Human Haptic Perception in Virtual Environments: An investigation of the interrelationship between physical stiffness and perceived roughness

Theodoros Georgiou

Master of Science by Research

University of York
Computer Science

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ABSTRACT

Research in the area of haptics and how we perceive the sensations that come from haptic interaction started almost a century ago, yet there is little fundamental knowledge as to how and whether a change in the physical values of one characteristic can alter the perception of another. The increasing availability of haptic interaction through the development of force-feedback devices opens new possibilities in interaction, allowing for accurate real time change of physical attributes on virtual objects in order to test the haptic perception changes to the human user.

An experiment was carried out to ascertain whether a change in the stiffness value would have a noticeable effect on the perceived roughness of a virtual object. Participants were presented with a textured surface and were asked to estimate how rough it felt compared to a standard. What the participants did not know was that the simulated texture on both surfaces remained constant and the only physical attribute changing in every trial was the comparison object's surface stiffness.

The results showed that there is a strong relationship between physical stiffness and perceived roughness that can be accurately described by a power function, and the roughness magnitude estimations of roughness showed an increase with increasing stiffness values.

The conclusion is that there are relationships between these parameters, where changes in the physical stiffness of a virtual object can change how rough it is perceived to be in a very clear and predictable way.

Extending this study can lead to an investigation on how other physical attributes affects one or more perceived haptic dimensions and subsequently insights can be used for constructing something like a haptic pallet for a haptic display designer, where altering one physical attribute can in turn change a whole array of perceived haptic dimensions in a clear and predictable way.

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PREFACE

Statement of Ethics

This experimental study, design and participant tasks have been all designed based on the ethical principles of "*Do No Harm*", "*Informed Consent*" and "*Data Confidentiality*".

Do no harm

The participants in the experiment were not put in any harmful situations or asked to take any risk different from those normally encountered in everyday life. All participants were informed they could withdraw from the experiments at any point with no consequences or questions asked.

Informed consent

The participants recruited for the current research were all informed about the experiment design and tasks that they were going to undertake. All of the participants were over 18 years old and were well informed with the appropriate information before the experiment with a briefing session, and a debriefing session after the experiment. All participants were also asked to sign a consent statement form before the experiment.

Data Confidentiality

In order to process and analyse the experiment results, data were collected from the participants. All the information gathered was kept confidential and accessible only to the experiment and the supervisor of this research. In addition, any data recorded from the participants were stored and referred to anonymously, only by the participant number.

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Author's declaration

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-Theodoros Georgiou

CHAPTER 1 - INTRODUCTION

Technology is by definition the use of knowledge and tools to solve problems or improve any pre-existing solutions to known problems. Since the dawn of the computer age, technology concentrated in displaying data to the user primarily via visual messages.

This sensory "monopoly" gave rise to a new problem, where a user can become overburdened by an ever-increasing amount of visual information they have to take in and process [**3**]. This at first does not seem to impose a serious problem, since in our everyday life we can cope with huge amount of complex information of many different types, coming from our surrounding with virtually no difficulty but we need to keep in mind that in the real world, we have five traditionally recognized methods of perception, or sense (hearing, sight, touch, smell and taste), and by combining them we can prevent one from becoming overloaded [**3**] [**4**].

To compensate for this in computer interaction, research in the last decade started looking at other modes of human computer interaction. This gave rise to what is called "multimodal" interaction. As the name suggests, multimodal interaction refers to the mode of communication with another system using more than one mode of interaction. This caused two major groups of multimodal interfaces to come together. The first group of interfaces is combining a number of user input modes beyond the traditional keyboard and mouse, such as speech, touch and manual gestures [**5**], gaze and motion control.

The other group of interfaces is combining input and output methods in order to make interfaces that merge a visual modality (e.g. a display, keyboard, and mouse), with a voice modality (speech recognition for input, speech synthesis and recorded audio for output). However other modalities, such as pen-based input or haptic input/output may be used.

Adapting technologies in our everyday computer use, to allow interaction and communication of information between the computer and its user via other senses along with vision is one possible solution. Extensive work has been done with auditory communication of information, e.g. [**4**], and the sense of touch as a mean to convey information in both safety critical systems and systems of casual use, such as mobile phones, and combinations of the two.

In order to design and create better interfaces that use haptics as a mean to express information, we first need to understand how the sense of touch works, in a similar way studies contacted for other senses helped us understand the sense of vision and hearing.

In addition, for creating and adapting haptic interactions with technologies in our everyday life, we also need haptic displays. The main reason graphics are being used so much is mostly because of the visual dominance as a sense [**6**]. Another reason is the high quality of visual displays, with the ability to produce high definition images and graphics. Haptic interfaces on the other hand lack in this area as they are, at the moment, confined in more specialised areas such as the area of medicine and the training of surgeons performing robot assisted surgeries [**7**].

Anderson and Sanderson [**8**] performed a number of studies, set to investigate the different dimensions of sound and their importance when trying to convey a message. In order to better understand the sense of touch, we need to first understand, not only how it works (physiology), but also how we perceive touch, a similar way Anderson et al. [**8**] did for hearing and sounds. This way, we will be able to utilise touch more efficiently in system interfaces and for communicating messages and information in systems.

The closest to this so far is what is known as *tactons* (or *tactile icons*) [**9**]. These tactons utilise different dimensions of the tactile sense (such as vibration frequency and vibration wave shape) to produce a number of individually distinguishable, unique icons that can be felt through touch the interface implementing them. This proves that changing one tactile dimension affects the way the entire surface is perceived.

In addition to this, the area of haptics studies extensively how physical attributes of an object (such as the physical stiffness and the micro-texture of the object's surface) affect how that object is perceived to feel. For example, an object with high measured physical stiffness (e.g. an iron bar) is expected to feel "harder" than one with lower physical stiffness (e.g. a sponge). In the same way an object with coarse surface like for example a piece of sandpaper is expected to feel "rougher" than a something like a piece of porcelain.

On the other hand, there is not enough literature to explore how one physical attribute affects the perception of another. More specifically, not much has been done to date on how the physical stiffness of an object, for example affects how "rough" that object feels. The closest that could be found was an experiment by Unger [**10**], exploring how the physical stiffness of a probe affected the perception of the object's roughness when felt with that probe. This gap in the domain knowledge formed the basis of the motivation for this project.

More specifically, in this project an investigation was carried out on how the physical stiffness of an object affects the perception of how rough its texture feels. This was implemented and carried out in the virtual environment using a force feedback device, where the physical attributes for stiffness and roughness could be easily produced and controlled.

The next chapter contains a literature review, providing the reader with an introduction to haptics in general. This is followed by Chapter 3, explaining how psychophysics can be used as a method for quantifying perception, followed by a chapter (Chapter 4) on the relevant literature review on the perception of "*hardness*" and "*roughness"*, from both the psychological and the human computer interaction point of view.

Chapter 5 contains a full description of the motivation to undertake this project and the gap in the domain knowledge identified and intent to fill with this study. This chapter is followed by a chapter, Chapter 6, containing the technical details of the force feedback device used for the experiments and a preliminary experiment contacted to verify the fidelity of the force feedback device in the force range it will be used in. Chapter 7 contains the experimental setup and methodology used for the experiment along with the analysis of the data obtained and a discussion of what conclusions can be drawn from them.

The conclusions of this study are then presented in Chapter 8, which is immediately followed by a chapter on future work.

CHAPTER 2 – INTRODUCTION TO HAPTICS

2.1 What are Haptics?

Haptics refers to the sense and manipulation through touch, and can refer to any form of nonverbal communication involving touch [**11**]. The word haptics derives from the ancient Greek word "ἅπτω" and translates directly to "I touch".

This term has been widely used since the early part of the twentieth century by psychologists for studies on the active touch of real objects by humans. During the later parts of the twentieth century (1980s), researchers started looking at novel ways of interaction with machines relating to touch. It soon became apparent that this was creating a new discipline that needed a name. Instead of creating a new name, they decided to redefine the pre-existing term for 'haptics', broadening its scope to also include machine touch and human machine touch interactions. Therefore, the current working definition for haptics includes all aspects of information acquisition and object manipulation through touch by humans, machines, or a combination of the two; and the environments can be real, virtual or teleoperated [**11**].

Consequently, haptics can be divided into three main areas. The first one is human haptics, which is the study of human sensing and manipulation through touch (original definition). Then there is the area of machine haptics. This is defined as the design, construction and use of machines in order to replace or supplement human touch. Lastly, there is the area of computer haptics. In this area, algorithms and software is used for generating and rendering the feel of touch on virtual object. This process is analogous to computer-generated graphics.

Most dictionary definitions fail to differentiate between haptic and tactile [**12**]. As mentioned above, many researchers and developers use the term haptic to include all haptic sensations and limit the use of tactile to mechanical stimulation of the skin. Erp et al. [**12**], in their accepted ISO definition present a diagram (see Figure 1) that summarises haptics and shows the relationship between the components that make up the field of haptics.

Therefore, *haptics* refers to the application of touch (tactile) sensation and kinaesthesia (knowing where your limbs are in relation to your body) as a mode of interaction with someone's immediate environment. In other words, touch and kinaesthesia are subgroups of the broader term referred as haptics.

