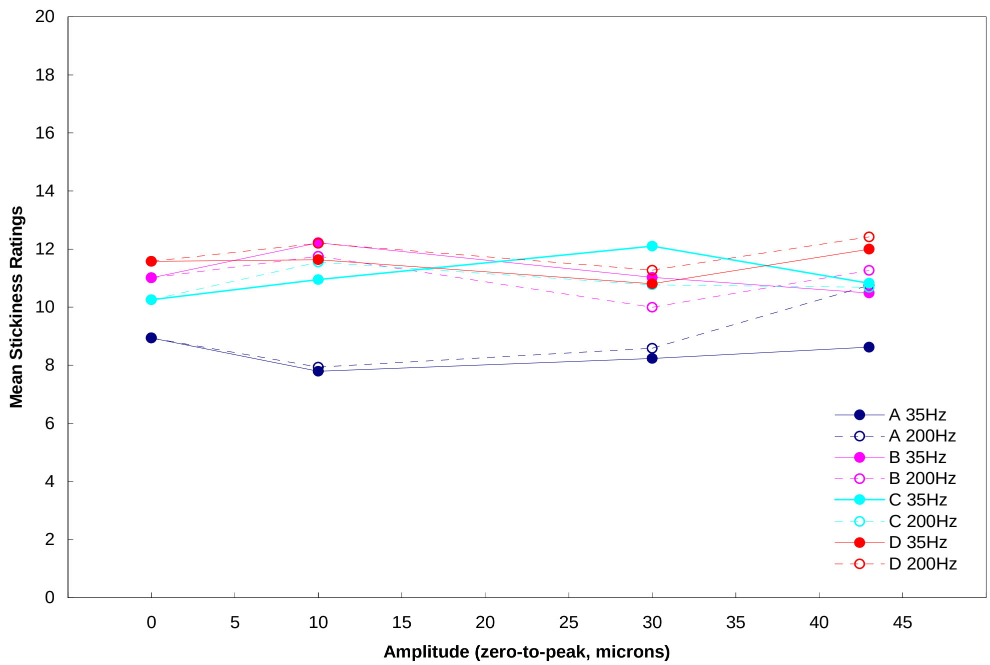


Figure 6.4 ***Stickiness*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

6.2.3. Discussion

No single variable in this experiment was responsible for the changes in subjective ratings for *warmth*, *roughness* and *stickiness*, suggesting that different factors more than vibration and surface texture properties contribute to the perception of each of these textural continua.

Friedman ANOVA confirmed that applied vibration had no significant effect on subjective *roughness* across all stimuli. Contrary to previous research, however, no evidence was found that the amplitude of imposed vibrations affected perception of *roughness*. According to Hollins *et al*. (2000a), the subjective rating of *roughness* is not affected by the frequency of an applied vibration to a grated stimulus and that subjective *roughness* was a function of vibratory intensity. It was seen in this present study that neither vibratory amplitude nor frequency could manipulate the perception of *roughness*. Hollins *et al*. (2000a) did not use a frequency lower that 150Hz, therefore the difference reported here for the smooth tile and 35Hz vibration cannot be directly compared. It is, however, seen that there are differences between the ratings for the smooth stimulus and the patterned ones. This seems to suggest that the spatial features of the stimuli were driving the responses of the participants, a hypothesis that has been put forward by Lederman (1982) in that spatial processing is dominant in *roughness* perception of coarse textures and not the vibrations caused.

For *warmth* perception, results in this present study showed that when vibration was applied to the topographically roughest stimulus, perception could be altered. It can be seen in Figure 6.3 that for 30μm and 43μm displacements that 200Hz is perceptually warmer than 35Hz. This could potentially align with the results of Bensmaia and Hollins (2005), who reported a marginally significant difference between the spectral amplitude of fine textured surfaces and the subjective *warmth* ratings of their participants, despite hypothesizing that *warmth* was highly unlikely to be attributed to a vibratory code.

The differences between the smooth and the textured stimuli on *warmth* perception may be due to the effect that the textures have on the contact area of the finger with the stimulus. It would seem logical that rougher textures reduce the contact area and that the cooling rate of the finger would be slower for a smaller contact area. Jones and Ho (2008) explored temperature cues in a virtual environment by considering the way in which the skin interacts with thermal stimuli. They established that the skin has poor spatial resolution and that processing of thermal stimuli is based upon summation intensity over space. In other words, increasing the area of thermal stimulation increases the perception of both warm and cool temperature intensity. Furthermore, as the area of thermal stimulation increases, the detection threshold decreases. This, taken with the findings that if thermal stimuli changes within the band of 30-36°C it can only be detected if the rate of temperature change is rapid (Jones and Berris, 2002), could explain the differences between the smooth and textured stimuli in the present study. To that end, if the contact area is directly linked to intensity perception, then the rate of change would be hard to distinguish due to spatial summation.

Bensmaia and Hollins (2005) found that in fine texture analysis, ratings of *stickiness* were significant predictors of perceived dissimilarity between stimuli and that the vibration elicited by touch may convey in part, this particular textural continuum. With respect to the imposed vibration and *stickiness* in this present study, a complex relationship, again, appears to exist with the introduction of macro textured stimuli.

6.3. Experiment 2: Effect of imposed vibrations on affective responses

The aim of this experiment was to determine whether imposed vibration affect people's affective responses against the adjectives of *good quality*, *masculine*, *warmth*, *exciting*, *sophisticated* and *unique*.

6.3.1. Method

6.3.1.1. Procedure

A similar procedure to Experiment 1 was used, except that participants were given a context for their ratings of car interiors (Chapter 3), and the stimuli were rated against a set of affective adjectives. The context was introduced before the experiment started by asking the participants to make their judgements about the dashboards and control panels of the drivers cockpit. This was supported by activities that involved touching and discussing fittings from car interiors. Absolute magnitude estimation was used again, but the adjectives in this experiment were: *exciting*, *good quality*, *masculine*, *sophisticated*, *unique* and warm. These were presented in a random order, which was *unique* to each participant to decrease the probability of order bias. In this experiment, two blocks of data were recorded.

6.3.1.2. Data Analysis

As in Experiment 1, Friedman ANOVA was used to analyse the data.

6.3.2. Results

For the perception of *good quality* (Figure 6.5), no significant differences for each of the textured stimuli were found in participants ratings. This was also the case for *masculine* (Figure 6.6) and the perception of *warmth* (Figure 6.7).

For the perception of *exciting* (Figure 6.8), significant differences were reported in the subjective rating for circle (χ^2=18.254, df=6, p< .006). Wilcoxon pairwise comparisons showed a strong difference between vibration 1 and vibration 5 (Z= -2.845, n=12, p= 0.001, two-tailed). The square stimulus also showed significant differences

(χ^2=19.860, df=6, p< .003), with pairwise difference between vibrations 3 and 4 (Z= -2.510, n=12, p= 0.005, two-tailed) and vibration 3 and 2 (Z=-2.490, n=12, p= 0.005, two-tailed). For the rough stimulus, significant differences in ratings were also found (χ^2=14.398, df=6, p<. 025) and a pairwise difference between vibration 5 and the stationary condition (Z=-2.943, n=12, p= 0.001, two-tailed).

No significant differences in ratings and vibratory condition were found for the perception of *sophisticated* (Figure 6.9), however for the perception of *unique* (Figure 6.10) significant differences for both the circle ratings (χ^2=13.947, df=6, p< .03) with pairwise significance between vibrations 3 and 5 (Z=-2.667, n=12, p= 0.002, two-tailed) and the square stimulus (χ^2=14.533, df=6, p< .024). Pairwise comparisons revealed significant difference between vibrations 3 and 4 (Z=-2.756, n=12, p=0.001, two-tailed) and vibrations 4 and 6 (Z=-2.667, n=12, p=0.002, two-tailed).

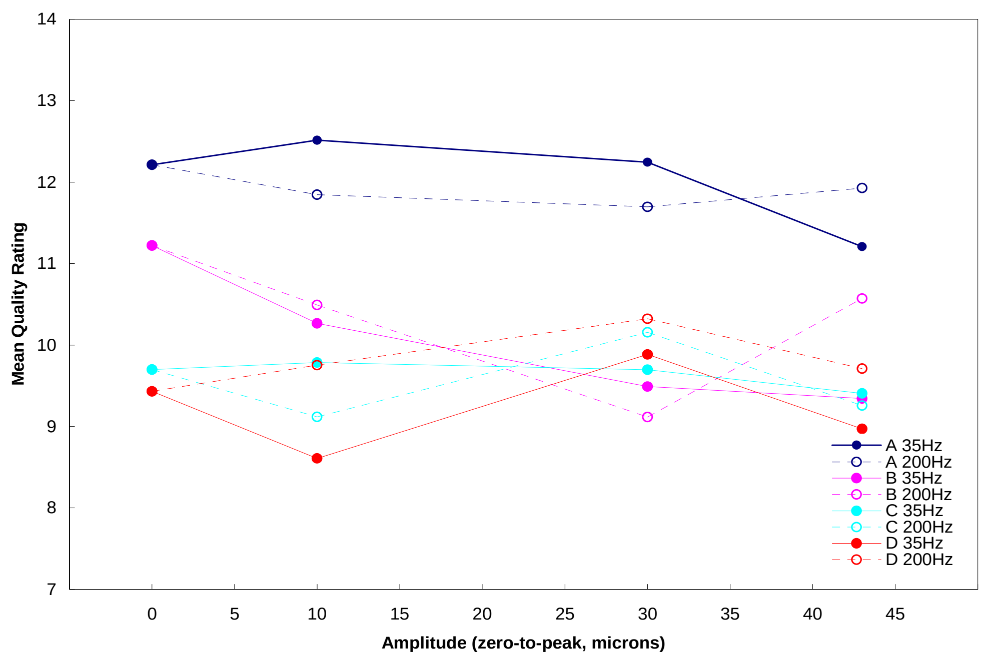


Figure 6.5 ***Good quality*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

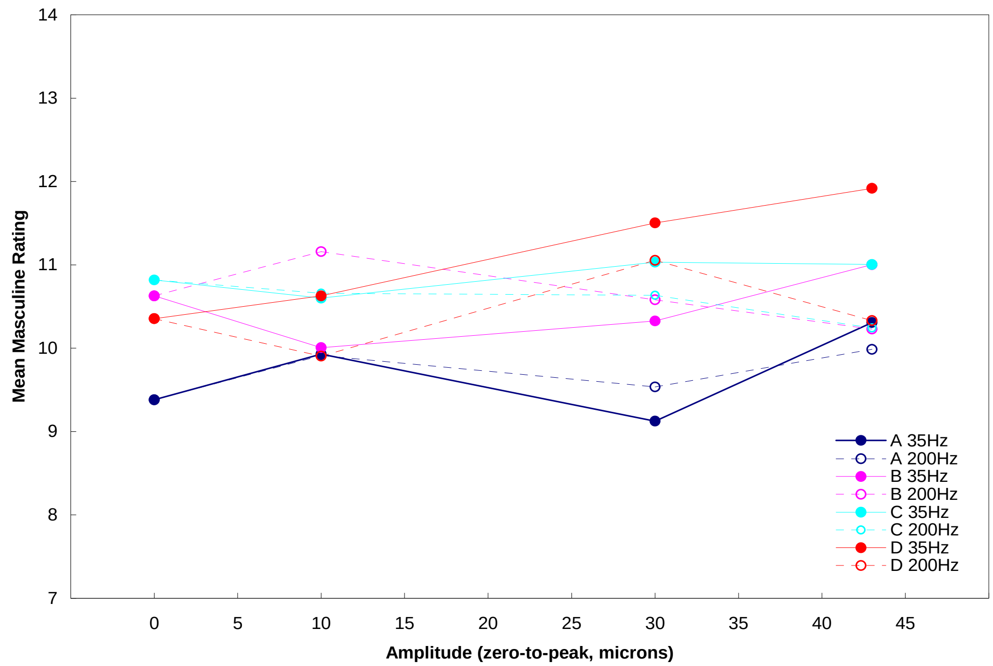


Figure 6.6 ***Masculine*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

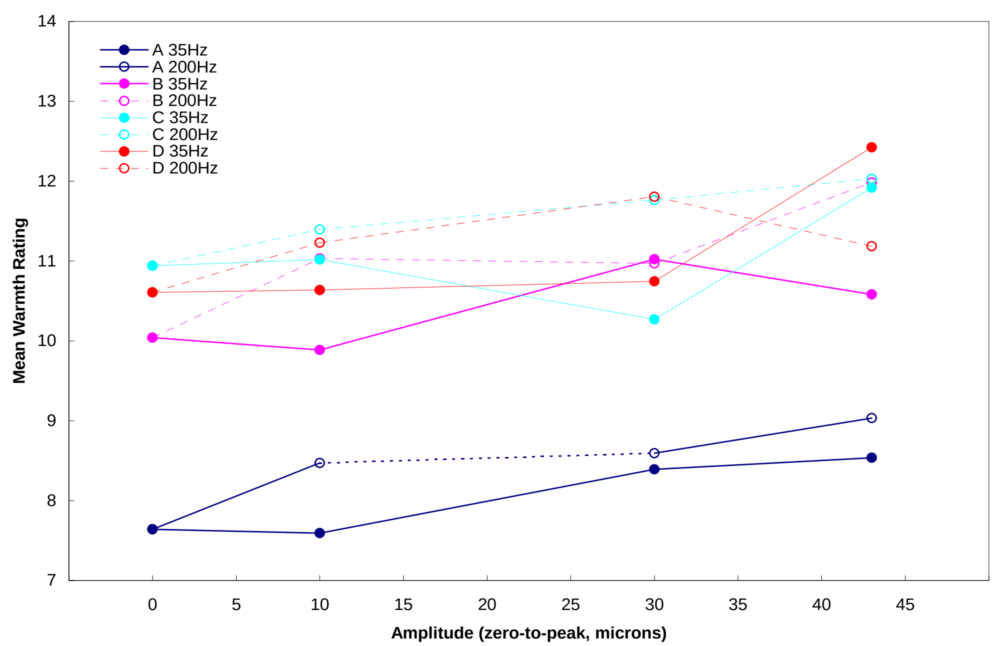


Figure 6.7 ***Warmth*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

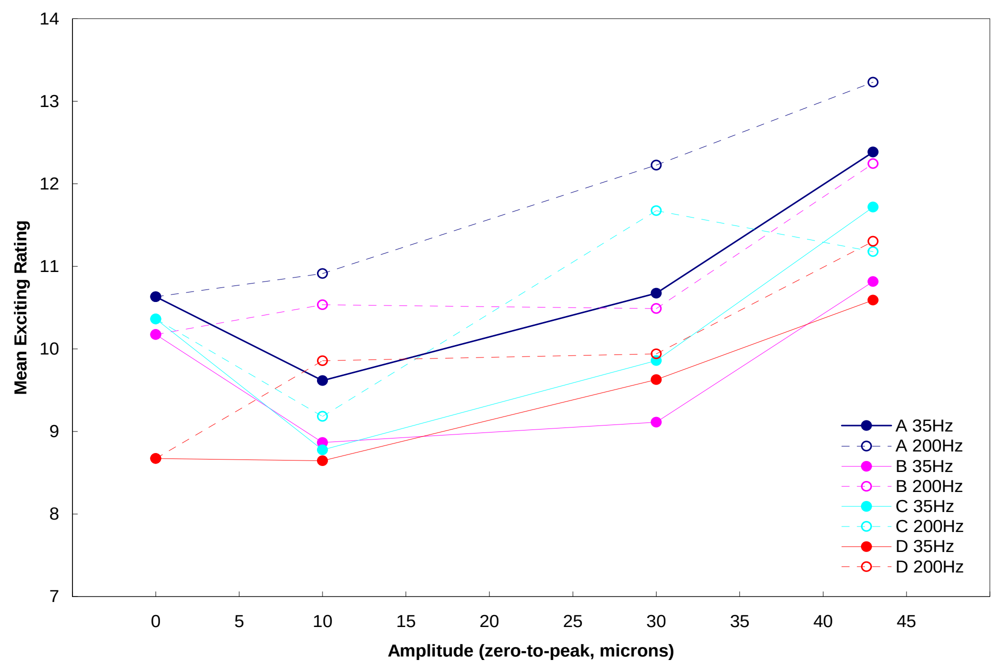


Figure 6.8 ***Exciting*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

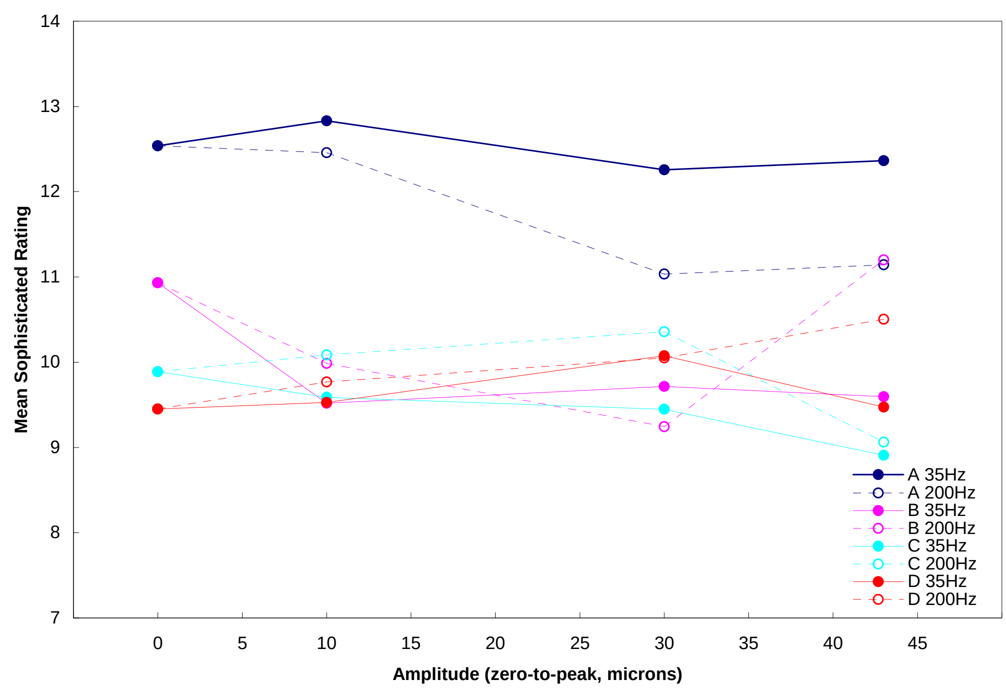


Figure 6.9 ***Sophisticated*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

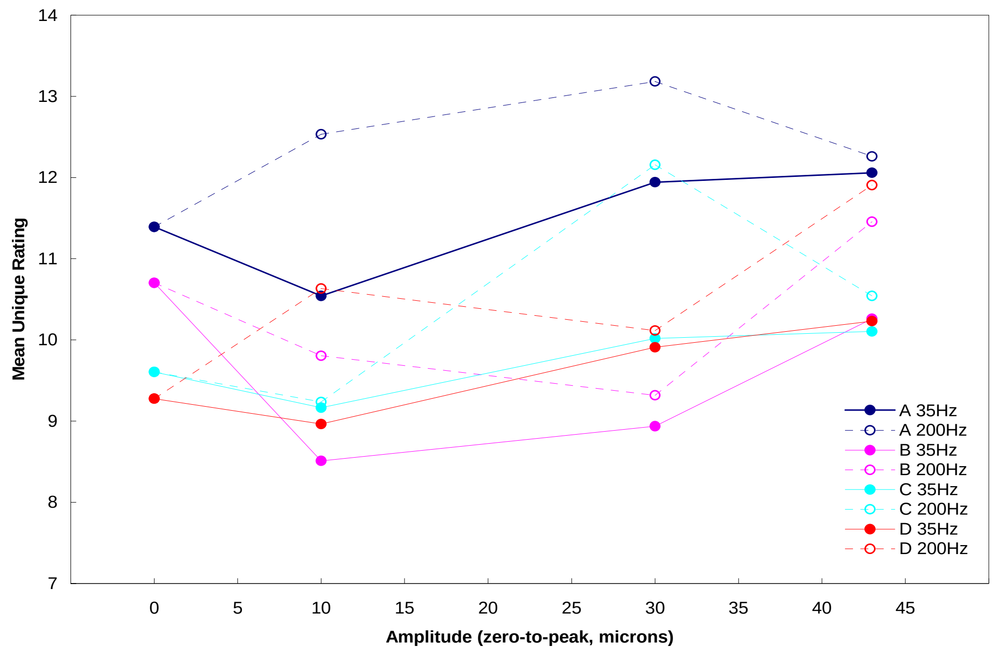


Figure 6.10 *Unique* ratings for all four textured stimuli with applied vibration and the stationary condition

6.3.3. Discussion

In this second experiment, no evidence was found that vibration had an effect on participant's ratings against *warmth* across all textured stimuli. This contrasts with the results of Experiment 1 where significant differences were reported for the rough stimulus. *Warmth* was rated by the participants in this experiment in the context of vehicle interiors, unlike the first context-free experiment. Also, each adjective was presented to the participants in a random order in this second experiment; therefore the position in the order was always different, whereas in the first experiment *warmth* was always the first subjective rating for each stimulus. Lederman and Jones (2006), and Jones and Ho (2008) suggest that decisions based on temperature perception take in the order of 900ms. Taking into consideration the cooling rate of the finger when it comes into contact with a room temperature stimulus - or the subsequent warming of the stimulus - the positioning of the adjective in the experiment may have caused this difference. Alternatively, the differences may have been caused by memory or familiarity effects. To this end, Experiment 3 was run to account for cooling rate and the time take to make temperature related ratings. In the third experiment, *warmth* to be always the first adjective, and the other five followed in a randomized order.