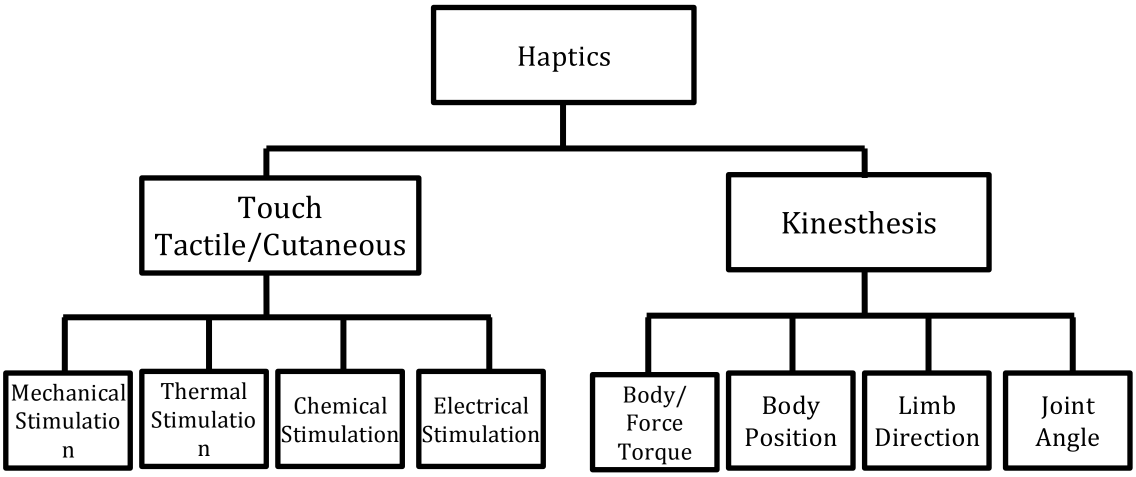

Figure 1 The components of haptics. "Touch" includes such diverse stimuli as mechanical, thermal, chemical and electrical stimulation to the skin. The "kinaesthetic" sense can be matched by kinaesthetic activity by which a user exerts force or torque on an object external to the active body part [12].

2.2 Development of Human Haptic perception

The evolution of the human hand into a prehensile tool, highly adapted for exploration, manoeuvring and object exploitation, is recognised as one of the most critical factors in the phylogeny of humans [**13**]. In a very similar way, the development of the skilful use of the hands for these purposes played a very significant role to human's ontogeny and helped them climb to the top of the food chain, dominating the planet.

The sense of touch is the earliest sense to develop in an embryo and respond to stimulation [**14**] [**15**]. Within eight weeks, an embryo shows reflexes based on touch. In the first years of life, humans can gain a considerable ability to use their hands for acquiring information about textures and surfaces in order to discriminate or identify them. Infants around 12-months of age were found to be able to discriminate shapes and recognise familiar (to them) objects from novel ones [**16**]. Also, studies have shown that exploratory techniques exist for infants as they do for adults, but due to development issues (infant's hands are not yet fully developed) it is significantly different and poses more limitations. Infants for example are able to sense and differentiate a soft from a hard object but because of smaller hands and not yet fully developed motor system they do this by gripping the objects in different ways and different frequencies [**17**].

Therefore, the sense of touch is constantly developing, starting at a very young age. During our first few years we are able to explore and understand our surrounding environment through the sense of touch, exploiting enough information to build a mental picture of the surface or the objects we are in contact with.

2.3 Physiological aspects of touch

The sense of touch is often defined as the sensation obtained by non-painful stimuli placed against our body's surface. The sense of touch, generally, is a very complex system with many different receptors in joints, muscles and the skin, with each one having its own characteristics and responding to different stimuli [**18**].

Tactile sensing is the result of a chain of events that starts when a stimulus such as heat, pressure or vibration, is applied on the body [**19**]. This stimulus triggers a response from specialized receptors, depending on the type, magnitude and location on the skin it is applied to [**19**].

Hairless (glabrous) parts of the skin, covering the palm and fingertip regions of the body, play the most active role in tactile exploration and tactile sensing. These areas have high density of specialized receptors for sensing the constituent components of what we call "touch" and are able to accurately detect any mechanical input due to skin deformation and vibrations caused by a tangential movement [**20**].

Tactile sensing, on the other hand, is the proper terminology of the perception used for describing the more general sense of touch. Tactile sensing or perception only accounts for small-scale forces coming from slight touch and surface movement, which allows us to feel the smoothness or bumpiness of textures [**20**]. These sensors responsible for detecting mechanical pressure are called *mechanoreceptors* and are mostly found on the glabrous parts of the skin. Haptics also include proprioception or kinaesthetic perception, which is responsible for perceiving the gross mechanical forces, like the weight and resistance of objects and the position of our extremities in relation to our body and other extremities [**20**].

Therefore, the ability of kinaesthesia and the high density of "touch" receptors in the skin of our hands make us humans very good in haptic perception and extremely efficient in the process of recognizing objects through touch [**21**].

2.4 Psychological aspects of touch

Haptic feedback can be an aspect of the design of human computer interactions, which has the potential of achieving a number of user experience goals. In order to do this, we first need to understand the physical interaction not only in the physiological sense but also the psychological and the cognitive aspects of such interactions.

First we need to consider that "touch" is intentional, socially invasive and committing [**22**]. With the simple gesture of reaching out to touch, intentions are shown, other's personal space may be invaded or taboos violated. One may also expose oneself to physical danger, pleasure or obtain information for the environment around one. Since touch is so intimate, social touch is considered salient and immediate [**23**] (e.g. a business handshake).

The intentions that may initiate or prolong a touch gesture vary. More caution is taken with what we touch than what we look at. This is something a designer must keep in mind when designing a haptic interface. The focus for the designer therefore, must shift from drawing the user's attention or designing visually ergonomic interfaces, to anticipating, directing and accommodating a potential user's preconception of what the interaction will do, and what the experience will be like [**22**].

There is always some kind of intention when touching something. This intention may be just to probe an object, communicate a message or just poke something to elicit a reaction or verify that an action is completed [**22**]. In some other, more recreational situations, we may use our sense of touch simply for the enjoyment of aesthetic pleasure or comfort, fidget to relieve tension, or connect physically or emotionally with another person or other living thing [**23**] [**22**]. In the same way, we avoid certain interactions through the perception that something can be potentially dirty, painful, forbidden or too intimate. Beyond this, many people (often culturally associated) are "haptically challenged", and do not generally find touching natural, informative or pleasant [**22**,**24**].

In addition, individuals may sense the world around them in a slightly different way from each other but being such a personal feeling, they may not be aware of this difference. Tests exist to check for perception differences in other senses. An example of such a test is the Ishihara test, designed for testing colour perception for red-green colour deficiencies [**25**].

The Ishihara test consists of a number of coloured plates, called Ishihara plates. Each plate contains a circle of dots appearing randomized in colour and size, and within the pattern are dots, which form a number or shape clearly visible to those with normal colour vision. These numbers or shapes, on the other hand, appear invisible or difficult to see, to those with a red-green colour vision defect [**25**] (see Figure 2).

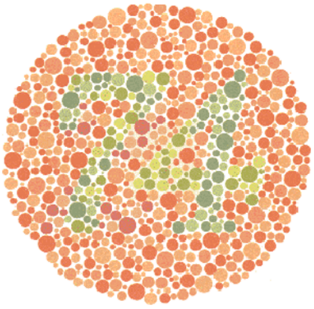

Figure 2 Example of an Ishihara test plate.

In this plate, if you have normal colour vision you'll see a 74. If you are red green colour-blind, you'll see a 21 and if you are totally colour-blind you will not see a number above.

There are undoubtedly perceptual differences in touch as there are on other senses such as vision, but there is no straightforward way of measuring it yet.

These differences are some of the parameters one must consider when designing a haptic interface in order to meet and satisfy some of the user experience requirements [**26**]. However, even though haptic interfaces, such as in art-related applications, are proven to improve users' performance and expand their creative process, users may reject a haptic drawing application. This may occur, for example, if the features it provides does not meet or support users' requirements and do not offer significant advantages over drawing in the real world [**27**].

Most existing systems use abstract representations of real world objects and any haptic representation tries to mimic real world sensation in approximation and not via solid psychophysical and psychological methods [**26**].

2.5 Intermodal sense of touch

Touch and tactual perception is not completely independent of vision [**28**]. Even though vision and touch are capable of processing the same or similar events, they may do it in a largely autonomous way, with little or no interaction. In some cases, vision may be better in negotiating perception than touch when both modalities are available, and one sense completely overrides the other for processing information about the same event. In general, both senses are differentially suited for different events and situations, and may interact differently depending on the nature of the perceptual performance involved [**29**]. This last statement underlines the complexity of intermodal interactions and how two different senses can overlap and override each other, work together or work independent of each other depending on the particular event they are trying to process.

Information coming from two modalities (bimodal) describing the same event or surface is found to be better than information from a single modality for sensing surface properties. More specifically, Manyam [**24**] found that people could judge shapes more easily and more accurately when both vision and touch were used than when only touch was available. In addition, Heller [**30**] found that people could judge more accurately the surface's texture when both senses (vision and touch) were available rather than either one alone.