The scores for *good quality* were similar to those for *sophisticated*; both were insignificant with respect to applied vibration. In an experiment that investigated physical attributes which could explain affective ratings of textures, Chen *et al*. (2009a) found that sophistication was not related to perceptual dimensions and it was speculated to be part of a higher affective adjective layer. The fact that in this present experiment, *sophisticated* was not a function of vibration also suggests that it could be part of a higher order processing system, such as that linked to experience.

The ratings against *exciting* were affected by the applied vibration. Looking specifically at the interactions between conditions, it appears that the significant differences may be led by the vibratory frequency. This can be seen in Figure 6.8. The ratings for *unique* were only affected by imposed vibration for the uniformly patterned stimuli; circle and square. The pairwise comparisons for *unique* suggest that both amplitude and frequency could play a part in these differences in rating (Figure 6.10).

6.4. Experiment 3: Investigation of order bias on effect of imposed vibrations on affective responses

In the second experiment, no evidence was found that the amplitude of the imposed vibration affected people's ratings against *warmth*. This contrasted with the results of the first experiment. A third experiment was therefore devised to investigate the difference in ratings against *warmth*. In the first experiment, *warmth* was always the first of the three adjectives against which the stimuli were rated, whereas *warmth* was placed randomly on the questionnaire in the second experiment. In order to investigate the order bias of ratings of *warmth*, a third experiment was conducted in which the adjective *warmth* as the first adjective to be scored for every condition of vibration across all physical stimuli. The context of vehicle interiors remained.

6.4.1. Method

6.4.1.1. Procedure

The same procedure as the second experiment was followed, except for the order of the adjectives on the questionnaires. The first word for each of the vibration conditions was always *warmth*, followed by *exciting*, *good quality*, *masculine*, *sophisticated* and *unique* in a randomized order. Once again, two blocks of data were recorded for analysis.

6.4.1.2. Analysis

Friedman ANOVA was used to analyse the results in the same way as Experiment 1 and 2.

6.4.2. Results

The ratings of both *good quality* (Figure 6.11) and *masculine* (Figure 6.12), no significant differences were reported with imposed vibration. *Warmth* perception (Figure 6.13) was significantly different with imposed vibration on the smooth stimulus (χ^2=25.337, df=6, p< .001). Pairwise comparisons showed that the most significant difference between conditions was between vibrations 2 and 3 (Z=-2.521, n=12, p=0.004, two-tailed). Significant differences were also reported in the ratings for the circle stimulus (χ^2=19.328, df=6, p< .04) between vibration 1 and stationary (Z=-2.429, n=12, p=0.006, two-tailed).

For the perception of *exciting* (Figure 6.14), significant differences were reported in the rating of smooth (χ^2=19.328, df=6, p< .004), circle (χ^2=15.770, df=6, p< .015), and square (χ^2=19.860, df=6, p< .003) with the application of vibration. For the smooth stimulus, pairwise comparisons showed two main differences, between stationary and vibration 5 (Z=-2.429, n=12, p= 0.006, two-tailed) and, vibration 3 and vibration 2 (Z=-2.073, n=12, p= 0.004, two-tailed). For the circle stimulus, three significant pairwise comparisons were shown: vibration 2 and stationary (Z=-2.521, n=12, p= 0.004, two-tailed), vibrations 3 and 4 (Z=-2.599, n=12, p= 0.003, two-tailed), and between vibrations 3 and 5 (Z=-2.429, n=12, p= 0.006, two-tailed). Finally, for the square stimulus, three significant pairwise comparisons were also found: stationary and vibration 4 (Z=-2.701, n=12, p= 0.002, two-tailed), stationary and vibration 5 (Z=-2.497, n=12, p= 0.005, two-tailed) and, stationary and vibration 6 (Z=-2.666, n=12, p= 0.002, two-tailed). For the rough stimulus, no significant differences were found (X^2=7.358, df=6, p= 0.289).

No significance differences in ratings were found for the perception of *sophisticated* (Figure 6.15), however for the rating of *unique* (Figure 6.16) significant differences in scoring with the application of vibration was reported for the smooth stimulus only (χ^2=17.078, df=6, p= 0.009).

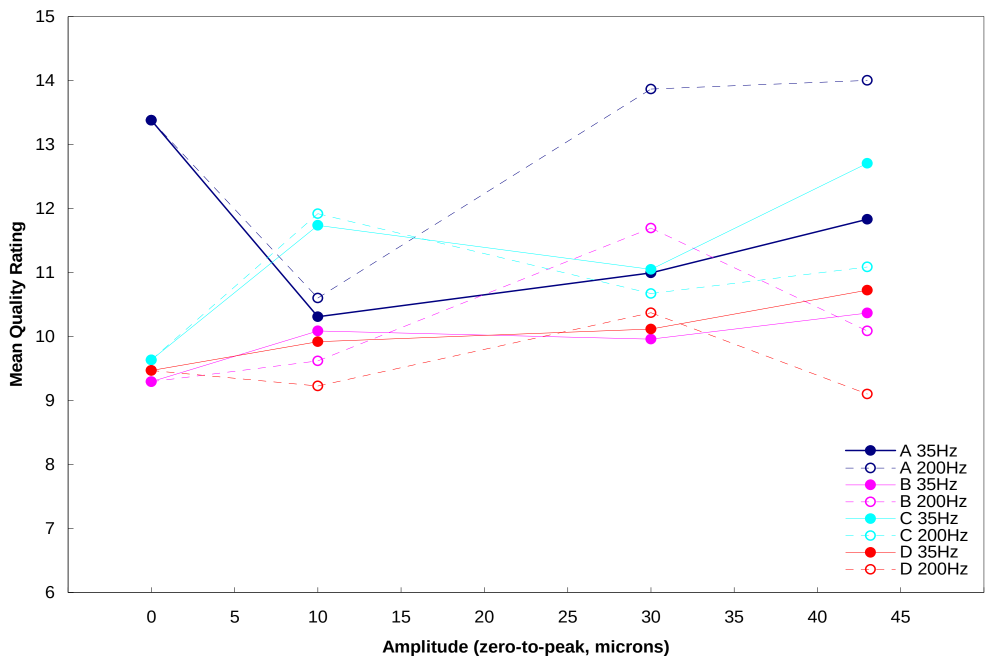


Figure 6.11 ***Good quality*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