Summing multimodal perception up, we can conclude that, even though any changes in tactual performance when vision is added to touch can be accounted for; there is not a simple global relationship that can help to define the interaction and association between the two modalities. The only way of possibly coming closer to the formulation of a relationship is by directly analysing and evaluating the kinds of information that are available as stimuli for a situation and evaluating the properties of the tactual and visual systems involved when engaging with the available stimulus information. This more practical approach is the only way of coming closer in analysing and understanding situations of intermodality relations.

2.6 Indirect touch

Indirect touch refers to the situation where a surface is felt through the tip of a tool. Similar to kinaesthesia or proprioception, the information someone can gather with the tip of a rigid tool can be perceived as if it was part of the body. It is believed this "ability" comes from post-tool-using evolution.

Despite the indirect touch, exploring a texture with a probe or a tool, a rigid link between the skin and the surface is shaped [**31**]. A rich impression of the object and not the tool can be constructed by only feeling the vibrations created by the object's texture surface [**28**]. As David Katz [**32**], observed, when you explore a surface with a tool, you feel the surface and not the tool; getting a rich impression of the surface you are in contact with, and not the tool or the vibrations themselves.

People physically contact objects in their surrounding environment by touching them, not only with their hands but also through tools. The use of tools to touch objects may seem unusual, but in fact, it is much more common than one may think. For example, when people use a pencil to draw on a rough paper, use cooking utensils or in much more specialised cases, performing minimal invasion surgery, are all examples where physical objects are felt through a tool object [**31**]. When drawing using a pencil on a piece of rough paper, the surface texture of the paper and the interaction components between the pencil tip of the pencil and the paper surface are felt and not the vibrations that travel through the tool (pencil). The vibrations are just the medium that conveys this information to the touch sensing receptors on our skin.

The sense of touch when coming through a tool can be characterised as a perceptual process. Therefore, three general components that affect how texture is perceived need to be taken into consideration [**33**]. The first one is the physics involved at the point of interaction between the tool's tip and the surface it is in contact with and the transmission of vibrations through the tool's shaft. The second component involves the filtering the skin and the responses of the mechanoreceptors impose on the information received. The third, and final, component involves higher order factors that are possible to alter the perception of surface texture. These factors include the mode of exploration (e.g. how fast the tool moves across a surface) or knowledge carried forward from previous experience with the same, or similar texture [**33**].

Moreover, touch can be characterised as being a temporally dissipative sense [**34**]. When a stimulus is received, the touch (or haptic) receptors involved begin to adapt to it, tuning the sensation caused by the stimuli out. This makes touch particularly sensitive to changes in haptic stimuli. No centralised organ exists to detect the sense of touch [**20**], like the other senses do (e.g. eyes for vision). Instead touch relies on sensors, called receptors, distributed through our entire body, encoding perceptual information upon receiving a stimulus. Our whole haptic sense then depends on our ability to piece together information coming from different spatial locations on our body [**34**,**23**]. Given that, and the fact that they are most sensitive in changes, haptics is an ideal medium for receiving a constant stream of useful information about our surrounding cancelling out anything that could be regarded as noise and reporting only the changes that occur.

2.7 Comparing direct and indirect touch

When exploring an object, people normally choose to use different stereotypical hand-movement patterns, depending on the property they are exploring. These patterns are called *exploratory procedures* (EP) [**35**] and participants in a number of studies were observed to systematically apply a specific EP depending on the attribute they were instructed to explore (e.g. moving their fingers back and forth across the surface when instructed to extract information about the surface's texture roughness) [**35**].

For the purpose of this comparison, the specific perceptual characteristic of texture investigated will be roughness. Roughness is considered to be one of the most important perceptual attributes of objects when they are being felt [**36**], and can be a persuasive cue for an object's identity [**37**]. When the texture of a surface comes in contact with the bare skin, the sensory system responsible for encoding and conveying information about touch related stimuli makes use of a spatial code to construct a spatial pressure map [**36**].

The spatial map produced consists of slowly adapting mechanoreceptors. The position of each activated mechanoreceptor directly maps features of the surface in contact, creating a direct correlation of features and stimuli [**21**] [**28**].

Alternatively, when the finger holds a probe, contacting the surface, the spatial map reflects the contours of the probe, and not those of the surface. Nevertheless, when the surface is explored with a probe, the surface properties that make up textures, give rise to vibrations, which are transmitted to the skin via the rigid link (tool or probe) [**21**], [**28**], and the spatial map constructed to replicate the tool's or probe's surface is tuned out.

Consequently, this vibratory input resulting from a probe passing across a surface is more than enough to provide a perceptual impression regarding the surface's roughness. The amplitude and frequency of these vibrations excites four mechanoreceptor sensor population groups in the skin. These mechanoreceptors are frequency-tuned, which means that their level of excitation depends on the frequency parameter of the vibration received [**36**]. When the same surface is felt with a bare finger, the total area of skin that the surface has instantaneously indented from a resting position defines the object's roughness perception; causing the speed the finger passes over the surface to play very little effect on the information perceived [**36**]. Alternatively, when exploring a texture with a probe, the speed the probe passes along the texture affects the frequency of the vibrations, and consequently the perception of the texture.

Therefore, the perception of textures, even though it appears the same when felt through a tool, the information received about the surface is different through a tool than that through bare skin. When exploring a surface through direct touch, a clearly defined two-dimensional spatial image of the texture and vibratory information are available to the receptors on the finger. Instead, when using a tool, the information received relies only on the vibrations transmitted through the tool's shaft. No special cues are available for texture perception since the pattern of deformation of the skin reflects the contours of the tool and not the surface [**33**]. In other words, there is a big and important difference in the information sent to the central nervous system forming the spatial map of a surface texture when comparing the sensation information obtained by the two exploration techniques.

This can be reflected on the results from experiments performed by Susan Lederman and Roberta Klatzky [**38**], where they found that both, the accuracy and time taken for recognizing an object, were significantly different between direct and indirect touch conditions. More specifically, it took longer for participants to give less accurate descriptions of objects when exploring an object with a probe (indirect touch) than with bare skin (direct touch). Klatzky and Lederman note that this is mainly due to the elimination of thermal and spatially distributed force patterns and spatial and temporal kinaesthetic cues. The results from these experiments also show that, in order to achieve accuracy levels with a probe for the shape and size of an object, similar to those of bare finger exploration, people had to explore the object for more time [**38**]. They also found that a set of EPs exist, which is very similar to the one mentioned above for direct touch, for when a texture is felt through a probe. The only difference is with these EPs is not only the motion that is important, but other factors in the exploration such as speed and force applied play a major role.

Therefore, regardless of the mode of exploration, either if it was via direct contact or indirectly through a probe, the roughness of an object could be judged. The only difference was the magnitude of roughness perceived and the time it took participants to come to a conclusion on how rough the texture felt.

2.8 Chapter summary

The aim of this chapter was to give an introduction on what haptics are and their importance in our everyday interaction with the environment around us. Being the earliest sense to develop in an embryo and from a very young age, us humans are very capable of using our hands very skilfully as a highly adapted tool for object exploration and manipulation. Highly developed sensors located in our skin can detect very small changes on the environment they are in contact with (e.g. temperature and pressure differences) and report them back so we can react to them accordingly. Having such an advanced haptic sense is recognised as one of the most critical factors in the phylogeny of humans, and this just comes to highlight the importance of haptics in our everyday life.

Researchers in psychology began exploring haptics during the early part of the twentieth century, defining haptics as being any form of nonverbal communication involving touch. During the later part of twentieth century, advancements in technology and electronics meant that researchers began to look at novel ways of interaction with machines involving touch. Instead of devising a new name for this new discipline, they decided to redefine the pre-existing term for haptics, broadening its definition and hence its domain to include all aspects of information acquisition and object manipulation through touch by humans, machines, or a combination of the two. This made haptics a massively wide domain, including not only psychologists but also other scientific fields, like electrical engineers, computers scientists and even medical researchers.

The sense of touch is not only confined to direct contact with our skin. Studies have shown that indirect touch, which refers to a situation where a surface is felt through the tip of a tool, can provide an individual with sufficient information about the surface texture. This information is sent through the shaft of the tool (creating a rigid link) via vibrations to specialised sensors on the skin that translate them back to information regarding the surface texture. Even though humans are very efficient in this, studies have shown that a number of information dimensions are lost (such as the surface's temperature) and others are greatly affected by parameters, such as the speed and time of exploration, which would otherwise not be affected.

These limitations of indirect touch, and the fact a force feedback device that simulates forces through a probe (single point of interaction) is used, had to be taken into account for this study and special arrangements were made in the experimental design to accommodate for them (i.e. provide participants with unlimited time for exploration and freedom to explore the surface with any speed they felt more confortable with). More on this on Chapter 7, page 82.

Overall, our haptic sense is a very highly evolved sense and plays a very important role in our every day interaction with our immediate environment. The downside is that touch is a very personal sense, that cannot be easily verbalised and measuring touch acuity or deficiencies in the same way we do for other senses, such as sight and hearing, is very difficult.

One possible method we can use for understanding how we sense the world around us, and attempt to quantify this sensation is with the use of psychophysics and psychometric tests. The next chapter reviews what psychophysics are and lists and explains a number of methods that can be used for measuring human perception, hence quantifying how we perceive physical stimuli from our immediate environment.