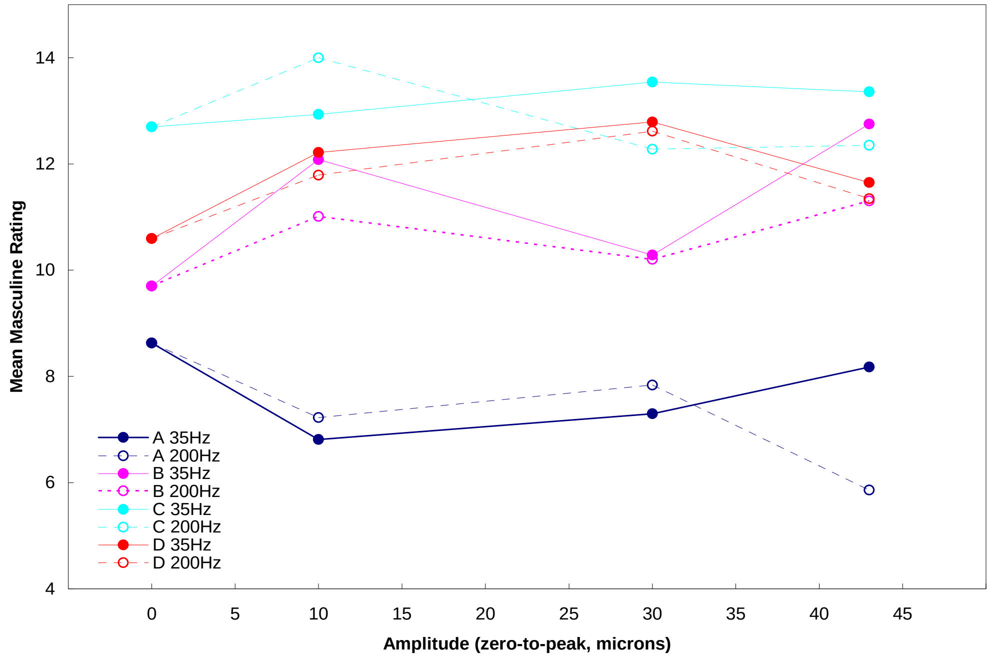


Figure 6.12 ***Masculine*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

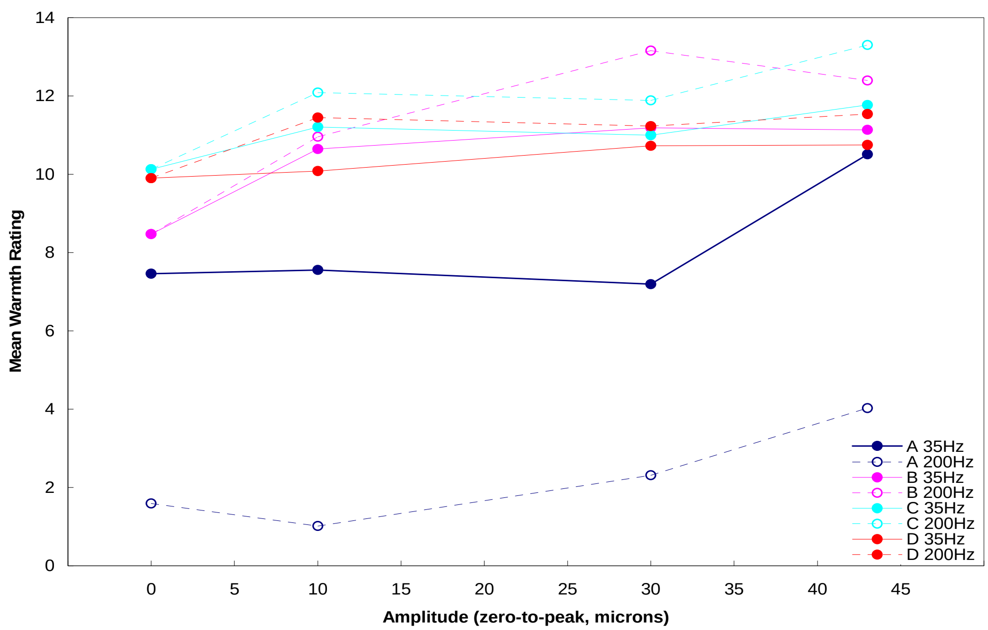


Figure 6.13 ***Warmth*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

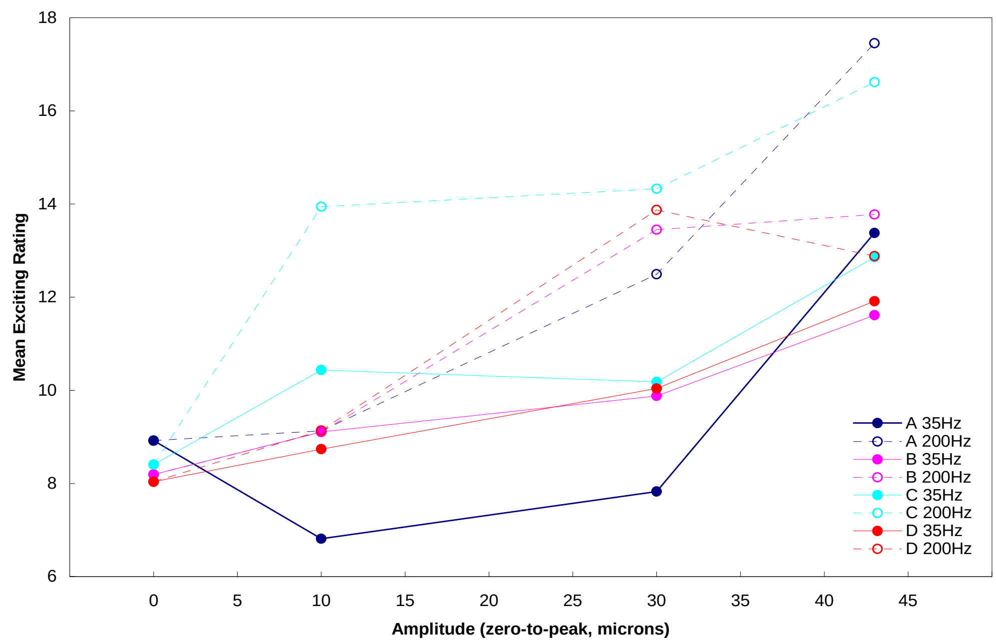


Figure 6.14 ***Exciting*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

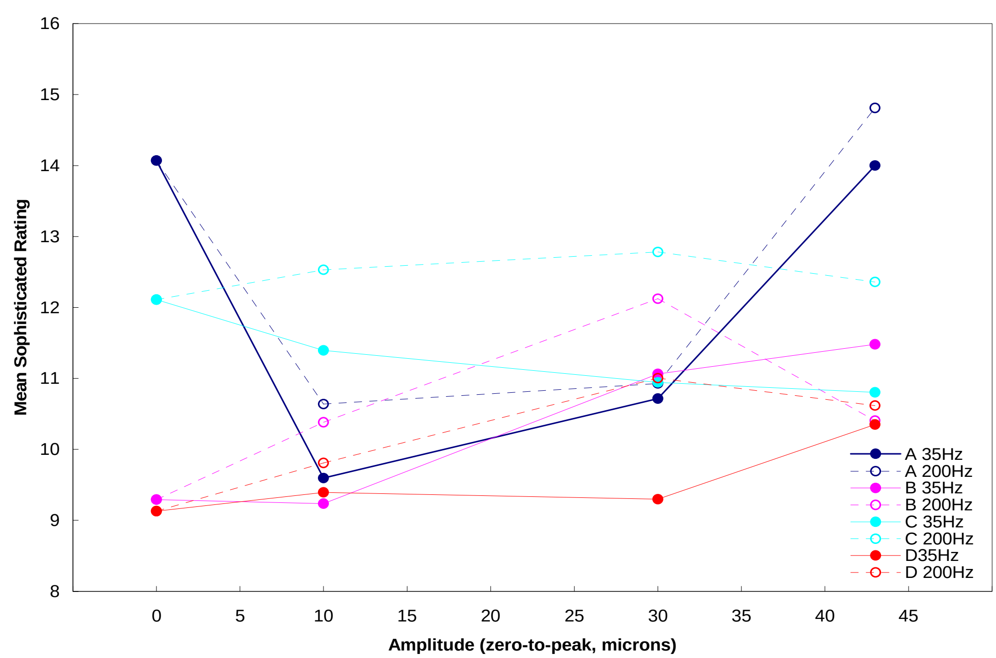


Figure 6.15 ***Sophisticated*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

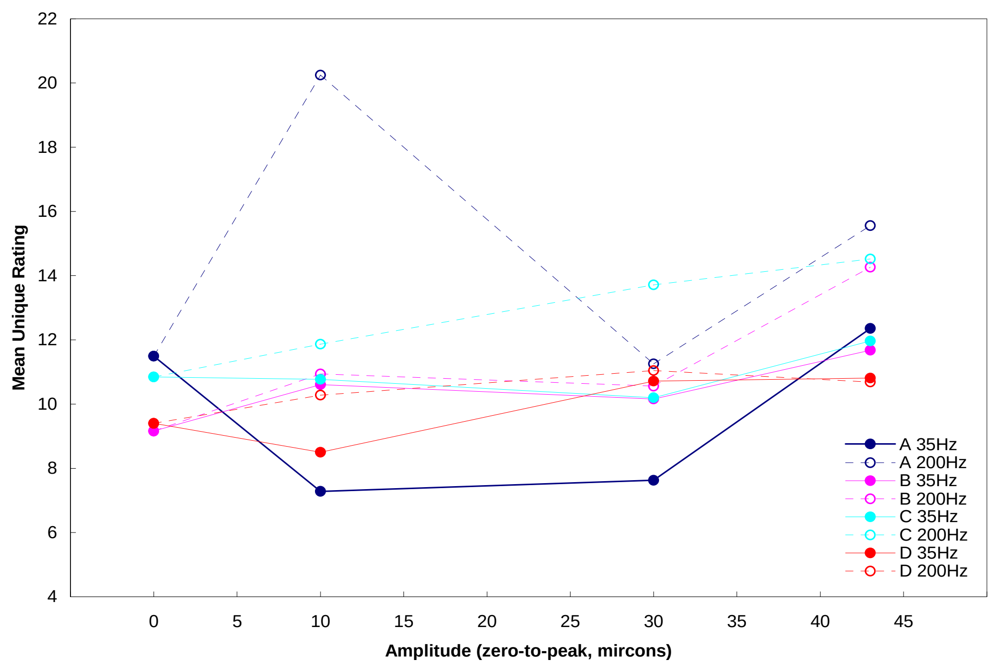


Figure 6.16 ***Unique*** **ratings for all four textured stimuli with applied vibration and the stationary condition**

6.4.3. Discussion

With the repositioning of *warmth* as the first adjective of the questionnaire for all test conditions, ratings for both the smooth and circle stimuli showed significant effect with imposed vibration. This differed from both Experiment 1 and Experiment 2. In Experiment 1, the positioning of *warmth* was always first, as with Experiment 3. The difference in which stimulus had different ratings when vibration was imposed between Experiments 1 and 3 could be due to the introduction of context. It is most probable that an order effect does exist here though as the *warmth* ratings in Experiment 2 showed no significant differences with imposed vibration. This order effect could be due to the perception of warmth being best rated in the initial moments of contact, when there is the most noticeable change in *warmth.*

In general, the average ratings reported for each of the affective adjectives in this present experiment were higher in comparison to Experiment 2. This could be indicative of participant learning, memory or familiarization of not only the conditions of the experiments (vibration, stimulus and adjectives), but also magnitude estimation. Zwislocki and Goodman (1980) discuss how participants tend to produce an initial number that is either too small or large in comparison to the further presented stimuli with experimental blocks. This could be a contributing reason to the increases in ratings between Experiment 2 and 3.

Exciting was rated in a similar way between the affective experiments with imposed vibration. *Unique* was again, consistent with Experiment 2. *Good quality* and *sophisticated*, however, did not have any significant contributors to the subjective ratings in this experiment, as did *masculine*. The differences in the results across the two affective studies showed that high level adjectives (Chen *et al*., 2009a), even though successfully manipulated, are difficult to predict with limited test vibrations.

6.5. General Discussion

Analysis of the three experiments together provides evidence that the imposed vibrations to a variety of surface textures did affect participant ratings for both textural and affective adjectives, most notably *warmth, exciting* and *unique*. Kolmogorov-Smirnov test for normality showed that the data was not normally distributed. Therefore, Friedman ANOVA of the seven vibration conditions across each stimulus was conducted, and revealed that imposed vibration increased ratings some ratings.

The analysis of *roughness* in this present study did not yield the same results as those obtained by Hollins, Fox and Bishop (2000), whose study stated that as the amplitude of a vibration increased, the perception of smoothness (the antonym, *roughness*, was reported in this present study) decreased. We found that imposed vibration, more specifically the amplitude, had no significant main effect on the ratings of *roughness*. There are some factors which could explain why this is the case. Firstly, Hollins *et al*. (2000a) used two alternative forced choice. This method required the participants to compare two stimuli, one stationary and the other vibrating, and asked them to determine which was smoother. In this present study, participants were not asked to compare stimuli, but to make subjective ratings for each stimulus as it was presented, which may have a more holistic undertone. The participants were also asked to consider more than one adjective. In this present study, a relationship which was noted in Chapter 5 with frequency and amplitude perception, a complex relationship is reported that exists between stimulus topography and vibration perception. In order to further understand the departure of results between Hollins *et al*. (2000) and the present results with *roughness* perception, a two alternative forced choice experiment may be required to determine whether this is because of measurement technique, of if results are specific to the stimuli.

As seen in the Figure 6.2 and 6.3, for *roughness*, and *warmth* there were distinct differences in how the smooth stimulus was rated with imposed vibration compared to circle, square and rough. This is not surprising considering the topographical difference between the smooth stimulus and those with macro-patterning. This may be due to spatial information having more prevalence than vibration information when it comes to making judgements or that vibration is negligible when surface textures are coarse. This suggests that the role of vibration may not be so clearly defined. *Stickiness*, for example, has been tenuously linked to vibratory cues (Bensmaia and Hollins 2005). This current study also reported rating fluctuations both above and below the rating for the stationary condition. The non-significant nature of the imposed vibration for the adjectives in this present study could be due to the limited range of frequencies and amplitudes explored; therefore expansion on the range could substantiate the role for vibration in these textural dimensions.

All experiments in this study examined the effect of vibration in the perception of *warmth*. Vibration had a significant main effect in Experiment 1 for the rough stimulus, and a main effect for smooth and circle stimuli in Experiment 3, where it was the first adjective to be rated for each condition. These results suggest a stronger link between *warmth* perception and vibration than the hypothesis given by Bensmaia and Hollins (2005).

Bensmaia and Hollins (2005) reported the concept of textural timbre, which is linked to vibratory frequency and temporal processing. In their study, they had one particular stimulus, corduroy, which could not be characterized by the textural continuum model. It was suggested that a further dimensionless quality of touch, most probably determined by frequency, existed due to the periodic structure of the stimulus. This still remains to be investigated however. In this present study, imposed vibration was a significant contributor to the ratings for both *exciting* and *unique* across Experiment 2 and 3 although which stimulus this affected differed across the experiment. Hollins, Fox and Bishop (2000) discussed the theory that if a vibration is imposed on a surface texture, temporal entrainment may occur. This means that subjective ratings will be determined by the frequency element of the 'virtual' fine texture imposed on top of the physical texture. This was not the case with smoothness perception in their experiment; however in this present study, it is suggested that in the case of *unique* and *exciting*, temporal entrainment may have occurred, indicating that these affective adjectives could be a function of vibratory frequency. It could be that textural timbre is important in the role of evaluating response ratings to affective adjective as these results have indicated. Furthermore, this provides evidence that low frequency vibrations may not just be involved in the detection of localized slip detection as suggested by Svinivasan *et al*. (1990) as clear differences are seen in Figures 6.8 and 6.14 for *exciting*, and Figures 6.10 and 6.16 for *unique*.

In Chapter 3, the affective adjectives investigated in Experiments 2 and 3 were studied with topographical and vibrational data. It was shown that for principal component 1, *good quality* and *sophisticated*, that the magnitude of the peak spatial frequency was a good indicator of subjective ratings. This was also the case for principal component 3, but with the addition of topographical *roughness*. For principal component 1 however, *exciting* and *unique* could not be quantified. In this present study, ratings for *exciting* and *unique* appeared to be influenced by vibration; specifically by frequency.

As a limited frequency and amplitude range were used, further investigation is proposed to understand the complex relationship reported here that exists between stimulus topography and vibration perception. In order to attempt to visualise what these stimuli with imposed vibrations may have looked like, the original traces taken with the HET in Chapter 3 were combined with sine waveforms in Matlab. For each of the textured stimuli used in this present study, a

35Hz and 200Hz waveform with 20μm amplitude was added. The results of which can be seen in Figures 6.17 to 6.20. It has been shown in Chapter 5; a complex relationship existed between vibratory amplitude and surface feature depth, and vibratory frequency and texture spatial wavelength. These figures therefore may not indicate exactly how the profile of a new surface texture might be constructed, but they do show what the vibratory pattern may need to be to elicit feelings of *exciting* or *unique,* for example. It can be seen that the resulting waveforms are strongly periodic at the 35Hz frequency and that for smooth and circle stimuli; 200Hz also produces strongly periodic profiles. With the square and rough stimuli however, the distinct periodicity of the sine wave is less distinguishable. This may explain why for *unique* in both

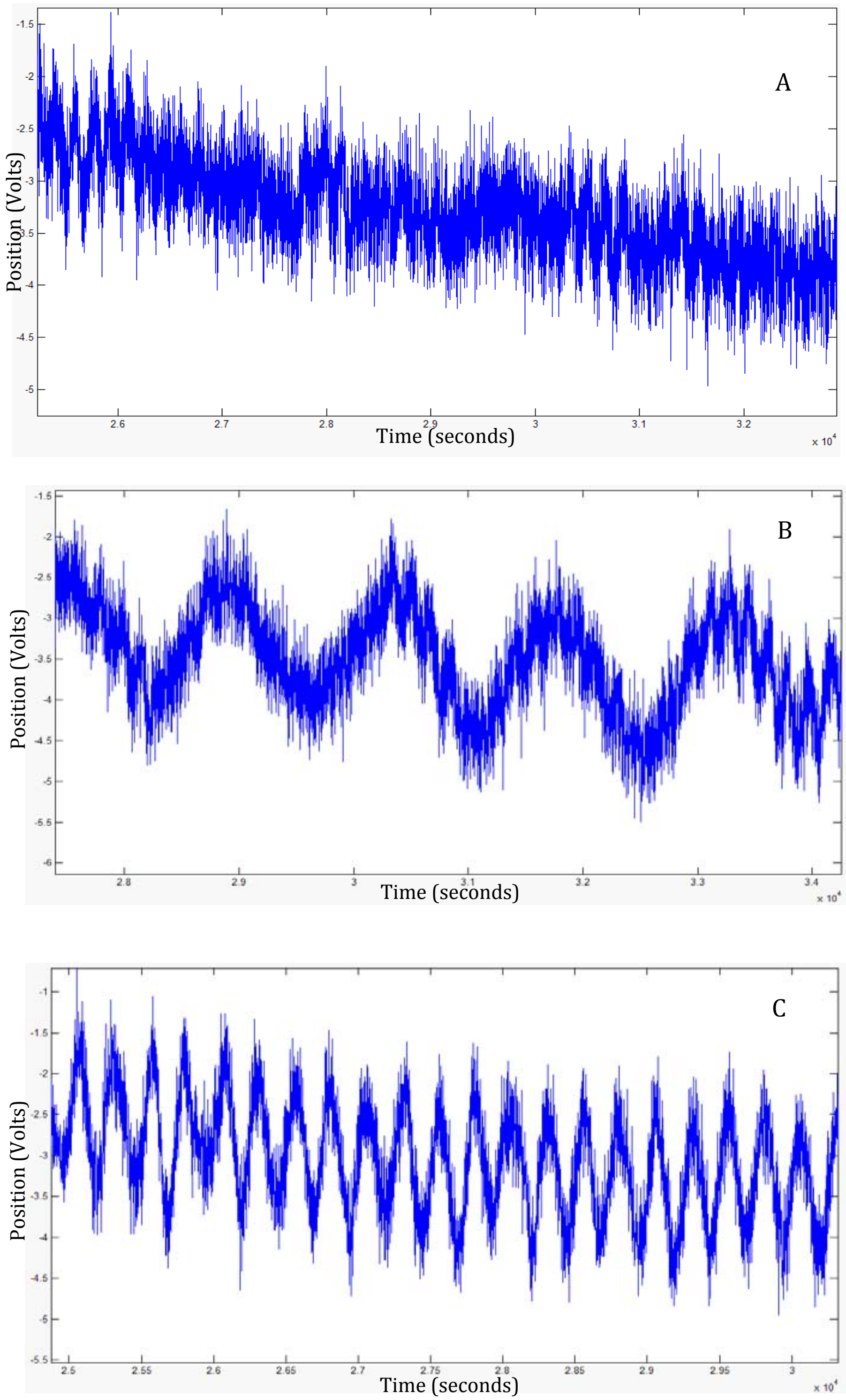


Figure 6.17 A-C. (A) Trace from HET of smooth stimulus. (B) Trace with 35Hz applied vibration. (C) Trace with 200Hz applied vibration.

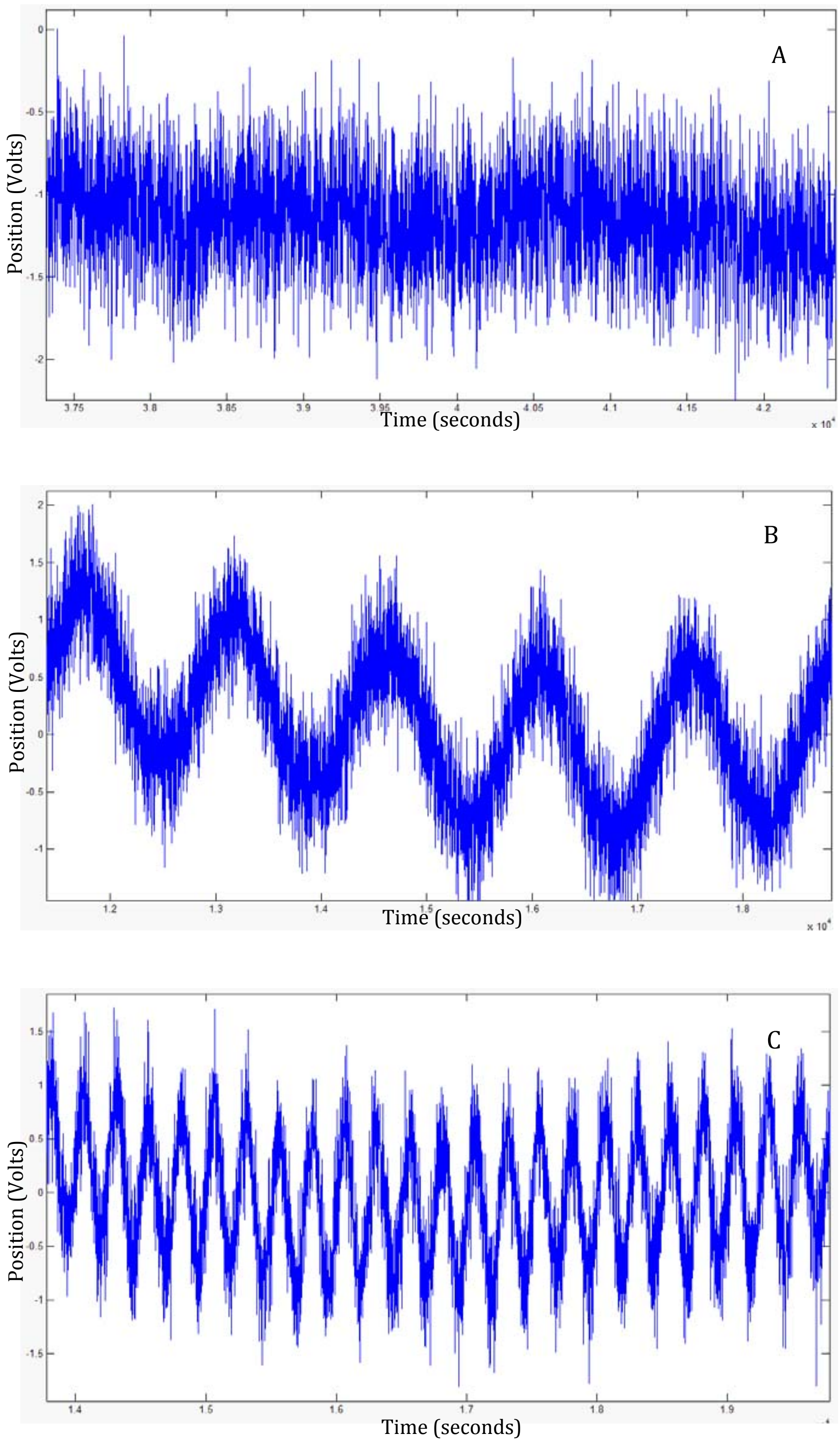


Figure 6.18 A-C (A) Trace from HET of circle stimulus. (B) Trace with 35Hz applied vibration. (C) Trace with 200Hz applied vibration.