CHAPTER 3 – PSYCHOPHYSICS

3.1 introduction

Psychophysics is defined as the relationship between the sensation (psychological effect) and the physical stimulus [**39**]. Gustav Fechner was the first to refer to this relationship as "*psychophysics*" in his book *"Elemente der Psychophysik"* in 1860. This book was targeting at discovering a *psychophysical function* that would show the relationship between the intensity of the physical stimulus and the perceived stimulus intensity; something Fechner saw as a very important problem. Instead of measuring the perceived intensity directly, Fechner used an indirect method of measuring the ability of participants to discriminate between two physical intensities.

The two most important questions about the senses regarding psychophysics are (a) their limits and (b) their growth function, namely, the way the human nervous system interprets increases in the stimulus intensity to produce increases in sensory experience (sensory perception). These two psychophysical questions can be further divided into three main areas; detection, discrimination and scaling.

The difference between these areas is that *detection* is mostly concerned with asking the question of "What is the minimum amount of physical energy required to detect a stimulus?" whereas discrimination asks the question of "What is the minimal difference in physical energies required to discriminate between two stimuli?". The method of *Scaling*, on the other hand does not evaluate the stimuli on the physical energy level. Psychophysical scaling methods aim at formulating as accurate a theory as possible that allows the computation of perceived stimulus properties from purely physical attributes [**40**].

The sensitivity is therefore measured in what is called an *absolute threshold* for detection and the difference threshold, or just noticeable difference threshold, for the discrimination. This just noticeable difference threshold (JND) is therefore, according to Gescheider [**41**], "the smallest amount of stimulus energy necessary to produce a sensation". In other words, JND is the smallest amount of detectable difference between two stimuli intensities that an individual can perceive.

For the purpose of this study, two psychophysics methods were used: the *Method of Discrimination* with *constant stimuli* and *Unidimensional scaling* with *Steven's Power*

Law. Both methods are described in the sections below, along with a brief definition on what is a threshold.

3.2 What is a "threshold"

Threshold is defined as being the limit, below which a given stimulus or the difference between two stimuli ceases to be perceptible [**42**]. Even though this is the dictionary definition of thresholds (in reference to psychophysics), it can be termed as misleading since it suggests that there is one point along a physical range below which an observer would never be able to detect a stimulus or stimulus change and above which the observer will always be able to detect a stimulus or stimulus change (see Figure 3). This is not true though. Even under the best-controlled experimental conditions, with participants that are highly motivated, there will be variability in the responses given near the stimulus threshold (Figure 4).

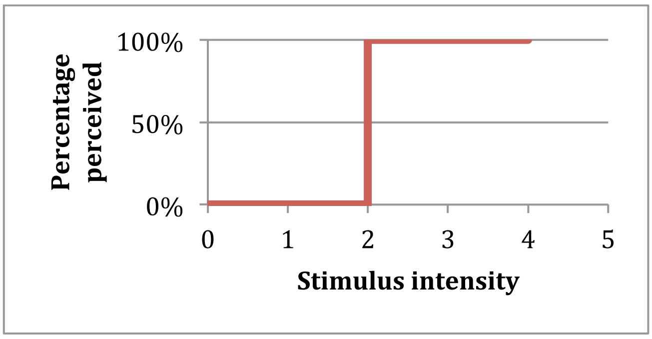

Figure 3 Ideal psychometric function

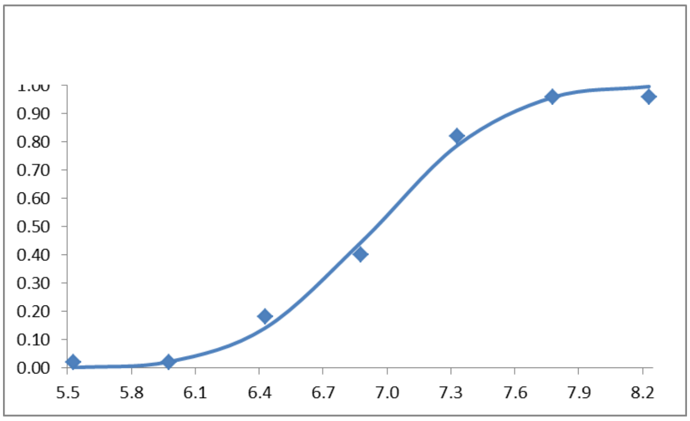

Figure 4 Expected psychometric function

(Function taken from Dr Mikellidou experiment on the perception of length of a visual stimulus, for the department of Psychology, University of York)

Therefore, the ideal shape as shown on figure 3 is near to impossible whereas the more realistic shape shown on figure 4 is the one most commonly expected.

The variability observed near the threshold values is usually attributed to variability in the state of the participants, produced by momentary changes in attention or even changes in sensitivity of the sense organ. Therefore, since responses to the same stimulus can be variable, the participant's threshold must be defined statistically rather than absolutely.

3.3 Method of Discrimination

In stimulus discrimination [**42**] [**39**], the difference threshold for a participant of a pair of stimuli is measured rather than the absolute threshold for a single stimulus. This *difference threshold* is defined as the difference between two stimuli that is just large enough to be detected. The two stimuli can be either presented successively in two time intervals, or simultaneously in two spatial positions, depending on the nature of the stimuli.

A difference threshold is always measured and defined with respect to a standard, or reference stimulus. Therefore, the standard is always presented on every trial along with a comparison, which has a lower, greater or equal intensity of the stimulus to that of the standard. Two methods exist of comparing each stimuli pair and those can be either with either a *Three-category* or a *Two-Category (Forced-Choice) method.*

With the *three-category method*, the participants can use three possible responses when they are asked to compare the two stimuli; and those can be that it is of "lower", "greater" or "equal" intensity to that of the standard. On the other hand, when the *two-category method* of response is used, the participant is forced to choose between two responses by deciding if the comparison stimulus is "lower" or "greater" than the standard stimulus.

Two statistics are calculated from discrimination experiments: the difference threshold or Just Noticeable Difference (JND), and the point of subjective equality (PSE). The JND is the point where the minimum amount of physical change gives a perceived change. It is defined as the physical difference between two stimuli that is correctly detected 50% of the time for a three-category method and 75% of the time for a two-category method. The PSE is the physical value of the comparison that is perceived to be identical to the standard and they do not necessarily have to be equal. It is the point that they are *perceived* to be equal.

When measuring discrimination thresholds, the three-category method is considered to be less accurate than the two-category (forced choice) method [**41**]. This is largely because it allows (and many will argue that it encourages) the use of the "equal" response. This is mostly because it is highly unlikely for two stimuli to be exactly equal, therefore participants need to set some criteria for themselves in order to judge two stimuli to be the same or different. There is no guarantee that different participants will adopt the same set of criteria or that the same participant will follow the criteria they set from one trial to the next. This causes a dramatic instability of the "equal" response, which may greatly affect the results by increasing the value of the JND.

Alternatively, the forced choice method, participants are forced to choose between two responses; "lower" and "greater". When a participant is uncertain, like when the two stimuli appear the same, the participant is assumed to choose equally between the "lower" and "greater" response [**42**].

3.3.1 Method of Limits

The method of *Limits* is often used in measuring *difference thresholds* as well as *absolute thresholds* (discussed above) [**42**] [**39**]. When looking for difference thresholds, two stimuli are presented simultaneously in pairs. One of the two stimuli retains its intensity throughout each series of trials, called the *standard stimulus*, and the other changes in intensity between each trial, called the *comparison stimulus*. This change in stimulus intensity for the comparison stimulus can start from a clearly discriminable point above the standard and move closer to the standard by a constant decrement for each trial (descending series) or start from a similarly discriminable point below the standard and again moves towards the standard by increasing the intensity (ascending series).

The participant has to then report how the two stimuli intensities compare to each other for every trial. If, for example an ascending series is used, the participant starts by reporting that the comparison stimulus feels of "lower" intensity and as the series progresses, the participant will start reporting that they feel "equal" when the two stimuli intensities are close to each other and "larger" when the intensity level is bigger for the comparison than the standard. The reverse occurs in the case of descending order.

By doing this, two transition points are obtained. These are termed as the *upper limen* and the *lower limen.* The upper limen is the point in the physical dimension where "larger" responses turn to "equal", and, similarly the lower limen where the "lower" responses turn to "equal".

After a number of upper and lower limens are obtained from each participant, mean average values can be calculated. The space between the upper and lower average limen value is called the *interval of uncertainty* (*IU*) and is calculating by subtracting the average lower limen from the average upper limen. This UI is a range on the stimulus physical dimension, in which an observer cannot perceive any difference between the comparison and the standard stimuli. Therefore, the point of subjective equality (PSE) using this method, can be calculating by dividing the UI by two, hence finding the midpoint of the range in which no perceivable difference occurs.

Method weaknesses

In the method of *limits*, the stimulus is gradually changing towards the threshold for several trials, and there may be the tendency of an observer to acquire a habit of repeating the same response [**42**]. This may result in a participant continuing to give the same response a few trials after the threshold was reached. Errors of this kind are called *errors of habituation* [**41**] and may affect the data by increasing the threshold during ascending series and decrease the threshold during descending series.

Contrary to this constant error, a test participant may anticipate the arrival of the stimulus threshold and report the change of the sensation prematurely [**41**]. This is called an *error of expectation* and ascending series thresholds will be deceptively low and descending series thresholds too high.

These two errors are very unlikely to be of equal magnitude and therefore they cannot be considered as cancelling each other out [**41**] [**42**].