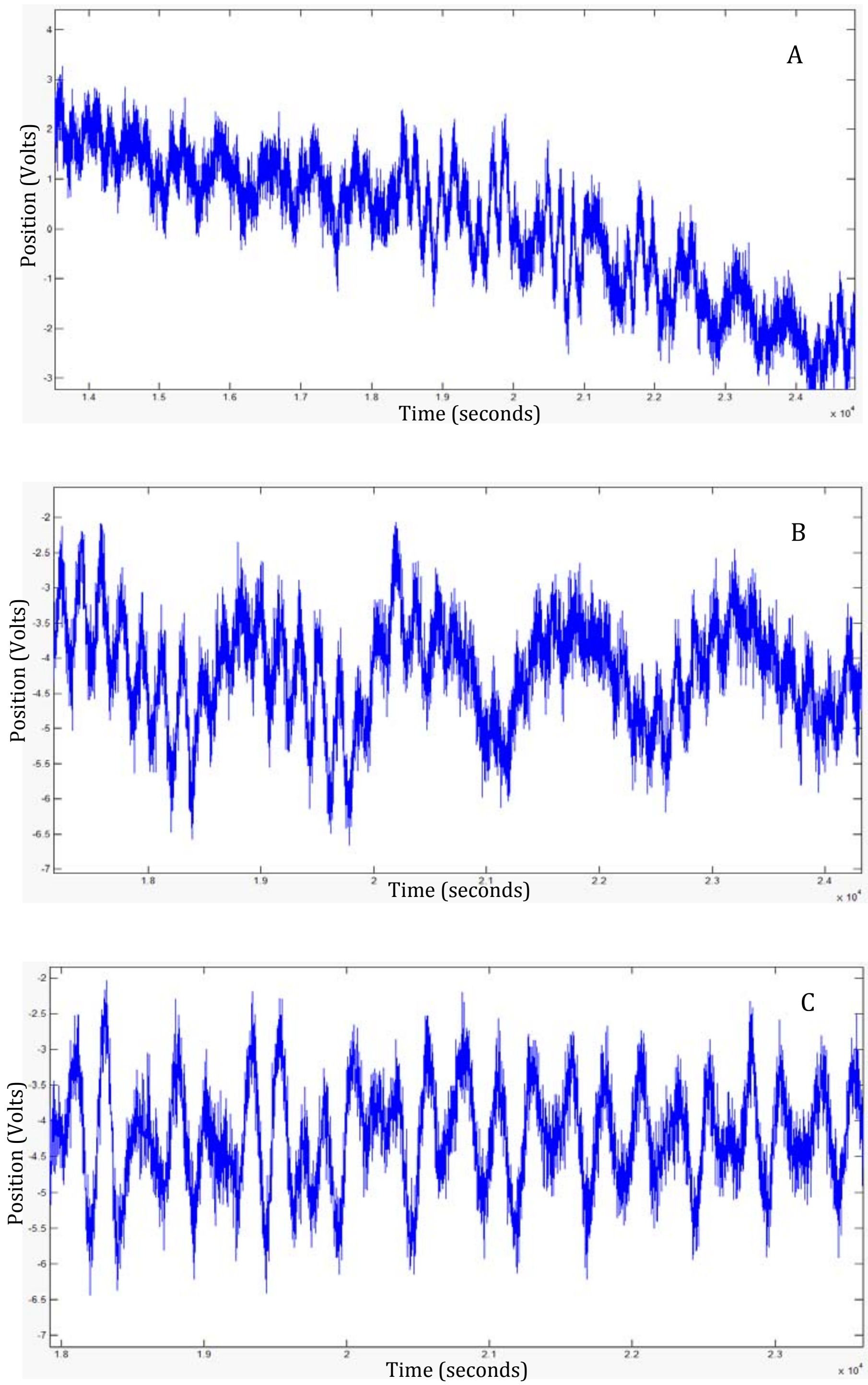


Figure 6.19 A-C (A) Trace from HET of square stimulus. (B) Trace with 35Hz applied vibration. (C) Trace with 200Hz applied vibration.

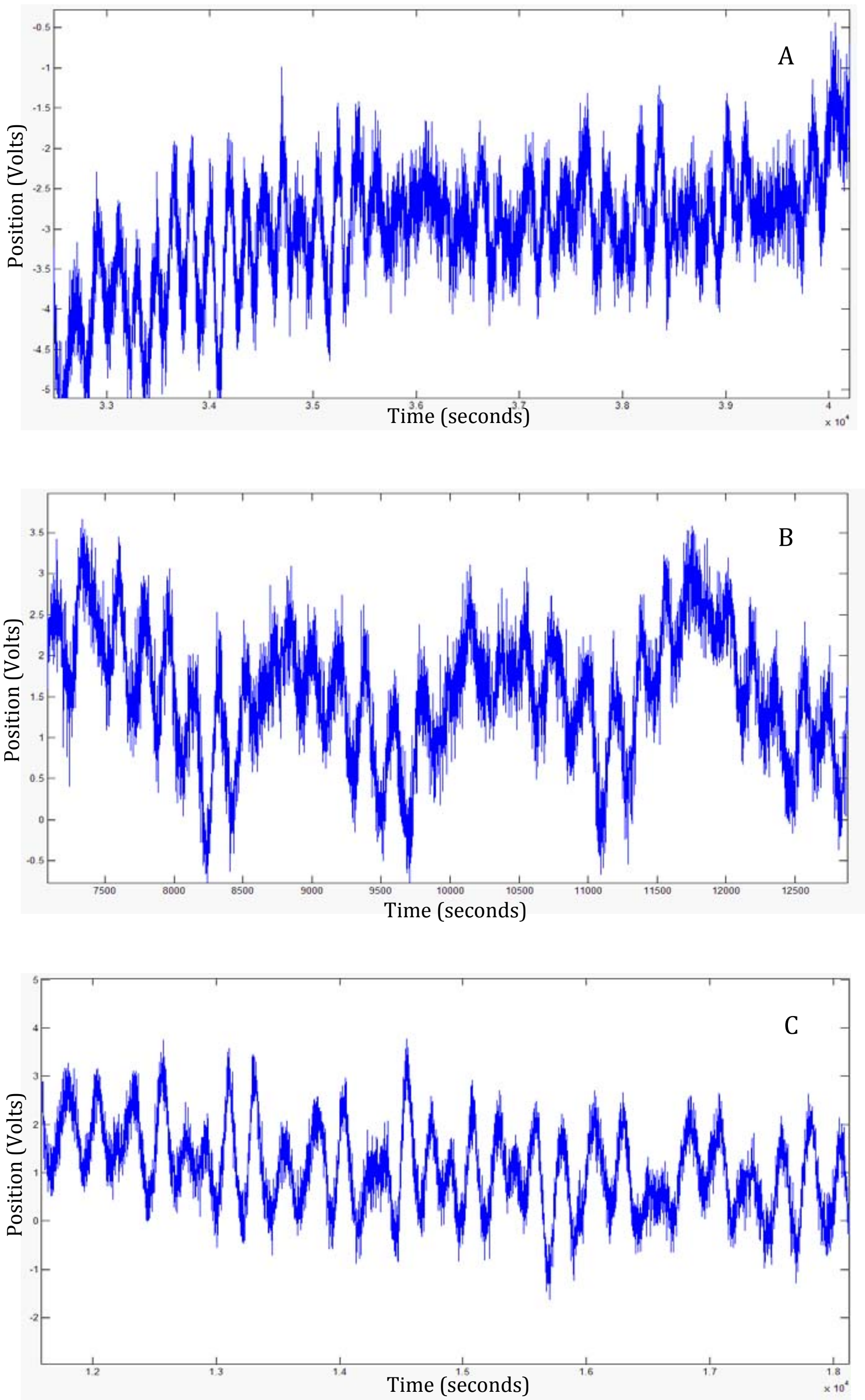


Figure 6.20 A-C (A) Trace from HET of rough stimulus. (B) Trace with 35Hz applied vibration. (C) Trace with 200Hz applied vibration.

Experiment 2 and Experiment 3, no significant differences with vibration were reported for the rough stimulus. This suggests then, that for a texture to feel *unique* in the car interior context, a more distinguishable periodicity evokes a more significant response.

6.6. Summary

This study investigated affective responses to vibrating tactile textures. Experiment 1, investigated the textural adjectives of *warmth*, *roughness* and *stickiness* to compare the results to previous researches which suggests that it is the amplitude of an imposed waveform which governs the perception of *roughness*. The present study's results did not find agreement with psychology literature. *Warmth* perception for the rough stimulus did differ with imposed vibration. The second experiment aimed to determine whether imposed vibration affect participant's affective responses against the adjectives: *good quality*, *masculine*, *warmth*, *exciting*, *sophisticated* and *unique*, in the context of vehicle interiors. The results showed that both *exciting* and *unique* were significantly affected by imposed vibration, but no main effects for *warmth*. Experiment 3 was conducted to confirm these results and further explore word order for *warmth* by placing it first for each stimulus presentation which resulted in an interaction effect between stimulus and amplitude. The perception of *warmth* varied with word position and quite possibly context, as smooth and circle were significantly effected by imposed vibration. *Unique* and *exciting* were also affected by imposed vibration, but not in the exact same way as Experiment 2.

The vibratory profiles in Figures 6.17 to 6.20 created from HET traces and imposed sine waveforms offer some specification towards designing affective surface textures based on vibratory profiles. Manufacturing tactile textures that elicit these vibration patterns would be the next line of enquiry into affective tactile texture research.

Chapter 7

Conclusion

7.1. Research conclusions

The findings in this thesis apply directly to the field of affective engineering, the perception of vibratory stimulation and to the design process. The research can offer companies the opportunity to be innovative in their product design, something which may be needed to remain competitive in an ever increasing global marketplace. It is important though for designers to find a balance between innovation and novelty as discussed by Hekkert and Leder (2008) and sophisticated use of texture could provide an essential tool in product development. To recapitulate, the specific objectives of this research were to:

1) Determine whether affective assessment was possible for tactile textures, and if so, what contributes to this discrimination.
2) Investigate whether vibration alone could convey textural information.
3) Establish if there is a difference between imposed and texture-elicited vibration
4) Develop a methodology to assess the role of imposed vibration in manipulating texture ratings for both textural and affective descriptors.

These objectives, on their own, contribute to knowledge, but together form a coherent narrative offering a new insight which will inform the design process.