3.3.3 Method of Adjustment

During this method, participants are presented with both stimuli simultaneously, and are asked to adjust one of them (the compare stimulus) until it is perceivable identical to the other (standard stimulus) [**42**]. This is also often referred to as the *method of average error*, since an experiment employing this method is mostly intended to highlight the discrepancies between the observer's settings, as applied to the comparison stimulus, and the physical values of the standard stimulus.

Over the period of a number of repeat measures, a participant's responses may sometimes vary by a considerable amount compared to the values of the standard, by overestimating and/or underestimating the values; but this will not stop most of the matches from clustering around the value of the standard. The mean of the values obtained can then be calculated to determine the PSE value. If no constant errors exist, the PSE value should correspond closely to the physical value of the standard stimulus. The *Constant Error* (CE) is calculated by subtracting the physical value of the standard stimulus (V_{st}) from the value of the PSE (i.e. CE = PSE – $V_{st.}$).

Ideally the CE will be zero, but whether it is or not, the standard deviation of the mean calculated can be used as the JND. A large standard deviation value would indicate poor discrimination, i.e. the two stimuli appeared identical over a wider range of physical values of difference between the standard and the comparison.

Method weaknesses

This method is difficult to apply under two unique conditions [**41**] [**39**]. The first condition comes when the stimuli are not continuously variable. This happens in the case that variations are varied in steps and a participant cannot go through the whole range of the stimuli intensity. This makes the measurement of JND greatly inaccurate. The other condition is when the two stimuli cannot be presented simultaneously to the participants. When the standard stimulus must be presented first and then replaced by the comparison stimulus for the participant to adjust, it is impossible to counterbalance or measure the stimulus order effects.

Finally, another limitation of this method arises from giving the participant full control over the comparison stimulus. This makes it difficult, or even impossible, to maintain constant conditions during the threshold measurements [**41**].

3.3.3 Method of Constant Stimuli

In the method of constant stimuli, pairs of stimuli, (called the standard and the comparison stimuli) are presented in a random order to the participants, making sure that nothing would indicate to them which one is "larger" (the comparison or the standard) in every trial [**42**] [**39**]. The participants can use only one of two responses (forced choice method) to describe what they think the difference between the two stimuli is. Since only two choices are available, a single psychometric function, which plots the proportion of "greater" responses against the value of the comparison stimulus or the physical difference between the pair, can be used to summarise the data (see Figure 5).

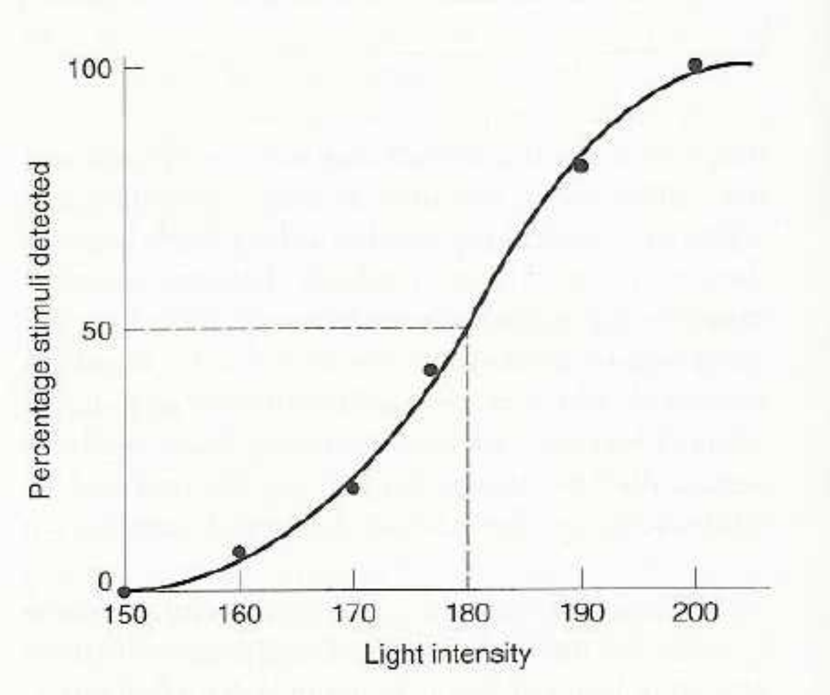

Figure 5 Psychophysical function using the method of constant stimuli for light intensity

The PSE is then judged as the value at the 50% (or 0.5) mark, assuming that when the comparison stimulus appears equal to the standard, the participants will call it "larger" 50% of the time and "smaller" the other 50% [**42**]. This psychometric function is usually assumed to be well fitted by a normal ogive (the cumulative of the normal distribution). This plot of the ogive can be done easily by eye so that the PSE and JND can be deduced by inspection. However, a more accurate method is to use a plot in log-log coordinates, rather than the proportions. This will produce a straight-line psychometric function and a standard linear regression technique can be used for fitting a straight line through it.

The upper difference threshold can then be calculated as the difference between the PSE and the value at the point ($S_{.75}$) where the comparison stimulus was judged to be "greater" 75% of the time ($S_{.75}$–PSE). The lower threshold is then the point ($S_{.25}$) at which the standard stimulus was judged to be "greater" 25% of the time, subtracted by the PSE (PSE–$S_{.25}$). The JND is then calculated to be the average of the upper and lower difference threshold values (see Figure 6).

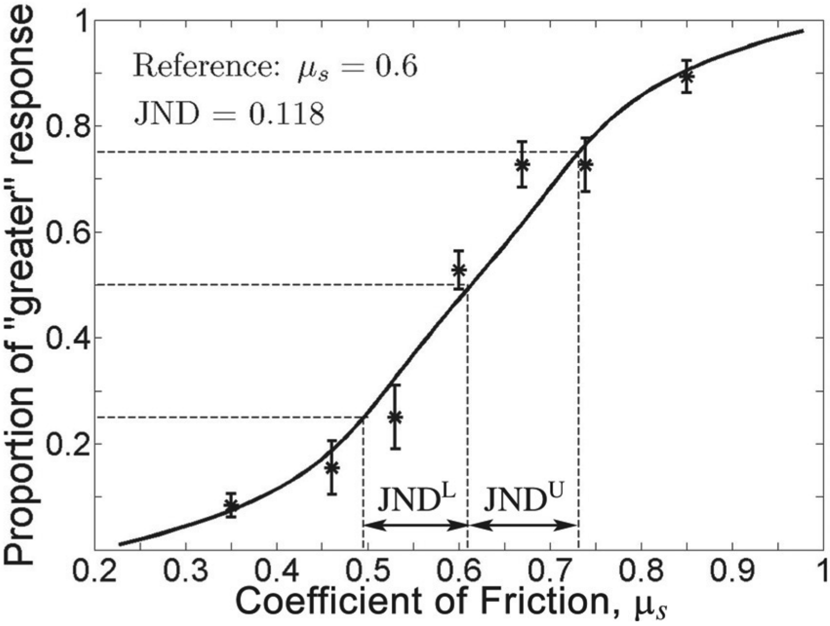

Figure 6 Psychophysical function of the perception of friction coefficients, showing the 0.25 and 0.75 JND points [43]

The reason for taking the 75% and 25% points to define the JND is simple and has to do with statistics of probability. The PSE is defined as the point where the change between the intensity of two stimuli is detected 50% of the time, but in the forced choice method, the chance performance is again 50% since the participant can choose between two responses, even when the stimuli appear equal. Accordingly, a participant is said to be able to detect a difference in the threshold in the appropriate direction, when he or she is correct 75% of the time (25% on the opposite direction). This 75% figure includes the 50% that can occur by chance, but also includes half of the remaining 50% that was correct by true detections. Therefore, a participant is actually detecting a difference 50% of the time when he or she is correct 75% of the time.

Method weaknesses

When using the method of *constant* stimuli, the PSE value does not always correspond exactly to the physical value of the standard stimulus. The difference between the calculated PSE and the physical value of the standard stimulus is a psychophysical quantity called the *constant error (CE)* [**42**]. This CE reflects the effects of some uncontrolled factor, which systematically influences what is being measured. This makes the numbers recorded systematically either too high or too low by a certain amount [**42**]. Space and time errors are constant errors since they affect the observer's judgement. If, for example, the standard stimulus is constantly presented first and the comparison stimulus second or having a constant orientation in the physical space (e.g. left for the standard, right for the comparison), the comparison stimulus would gather a greater proportion of "greater than the standard" responses because of a natural tendency underestimate the stimulus intensity of the stimulus sensed first [**39**] [**41**].

3.4 Choosing a psychometric method

So far the *method of discrimination* with *limits*, *constant stimuli* and *adjustment* are considered as possible psychometric methods to be used in this study. All methods have their strong and their weak points, and therefore there is not a panacea method for all situations. This section aims to analyse the weak points of every method in order to help with choosing the most suitable one for this study.

With the method of limits, the *error of habituation* and the *error of expectation* need to be considered and addressed. These errors can be prevented, or at least minimise the effect of these errors on the data is by varying the starting point, so that the participants will not anticipate the threshold after a certain number of trials. This seems to tackle the error of expectation, but having more trials can escalade the effects caused by *habituation.* According to [**42**] keeping the test sessions as short as possible, the chances of habitual tendencies are minimised [**41**]. But this means fewer trials, and therefore a greater chance of *error of expectation*. The solution is therefore a delicate balance between repetitions and keeping the overall session as short as possible. This balance may be difficult to achieve and may vary significantly between individual participants. This uncertainty over the right balance meant that the method of limits was not used in this study.

The method of adjustment is difficult to apply in two conditions: when the stimuli are not continuously variable and when the two stimuli cannot be presented simultaneously to the participants. Even though in this study, the stimuli can be continuously variable and both stimuli can be presented simultaneously, this method will also not be used in this study. The reason is the third limitation, as described in page 20 above, which result from giving the participant full control over the comparison stimulus. This makes it difficult, or even impossible, to maintain constant conditions during the threshold measurements. Therefore, even though this method may be the fastest of all considered, it will not be used because of this lack of certainty.

The last method considered in the sections above is the method of constant stimuli. The only apparent limitation of this method is when defining the PSE as the point where the change between the intensity of two stimuli is detected 50% of the time. This is the same rate as when a participant was making choices by chance (50% chance either way in forced choice method).

As explained on page above, a relatively easy way of going around this limitation is by considering the PSE at the point where a participant is able to detect a difference in the threshold in the appropriate direction and be correct 75% of the time (25% on the opposite direction). This 75% figure includes the 50% that can occur by chance, but also includes half of the remaining 50% that was correct by true detections. Therefore, a participant is actually detecting a difference 50% of the time when he or she is correct 75% of the time.

Thus, having considered the available psychometric methods, the one chosen use in this study as the most appropriate one is the *method of discrimination* with *constant stimuli*. It fits the aim of the study and has weaknesses and limitations that can be supported to overcome in the context of this study.

3.5 Scaling

Traditionally, *scaling* had as its purpose to discover the form of the psychophysical function that best describes the relationship between the physical intensity of a stimulus (e.g. light) and corresponding psychological intensities (e.g. brightness) [**39**].

Two forms of scaling exist, unidimensional and multidimensional scaling. Both of these methods are described in the sections below.

3.5.1 Unidimensional scaling

Unidimensional scaling is used in conditions where all other dimensions of a stimulus are kept constant, while one dimension is varied. In 1957, Stevens and Galanter separated unidimensional scaling into two distinct dimensions; the *prothetic* (dimension of quantity) and the *metathetic* (dimension of quality) [**44**].

The *prothetic continua* are defined as attributes "*for which discrimination appears to be based on an additive mechanism by which excitation is added at the physiological level*" [**44**]. For example, these attributes may be the brightness for a visual stimuli, or warm, cold and pain for tactile stimuli.

The *metathetic continua* are defined as attributes "*for which discrimination behaves as though based on a substitutive mechanism at the physiological level*" [**44**]. For example, the hue in a visual stimulus and the position in a tactile stimulus, both contain *metathetic* attributes.

Therefore, because a psychophysical function relates a quantitative physical dimension to a quantitative psychological dimension, only the *prothetic* (quantitative) dimension is relevant in discovering the form of such a function.

As described in the previous sections, Gustav Fechner developed and systematised the various methods of measuring thresholds. However that was not his ultimate goal. His goal was to use them to find the form of the psychophysical function; in other words, how big does a difference need to be when two large stimuli are being compared as opposed to two small stimuli being compared? Naturally, one could logically deduce that a small change is more noticeable against a small-magnitude background than against a large-magnitude background. For example switching on a light bulb in a dark room can have a blinding effect, but it will make no difference in a well-lit room. Similarly, a small difference between two stimuli of small-magnitude is more noticeable than the same differences between two large-magnitude stimuli. For example a difference in weight between two apples is more noticeable than the same physical difference between two watermelons [**42**].

Weber's Law

Ernst Heinrich Weber discovered a significant relationship in 1834 between the size of the JND and the size of the standard in lifted weights. This relationship came to be known as Weber's law and formed the basis of much of the work of researches such as Fechner (above) [**41**]. Weber's Law states that the ratio between the JND to the standard is a constant over a wide range of standards and can be described by the following formula:

$$K = \frac{JND}{Standard} \tag{1.}$$

where K is a constant known as the *Weber's constant*, or *Weber's fraction*. Weber's law signifies the existence of a percentage increase in the comparison stimulus over the standard for it to be discriminated to the same criterion. For example, if the Weber constant for an attribute is 1/30, the JND is 1 for a standard of 30, 2 for a standard of 60 and 10 for a standard of 300.

The Weber's law is also commonly notated as:

$$K = \frac{\Delta I}{I} \tag{2.}$$

Where K is again Weber's constant, ΔI is the change in the standard (JND) and I is the value of the standard.

This law is a way of quantifying discrimination ability. Fechner, who was one of Weber's students, saw a way of extending this law as a description of the discriminability of stimuli, so in Fechner's method of *indirect scaling* Weber's law provides the unit of sensation magnitude.

Indirect scaling and Fechner's law

Fechner believed that it was impossible to measure sensation directly, since as he understood, participants are not capable of assessing the magnitude of a sensation they feel, but only if a stimulus gives a stronger or a weaker sensation than another stimulus [**39**]. Considering the work of Daniel Bernouilli, Fechner proposed that the relationship between stimulus and sensation should be logarithmic instead of linear. A better way to understand this relationship is through an example, and Bernoulli [**39**] gives a very nice one in terms of economics, and how salary increase can relate to peoples' happiness.

Bernouilli, who was a mathematician, proposed a mathematical function that predicted that equal *percentage changes* in money (rather than absolute value increases) will produce equal increase in utility (satisfaction or happiness). To apply Bernouilli's law, to salary rises, the two salaries need to increase by the same percentage in order for two employees earning different amounts of money to have the same level of satisfaction. Therefore, if someone earning £10,000 per year will be as happy receiving a £1,000 rise as someone who has a salary of £20,000 receiving £2,000 rise. If both employees received a £1,500 rise, the higher paid employee would be more disappointed and less satisfied than the lower paid employee.

This can be considered as a metaphor to stimulus increase (salary) and its relationship to a perceptual magnitude increase or decrease (employee's satisfaction level).

Fechner made three assumptions when deriving his logarithmic law.

The *first* assumption was that a physical difference between two stimuli is subjectively equal regardless of the magnitude of the two stimuli; i.e. if it is a small difference between two small-magnitude stimuli, or a large difference between two large-magnitude stimuli. Therefore, if we have the weight of two small objects as the stimulus and we find the difference that is just detected (JND) to be 1 gram, and two larger objects have a JND between them of 5 grams, the subjective difference in weight at the high end of the scale for the larger object will be the same as the subjective difference of the smaller objects at the low end of the scale.

The *second* assumption was that Weber's Law is true across the entire stimulus intensity range. This is known not to be true since it is proven that Weber's Law breaks down near the threshold values.

Finally, Fechner's *third* assumption was that noticed differences that have the same probability of detection are also subjectively equal, except if they are never or always detected. Thus, differences that are detected 75% of the time are also equal to one another.

With these three assumptions in mind, Fechner deduced that the form of the psychophysical function was logarithmic. This logarithmic relationship can be seen in Figure 7.

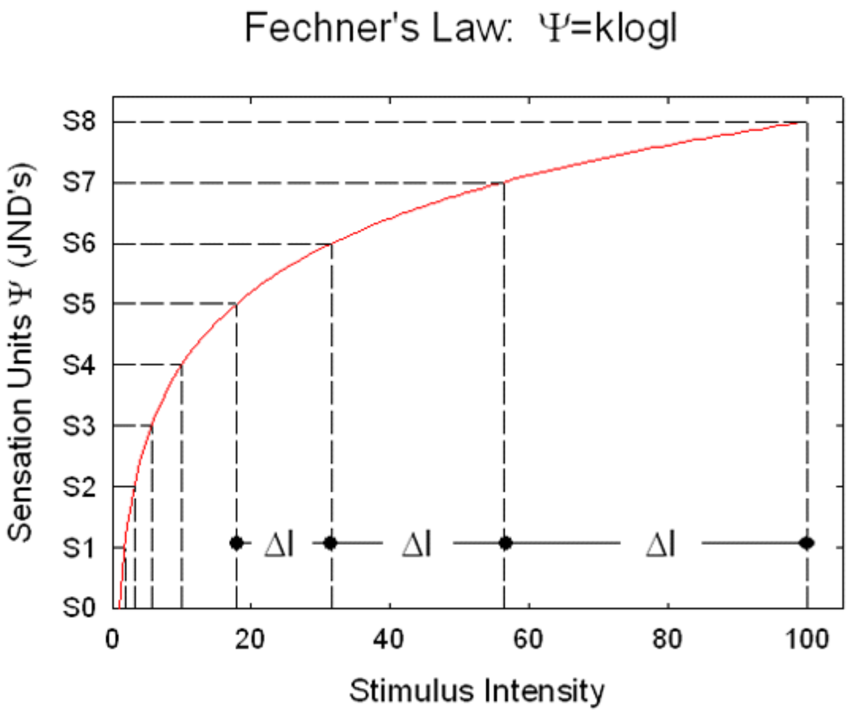

Figure 7 Fechner's Law of Logarithms

In this figure, the sensation begins at the absolute threshold mark and the stimuli are differing by equal numbers of JNDs along the abscissa. According to Weber's Law, the JND value increases as stimulus intensity increases. Therefore, the stimuli differing by equal values of JND becomes more widely spaced as we move to the right along the stimulus scale (abscissa).