7.1.1. Affective rating of tactile texture

The principal contribution of this research is to the field of affective engineering, specifically that tactile textures can be rated against affective adjectives in a similar way to whole products, such as those discussed by Schütte (2002) and Longstaff (2009). In Chapter 3, an affective engineering framework was employed to collect and rate adjectives associated to the tactile environment of a car interior. Using Principal Component Analysis, it was shown that three components of affective touch existed for the eleven textured stimuli. These were *unique* and *exciting* (PC1), *sophisticated* and *good quality* (PC2) and *warmth* (PC3) therefore forming three independent dimensional within semantic space. These adjectives were subsequently used (with the addition of *masculine, roughness* and *stickiness*) in Chapter 6, a series of experiments which used the psychophysical scaling technique of magnitude estimation. The results of these studies with imposed vibration onto surface textures showed that affective adjectives could still be rated within the constructs of a psychophysical methodology. Chapters 3 and 6 provide evidence that affective responses to tactile textures could become part of the current textural dimensions model proposed by Hollins, Bensmaia, Karloff and Young (2000). Importantly, this research provides evidence that can benefit designers and engineers in texture selection for product design by showing that participants can affectively describe and rate textures.

Furthermore, this is the first study which aims to link vibratory stimulation, through imposed vibration of those elicited by texture, to the affective qualities of touch. This specifically begins a narrative which considers more rigorous approaches to producing guidelines for designers to embody emotional characteristics to texture selection for products. In this research, the adjectives were related to car interiors and how the participants feel, or want to feel when they engage with that environment. The methodologies for affective texture rating used in both Chapter 3 and Chapter 6 could also be applied to other product or environment contexts, such as fast moving consumer goods, consumer electronics or medical devices.

7.1.2. Identifying that *intensity, roughness* and *softness* perception can be conveyed through vibration alone

It has been acknowledged in Chapter 2 that vibration contributes to the perception of textural dimensions such as *roughness*, and that these vibrations are generated by the complex interactions between a surface texture and the fingerpad. In Chapter 4, the aim was to understand to what extent textural descriptors could be assessed with only vibratory cues, therefore no spatial processing cues from the fingerpad interacting with texture features. It was seen that vibration alone could convey different levels of intensity, *roughness* and softness depending on the frequency and amplitude of the waveform. It was also shown in the results that there was little difference in the perception of vibration in both static and dynamic touching of the vibrating platform. This specifically, contributes to the psychophysical narrative of vibration perception, as no known investigation of dynamic touch of a vibrating platform has been performed. This expressly links to the psychophysical literature on indirect touch (Yoshioka *et al*., 2007) and adds to this particular narrative as the way the finger experienced vibration in the present research is similar to feeling texture through a probe. The present research shows that textural information can be conveyed in a similar way to exploring a texture with a probe. It was also noted in Chapter 5, that when the scanning mode is altered, static or dynamic, it is the ratings against frequency which change. This should be taken into consideration by designers who wish to introduce tactile feedback, for example, to a product.

Ultimately, this experiment showed that when no spatial cues are available from texture interactions, *intensity*, *roughness* and *softness* can be conveyed. This knowledge can be applied to tactile feedback in product design to enhance user experience and can also contribute toward making virtual reality more realistic by conveying more information through the use of vibration.

7.1.3. Characterizing the difference between texture-elicited and imposed vibration

The results of Chapter 5 showed that vibrations from texture scanning are not perceived in the same way as the equivalent vibration. In Chapter 3, it is discussed that SA I afferents are involved in resolving textural features and in Chapter 5 it was seen that vibratory amplitude and texture feature depths, specifically, could not be matched.

Vibratory frequency and texture spatial wavelength could be matched, albeit with a four-fold difference in frequency. These findings illustrate differences in how texture-elicited vibrations and imposed vibratory stimuli are potentially processed by the somatosensory system. It is speculated that the reason for this difference is due to either different afferents being stimulated, such as the SA I group, or are the afferents being stimulated in a different way. In other words, are the afferents being activated at different points in time as indicted by texture features being scanned over the fingerpad, or are they being activated all at the same time as speculated with imposed vibration.

The implication of these differences in processing suggests that predicting a psychophysical response to a tactile texture from imposed vibrotactile data may be more complex than anticipated. This was especially evident in the divide between participants 1 and 2, and 3 and 4 in rating stimulus 1 for frequency matching. Stimulus 1 had a predicted frequency of 32.5Hz. As this is near 40Hz, which is thought to be the frequency at which the Pacinian corpuscles become dominant in vibratory processing, it was hypothesised that this transition may not be quite as clear cut. In short, this finding also infers another complexity in making assumptions in texture processing from vibratory studies, as variability in participants may be inherent to such investigations. Also, that vibratory studies in which the vibration is imposed, may not be directly translatable in understanding how texture elicited vibrations are perceived.

7.1.4. Tactile vibration contributes to affective texture assessment

Both vibrations elicited by texture scanning, and imposed vibrations to tactile textures, contribute to affective texture assessment. It was seen in Chapter 3 that the magnitude of the peak spatial frequency was a good indicator for the assessment of *quality* and *sophisticated,* and to a lesser extent *warmth*. As these frequencies can be classed as low frequencies (see Section 3.3.3), an additional hypothesis for their role in somatosensation to the slip detection theory (see Sections 2.2 and 5.3) has been offered. When vibration was imposed onto surface textures also contributed to the affective assessment of tactile textures; specifically, to the adjectives *exciting* and *unique*. The spectral manipulation of the tactile textures (by imposing mechanical vibration to them) proved to be successful in also altering affective texture perception. Therefore, the method described in Chapter 6 may offer an effective method for assessing which aspects of vibration influence the affective assessment of tactile textures. This method has allowed for the visualisation of new vibratory profiles which are speculated to represent what the fingertip experienced when vibrations are imposed onto tactile textures. These vibratory profiles, as shown in Figures 6.17 to 6.20, provide visual representations of combined vibrations – those elicited from the texture, and those imposed by the actuator. It is acknowledged that imposed vibration and texture elicited vibration are perceived differently, however, the imposed vibration method of Chapter 6 may help to identify certain vibratory characteristics which elicit a desired affective response. These profiles, therefore, may give insight towards producing specifications for tactile textures, either for manufacture or for use in virtual reality. It is reasonable to also suggest that the results of Chapter 6 may also provide another level of communication for devices where tactile feedback may enhance the users' experience, or indeed guide them. An example of this would be vibratory feedback for touch screen devices which give the user tactile confirmation that an operation has been successfully executed, such as a button press.

This contribution specifically, is important to the design process as a whole. Indeed, it has been discussed in Chapter 1 that texture selection is significant in creating product which engages the tactile sense. The contributions discussed will aid designers by informing texture selections which will be visually appealing, and tactually stimulating, for examples, a texture which evokes a sophisticated feel as explored in this thesis. The specifications in this work relate to car interiors, and can already inform texture choices in that area if the adjectives are suitable. Otherwise, this body of work can give direction toward generating new texture specifications to meet an affective agenda.

This work also shows the significance of applied vibration to a surface texture, in which the vibrations are either desired as part of the products functionality (such as tactile feedback on touch screens) or a by-product of the product in use, such as vibrations on a steering wheel. In either instance, vibration can influence the way a product is perceived, changing the associated quality, for instance. This is something which needs to be considered by designers and has been shown in this thesis.

7.2. Limitations of the research

7.2.1. Context or stimulus specific results

The research that was conducted in both Chapter 3 and Chapter 6 was based on the context of car interiors and used stimuli which came from the same engraved plaque set. It has not been proved in literature that if a context is introduced into a tactile texture experiment results would differ. It was acknowledged by Picard *et al*. (2003) that the adjectives they used for textile stimuli may not be transferable to other stimulus materials. In this present study though, the linguistic guidelines used by Barnes and Lillford (2009) were used which removed product related adjectives. How participants may feel about textures being *exciting* in the context of an MP3 player for instance may differ. This remains to be tested as does the assessment of the same stimuli for a different product application.

7.2.2. Limitations of vibrations studied

In the studies conducted in this thesis, the applied vibrations used only included simple sinusoidal and square waveforms. It has been demonstrated in Chapter 2 and experimentally in Chapters 3 and 6 that the vibrations the finger encounters by texture scanning are typically complex. Indeed, in the profiles suggested in Chapter 6 and the work of Bensmaia and Hollins (2003; 2005) show dominant frequency characteristics, but it is yet to be experimentally shown that the lesser dominant features do not contribute to texture perception. It was shown in Chapter 6 that the imposition of vibration to a variety of surface textures altered the perception of *exciting* and *unique* which has been speculated to have altered the spectral content of the stimulus, but how these two vibrations have integrated to form a perception is unknown. It is therefore suggested that spectrally complex vibrations are investigated further using a vibratory stimulator similar to that designed by Killebrew *et al*. (2005). By using a multi-pin stimulator, texture scanning can be simulated whilst offering the capability to investigate a much larger range of complex vibrations such as those used in Chapter 6. Furthermore, the investigation of a wider range of amplitudes and frequencies using the existing methodology in Chapter 6 may provide enough data to begin to build predictive models of affective responses to new tactile textures. At present, this is limited to two frequencies and three amplitudes imposed on four surface textures. An expansion on this would strengthen the methodology described for generating insight into affective texture discrimination and rating.

7.2.3. Individual participant's sensitivity thresholds

Sensitivity thresholds were not measured during the course of these present studies, although attention was paid to select vibratory stimuli which were documented by previous researchers to be above threshold level. Although it has been shown that vibratory thresholds are not required in high frequency discrimination and perception (Pongrac, 2007) it may be required for low frequency vibratory discrimination, especially those generated by coarse texture scanning. This may be useful in investigating further why affective data was not normally distributed in these present studies.

7.3. Recommended future research

The aim of the research was to offer new insight into how tactile textures and imposed vibrations are affectively assessed by participants. New vibration profiles were generated and these profiles are speculated to elicit heightened ratings for *exciting* and *unique*. These outcomes were produced in the context-based environment of car interiors and only included simple imposed waveform vibrations.

7.3.1. Wider context-based texture assessment

At present, there is not known research which indicates that texture assessment results are exclusive to the context in which ratings were given. Using similar stimuli (textured ABS plaques) it is suggested that similar experiments are conducted to assess whether ratings change depending on which product the textures are used for.

7.3.2. Complex vibration experimentation

In these present studies, only simple waveforms were studied. This was partly due to the capabilities of the apparatus, but also to establish a workable methodology based on previous psychophysical researches. Although it can be argued that complex vibrations were produced by including imposed vibration onto tactile textures, more investigation is needed in how complex vibrations are perceived without spatial cues.

It is therefore suggested that spectrally complex vibrations are investigated further using a vibratory stimulator similar to that designed by Killebrew *et al*. (2005). By using a multi-pin stimulator, texture scanning can be simulated whilst offering the capability to investigate a much larger range of complex vibrations such as those used in Chapter 6.

7.3.3. Finger resonance investigation and sensitivity thresholds for texture scanning

In Chapter 3, finger resonance was discussed as a hypothesis for why no clear peaks were found with the Hall Effect transducer traces of finger vibration, despite the stimuli having different topographical properties. It is proposed that this should be investigated. Also, texture based sensitivity thresholds should be investigated as a potential reason for why the affective data in this thesis was not normally distributed. Sensitivity testing is an established technique in sensation measurement, and an alternative forced choice protocol is suggested for a wide stimulus set with different topographical properties such as those investigated in Chapter 3.

7.4. Summary

The overall aim of this thesis has been to investigate the contribution of vibration, both imposed and texture elicited, to the affective assessment of tactile textures. There has been substantial research conducted into the dimensions with which textures are described, most notably the perception of *roughness*, yet limited research has been conducted in affective texture discrimination or how vibration could play a part in affective discrimination. Also, there are researches which have begun to investigate how people interact with consumer products, an insight which is of interest to consumer product companies to enable them to remain competitive in an ever growing global marketplace. Innovation and novelty are suggested to be key to product survival and this thesis suggests that sophisticated use of texture to engage the modality of touch is a tool which should be exploited by designers. This research has shown that textures can be successfully rated against affective adjectives, and that vibratory parameters are involved in conveying and manipulating these qualities. Unilever (2010) have indicated a new research initiative investigating such principles.

The approach of this research was to create a multi-disciplinary work platform, incorporating affective engineering principles with psychophysical techniques and knowledge in touch perception. This was achieved in the experimental chapters of this thesis and offers new insight into the role of vibratory parameters in the affective assessment of tactile textures. The limitations of this research and how the results can be expanded on have been addressed in future research.

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Appendix A

A1. Experiment Protocol-Group A

Please take a seat.

Before we start this experiment, you must read this document.

In the room, you will see a table with a curtain hanging above it, a set of headphones and a sheet of paper.

Behind this curtain is a raised surface which is where the different vibrations we will be testing today will be presented. When signalled, you will put your hand under the curtain and feel the stimulus. There will be 60 in total for the session.

You are asked to keep your **finger stationary on the surface**; at no point must you make any lateral movement and please **maintain a constant pressure** that is comfortable for you.

You will be required to wear the headphones for duration of the study, through which you will hear pink noise. This is a static noise which has been chosen for you to listen to so that you will not be distracted by noises surrounding you during the study.

In this experiment, you will be presented with a variety of stimuli behind the curtain and you will be shown this before we start. Your task is to relate to me with the use of numbers how **intense, soft and rough** you feel the different vibrations are. To do this I will ask you to assign each word with a number that you feel is appropriate for the strength of vibration.

In order to help you understand this concept better, here are two lines, A and B.

B

There will always be a line shorter than A and longer than B, much in the same way with numbers – there are always smaller and bigger numbers than the ones you give.

You can use whole numbers, fractions or decimals and it can be as small or large as you like. The only condition is that the numbers you use must be positive.

When you have your finger on each stimulus, you will be prompted to give a numeric response to each of the words aloud so that it can be recorded on a spreadsheet. Please be sure say these numbers clearly, leaving approximately 2 seconds between your responses for each word. Remove your hand from the stimulus and return it to your side of the curtain. This will let me know that you are ready to move onto the next surface.

You are encouraged to give me your instinctive reaction when you touch the surface, do not dwell. Instinctive in this instance will mean with haste.

Once again, I will signal to you when I am ready for you to touch the next stimulus.

A2. Experiment Protocol-Group B

Please take a seat.

Before we start this experiment, you must read this document.

In the room, you will see a table with a curtain hanging above it, a set of headphones and a sheet of paper.

Behind this curtain is a raised surface which is where the different vibrations we will be testing today will be presented. When signalled, you will put your hand under the curtain and feel the stimulus. There will be 60 in total for the session.

You are encouraged to use **a stroking motion** using your dominant hands (the one you write with) index finger with a speed that approximately hits 45mm/s which is the length of this line whilst maintaining a **constant pressure**.

You will be required to wear the headphones for duration of the study, through which you will hear pink noise. This is a static noise which has been chosen for you to listen to so that you will not be distracted by noises surrounding you during the study.

In this experiment, you will be presented with a variety of stimuli behind the curtain and you will be shown this before we start. Your task is to relate to me with the use of numbers how **intense, soft and rough** you feel the different vibrations are. To do this I will ask you to assign each word with a number that you feel is appropriate for the strength of vibration.

In order to help you understand this concept better, here are two lines, A and B.

B

There will always be a line shorter than A and longer than B, much in the same way with numbers – there are always smaller and bigger numbers than the ones you give.

You can use whole numbers, fractions or decimals and it can be as small or large as you like. The only condition is that the numbers you use must be positive.

When you have your finger on each stimulus, you will be prompted to give a numeric response to each of the words aloud so that it can be recorded on a spreadsheet.

Please be sure say these numbers clearly, leaving approximately 2 seconds between your responses for each word. Remove your hand from the stimulus and return it to your side of the curtain. This will let me know that you are ready to move onto the next surface.

You are encouraged to give me your instinctive reaction when you touch the surface, do not dwell. Instinctive in this instance will mean with haste.

Once again, I will signal to you when I am ready for you to touch the next stimulus.

Appendix B

B1. Static touch

Intensity

Significance values of the amplitudes across each of the frequencies

Frequency (Hz)	Chi Squared	Significance (p)	Distribution type
35	48.090	0.000	Not normal
100	44.874	0.000	Not normal
200	47.73	0.000	Not normal
250	38.263	0.000	Not normal
400	17.691	0.089	Not normal

Significance values of the frequencies across each of the amplitudes

Amplitude	Chi Squared	Significance (p)	Distribution type
15.3	16.525	0.000	Not normal
28.3	15.794	0.000	Not normal
30.6	17.389	0.000	Not normal
36.9	17.137	0.000	Not normal
39.9	12.980	0.003	Not normal

50.5	15.052	0.000	Not normal
56.5	15.020	0.001	Not normal
73.9	17.072	0.000	Not normal
79.9	4.979	0.301	Not normal
93.4	5.333	0.272	Not normal
121.9	13.347	0.002	Not normal
131.5	13.859	0.001	Not normal

Roughness

Significance values of the amplitudes across each of the frequencies

Frequency (Hz)	Chi Squared	Significance (p)	Distribution type
35	48.885	0.000	Not normal
100	45.360	0.000	Not normal
200	35.892	0.000	Not normal
250	26.624	0.005	Not normal
400	8.716	0.648	Not normal

Significance values of the frequencies across each of the amplitudes

Amplitude	Chi Squared	Significance (p)	Distribution type
15.3	9.737	0.045	Not normal

28.3	13.113	0.011	Not normal
30.6	15.265	0.004	Not normal
36.9	13.404	0.009	Not normal
39.9	7.020	0.135	Not normal
50.5	3.915	0.418	Not normal
56.5	15.292	0.004	Not normal
73.9	7.958	0.093	Not normal
79.9	6.358	0.174	Not normal
93.4	6.667	0.155	Not normal
121.9	10.7667	0.029	Not normal
131.5	9.333	0.053	Not normal

Softness

Significance values of the amplitudes across each of the frequencies

Frequency (Hz)	Chi Squared	Significance (p)	Distribution type
35	22.140	0.023	Not normal
100	23.597	0.015	Not normal
200	28.281	0.003	Not normal
250	36.292	0.000	Not normal

400	8.934	0.628	Not normal

Significance values of the frequencies across each of the amplitudes

Amplitude	Chi Squared	Significance (p)	Distribution type
15.3	16.667	0.002	Not normal
28.3	7.711	0.103	Not normal
30.6	13.778	0.008	Not normal
36.9	15.702	0.003	Not normal
39.9	7.588	0.108	Not normal
50.5	8.809	0.066	Not normal
56.5	15.125	0.004	Not normal
73.9	16.215	0.003	Not normal
79.9	1.174	0.882	Not normal
93.4	6.695	0.153	Not normal
121.9	5.720	0.221	Not normal
131.5	15.429	0.004	Not normal

B2. Dynamic touch

Intensity

Significance values of the amplitudes across each of the frequencies

Frequency (Hz)	Chi Squared	Significance (p)	Distribution type
35	50.355	0.000	Not normal
100	49.543	0.000	Not normal
200	40.822	0.000	Not normal
250	33.825	0.000	Not normal
400	21.587	0.028	Not normal

Significance values of the frequencies across each of the amplitudes

Amplitude	Chi Squared	Significance (p)	Distribution type
15.3	14.240	0.007	Not normal
28.3	12.735	0.013	Not normal
30.6	15.592	0.004	Not normal
36.9	17.796	0.001	Not normal
39.9	10.384	0.034	Not normal
50.5	14.245	0.001	Not normal
56.5	13.778	0.008	Not normal
73.9	15.333	0.004	Not normal
79.9	12.800	0.012	Not normal
93.4	13.280	0.010	Not normal

121.9	15.313	0.004	Not normal
131.5	17.253	0.002	Not normal

Roughness

Significance values of the amplitudes across each of the frequencies

Frequency (Hz)	Chi Squared	Significance (p)	Distribution type
35	39.519	0.000	Not normal
100	40.437	0.000	Not normal
200	36.200	0.000	Not normal
250	32.477	0.001	Not normal
400	18.467	0.071	Not normal

Significance values of the frequencies across each of the amplitudes

Amplitude	Chi Squared	Significance (p)	Distribution type
15.3	10.000	0.040	Not normal
28.3	15.116	0.004	Not normal
30.6	15.527	0.004	Not normal
36.9	9.980	0.041	Not normal
39.9	9.608	0.048	Not normal
50.5	12.242	0.016	Not normal

56.5	15.789	0.003	Not normal
73.9	15.388	0.004	Not normal
79.9	11.434	0.022	Not normal
93.4	12.800	0.012	Not normal
121.9	12.898	0.012	Not normal
131.5	10.939	0.027	Not normal

Softness

Significance values of the amplitudes across each of the frequencies

Frequency (Hz)	Chi Squared	Significance (p)	Distribution type
35	18.597	0.069	Not normal
100	35.731	0.000	Not normal
200	25.394	0.008	Not normal
250	25.048	0.009	Not normal
400	17.109	0.105	Not normal

Significance values of the frequencies across each of the amplitudes

Amplitude	Chi Squared	Significance (p)	Distribution type
15.3	3.434	0.488	Not normal
28.3	10.384	0.034	Not normal

30.6	16.426	0.002	Not normal
36.9	5.031	0.284	Not normal
39.9	4.082	0.395	Not normal
50.5	8.041	0.090	Not normal
56.5	4.412	0.353	Not normal
73.9	12.426	0.014	Not normal
79.9	8.408	0.078	Not normal
93.4	8.480	0.075	Not normal
121.9	7.167	0.127	Not normal
131.5	9.010	0.061	Not normal