On the other hand, because JNDs are assumed to be subjectively equal (first assumption); these stimuli are equally spaced as we move upwards along the sensation scale (ordinate).

Thus, Fechner's law can be stated as:

$$S = C \log I \tag{3.}$$

The sensation S, produced by the stimulus is related to the logarithmic value of the stimulus magnitude (log *I*) multiplied by a constant C (not the same as the K constant from Weber's law).

This law is derived from Weber's law using his primary formula:

$$\Delta S = k\left(\frac{\Delta I}{I}\right) \tag{4.}$$

where ΔS is the change in sensation, which is proportional to the ratio of the change in the physical intensity of the stimulus ΔI to the intensity of the standard times a constant K. By treating this fundamental equation as a differential equation and integrating it, we derive to Fechner's logarithmic law formula above.

Magnitude estimations and Steven's Power Law

The logarithmic Fechner's law held for over 100 years without being questioned, dominating the field of psychophysics. An example of this domination is the measurement of acoustic stimuli that are still measured in the logarithmic units of *decibels*. However researchers started to find differences between their observed data and Fechner's logarithmic function when they started to measure sensations magnitude directly.

That prompted S. S. Stevens to publish a paper entitled "To Honor Fechner and Repeal His Law" in 1961 and argue that the correct form of the psychophysical function is not a logarithmic but a power function [**45**].

The way Stevens measured sensation was simple and direct. He would ask his participants to report directly giving magnitude estimations with numbers how intense they perceive various intensities of a stimulus in comparison to a standard stimulus. In a typical experiment of *magnitude estimation*, participants were given the standard stimulus and asked to assign a number to it. If a participant assigned the number 10 to the standard stimulus, when a comparison stimulus felt to be twice as intense, for example, the participant would report a number twice as high (20 in this case). The same was applied if a stimulus would appear two times less intense (5 for this example). This procedure would be repeated for the entire scale that was under investigation, with participants quantifying the sensation difference they sensed.

This helped Stevens to construct the *Stevens' power law,* which states that:

$$S = \alpha I^{\beta} \qquad (5.)$$

Where S is the sensation magnitude, I the stimulus magnitude, α a constant that reflects the number the participant chose for describing the standard and β is an exponent that depends on the type of stimulation and was previously calculated for every kind of stimulus and can be referred to from a table. A β value equal to one would show linear growth of sensation with stimulus intensity, $\beta < 1$shows lower growth of sensation with stimulus intensity and $\beta > 1$ a quicker growth (see Figure 8).

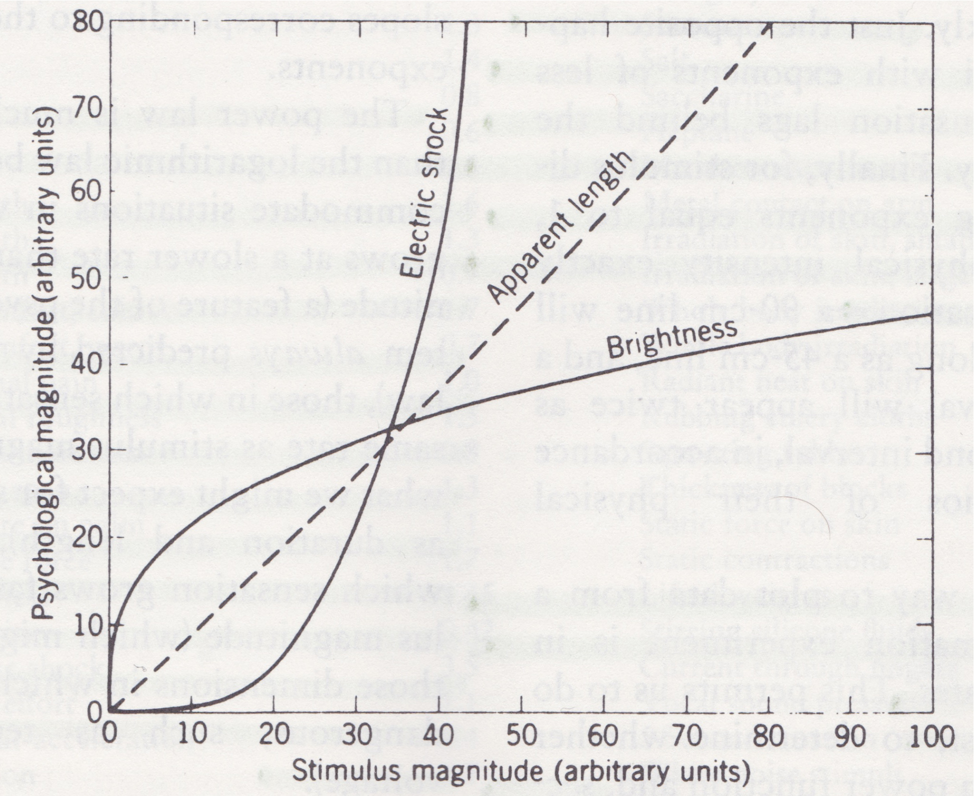

Figure 8 Psychophysical functions of three stimuli. Electric shock with β>1, apparent length with β=1 and brightness with β<1. Figure taken from [39]**.**

From this figure, it is easily observable that for an exponent β greater than 1 the sensation more than doubles as the stimuli intensity doubles (electric shock Figure 8). On the other hand, the opposite happens for an exponent β less than 1 (brightness Figure 8), while the sensation doubles as the stimulus intensity doubles for an exponent β equal to 1 (apparent length Figure 8).

A *useful* way of plotting data from magnitude estimations is through log-log coordinates [**46**] [**47**]. This kind of a plot, allows an observer to determine if the data follow a power function and to estimate the two constants of the power law (α and β). If we take logarithms of both sides of the equation (Equation 5., above) we obtain the following equation of a straight line:

$$\log S = \beta \log I + \log \alpha \tag{6.}$$

In this equation, the exponent β is the slope of the function on the log-log graph and log α is its intercept. The same three plots are shown in log-log coordinates in Figure 9 below.

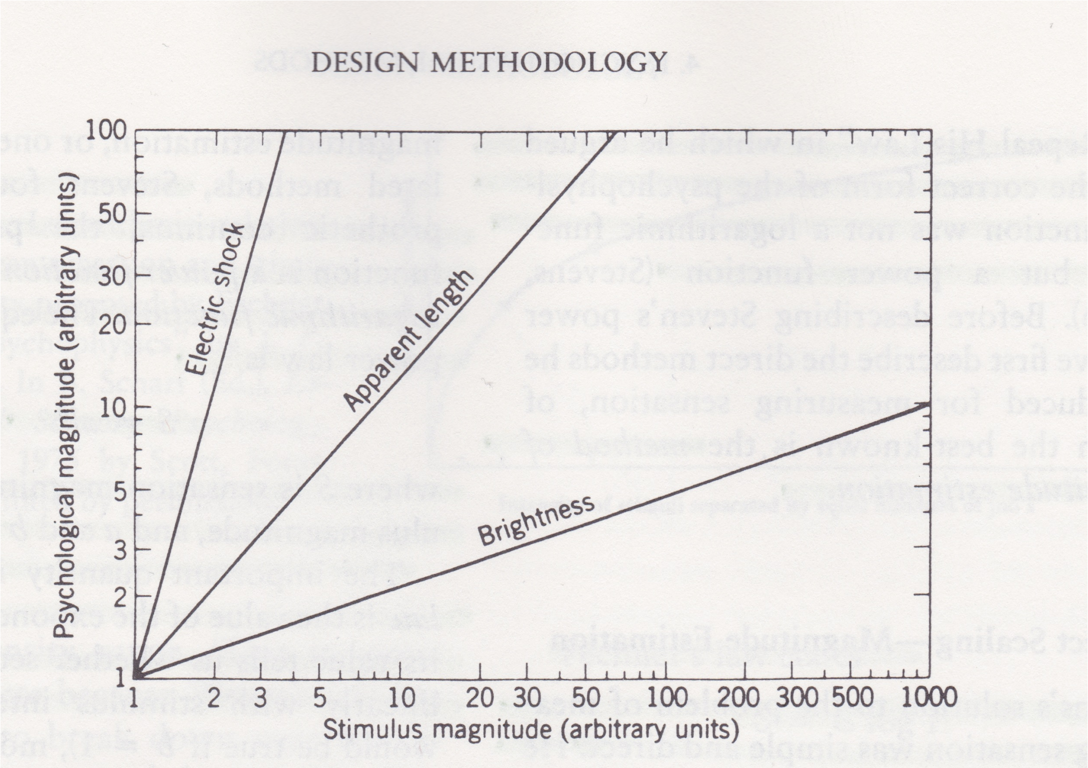

Figure 9 Curves as shown in Figure 8 plotted using logarithmic coordinates [39].

Steven’s power law has its critics that argue that its limitations and assumptions make it unreliable in analysing a psychophysical function. There is an argument that Steven’s power law approach is ignoring any individual differences between participants. This causes the power relationship to be unstable when data are considered individually for each participant [**48**].

In a more recent study, Kornbrot et al. [**49**] found that some of their participants in a psychometric experiment had individual psychometric functions with considerable diversity, even though their average psychometric function agreed with the expected values. This let Kornbrot et al. to conclude that individual analyses are not the same as those based on grouped analyses. These differences suggest that individual analyses should be conducted along with group analyses in order to accommodate for this weakness.

Therefore, the fact that method of magnitude estimations and Stevens power law is designed to describe the relationship between a physical change in the state of a stimulus and the change in how the stimulus is perceived as well as the ease by which one can overcome its main weakness made this the most suitable psychometric method for this study.

3.6 Chapter summary

Psychophysics aims to quantitatively investigate the relationship between physical stimuli and the sensations or perceptions they affect. It has been described as "the scientific study of the relation between stimulus and sensation" [**42**,**42**] or, more completely, as "the analysis of perceptual processes by studying the effect on a participant‘s experience or behaviour of systematically varying the properties of a stimulus along one or more physical dimensions" [**50**].

Two aspects of the psychophysical function are of utmost interest: the point where the function begins; also known as the absolute threshold, and its scaling factor, or how psychological magnitude increases with the physical magnitude. The absolute threshold gives the starting point of the function, which is also the amount needed a physical stimulus to increase in intensity to produce psychological awareness.

Through the years, numerous researchers tried to define a method to analyse how different stimuli with dissimilar physical properties are perceived to be. The most important ones were Weber, Fechner and Stevens; with each one building on the work of his predecessor, trying to find and exploit weaknesses and make their own method prevail. All methods have their strong and their weak points, and therefore there is not a panacea method for all situations.

This study is mainly concerned on how stiffness, a physical attribute of an object, alters the way it is perceived to be in terms of its roughness. It is therefore an investigation of how a change on the magnitude of a physical property of an object alters the perceived magnitude of a stimulus response. After reviewing the current literature and considering all the available options, a decision was made that the most suitable psychometric method to use for this study is Steven’s Power Law.

This method is designed specifically for investigating how changes on the physical magnitude of a stimulus affect the magnitude of a perceived response and has been used successfully for a number of years for analysing results of similar studies. The only disadvantage of this power law is its weakness in considering variability from individuals. As Kornbrot et al. suggest in [**49**] this weakness can easily be addressed by considering the data given by each individual participant along with the mean results of the group. Accommodating for individual variance help, not only to address Steven's Power Law most criticised weakness but also help the researchers looking at the results gain a better understanding to the bigger picture of the study's conclusions.

In addition, the method of *discrimination* with *constant stimuli* was used in a preliminary experiment to verify the fidelity of the haptic force feedback device used for this study. This particular method was chosen after carefully analysing the weaknesses of all available psychometric methods applicable to this study.

Both the preliminary experiment and the main investigation where these two methods were used are found in Chapter 6 - Experiment preface, page 64, and Chapter 7 – Experiment investigating the relationship between physical stiffness and perceived texture roughness, page 82.

The next chapter discusses how psychometric methods are used for exploring and understanding the way physical properties of a texture affects how the texture is perceived through touch.

CHAPTER 4 – TEXTURE HAPTIC PERCEPTION

Textural information can be obtained both by visually inspecting an object [**51**] or by listening to the sounds produced during exploration [**52**]. The sense of touch produces much finer and more complex textural information than the other sensory modalities do. During haptic exploration of a surface, we may perceive the surface as being rough, like sandpaper, or smooth, like glass; the surface may also vary among other sensory continua, such as hardness (e.g., stone) vs. softness (e.g. jelly), stickiness (e.g., tape) vs. slipperiness (e.g., soap). Also, whether a texture is thermally insulating (e.g., plastic) or thermally conductive (like metal) contributes to the textural percept [**53**] [**54**].

The next sections concentrate on how the roughness and stiffness of a texture is perceived haptically and how changes on a surface's physical structure can affect this perception.

4.1 Perception of texture roughness

The subjective sense of roughness seems to vary along a single dimension and has been shown to vary predictably with surface properties. More specifically, these surface properties that help to create the perception of an object's texture roughness are mostly raised elements that may form ridges and grooves of different heights and depths on the surface, or they may be scattered elements (or dots) of different diameters, heights and distribution densities.

4.1.1 Sandpapers and sandpaper-like materials

Early experiments on how texture is perceived used paper [**55**]. David Katz noticed that his participants exhibited great sensitivity to differences in the smoothness of paper and other planar materials, and found that they could discriminate two sheets of paper based on their textures. He concluded that vibrations were responsible for the perception of texture and how rough it was described by the participants. When he experimented with paper surfaces felt through the tip of a pencil rather than their fingertips, he found recognition and discrimination of textures to be almost as good. Performance was greatly disrupted, though, when Katz wrapped the pencil with cloth to damp the transmitted vibrations.

Katz work was pioneering and proved experimentally that the perception of texture roughness is directly related to the vibrations that texture produces during haptic exploration. On the other hand, paper does not provide sufficient control over its texture, therefore, subsequent experiments on texture perception made use of sandpaper. With sandpaper, the size, height and density of the elements that make up its surface texture can be more easily controlled and their effects more effectively linked to roughness estimations made by the experimental participants.

Magnitude estimation experiments investigating roughness and smoothness perception using emery cloths and sandpaper found that the perceived roughness was related to the grit number[1] by a power function [**56**]. More specifically they found that magnitude estimations of roughness would increase as the grit number decreased. This relationship between grit number and roughness estimated value would form a straight line when plotted using a power function (log-log) against each other with a negative exponent of -1.5. Interestingly, the same study concluded that when the same participants were asked to describe the same set of emery cloths in terms of smoothness (linguistic opposite to roughness) they produced a perceived smoothness power function relating it to grit number with an exponent of +1.5 [**56**], the direct opposite of roughness. This comes to prove that roughness and smoothness are opposites in the context of texture perception estimations.

In addition, for textures made up of raised elements, similar to the ones mentioned above (sandpapers and emery cloths), the perceived roughness increases monotonically with inter-element spacing of up to a point and then drops, forming an inverted “U” shape. Connor et al. [**1**] measured this relationship in 1990 using a plastic surface with embossed surface patterns made up of dots (truncated cones with a flat top) in a square tetragonal arrangement. In this arrangement the peak for roughness perception was found to be when the dots were 3.2mm apart (see Figure 10a).

4.1.2 Controlled surface textures

In addition to the relationship between the inter-element space and roughness perception, Connor et al. [**1**] also defined a relationship linking the diameter of the elements and the perceived roughness. This relationship shows that the texture is perceived as less rough with an increase in the diameter of the dots, even if the

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[1] Grit number refers to the number of openings per square inch in the sieve used for applying the abrasive powder on the cloth. Therefore, it is equal to the number of sharp particles per square inch.

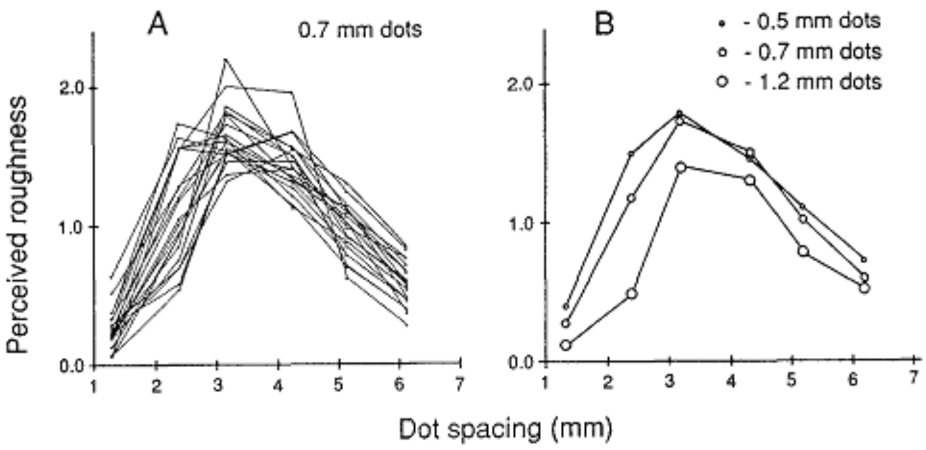

Figure 10 Normalised roughness magnitude against dot spacing. A) Curves for individual participants. B) Average curves for three dot dimentions [1]

distance is kept constant (see Figure 10B). Therefore, in textures made up of raised elements, both the inter-element space and the radius of each element play an active role to the perception of roughness [**1**].

4.1.3 Active versus passive touch

Studies also compared roughness magnitude estimation using active (participant moves his/her finger) and passive touch (stimulus moves under participant's finger pad) finding no difference in roughness perception between the two modes [**57**]. The same results were found in experiments using the discrimination technique, reporting no difference in roughness perception between active and passive touch or even between blind and sighted participants [**51**], indicating that the visual sense during exploration through touch plays no role.

There is however difference between static and dynamic touch [**53**]. With static touch (participant touches the surface and no movement takes place), estimations produced the expected correlation between the perceived roughness values and the size of the particles on the surface used, but only when the particles were larger than 100μm. Therefore, having no movement between the finger pad and the surface did not play any role in that situation [**53**]. On the other hand, when the size of the particles was below 100μm, the absence of movement seriously degraded the discrimination of roughness. The reported roughness increased as the particle size increased from 9 to 100μm by as much as a factor of three when movement was involved but only increased by a factor of 1.3 without movement (levelling off completely at 30μm). See Figure 11.

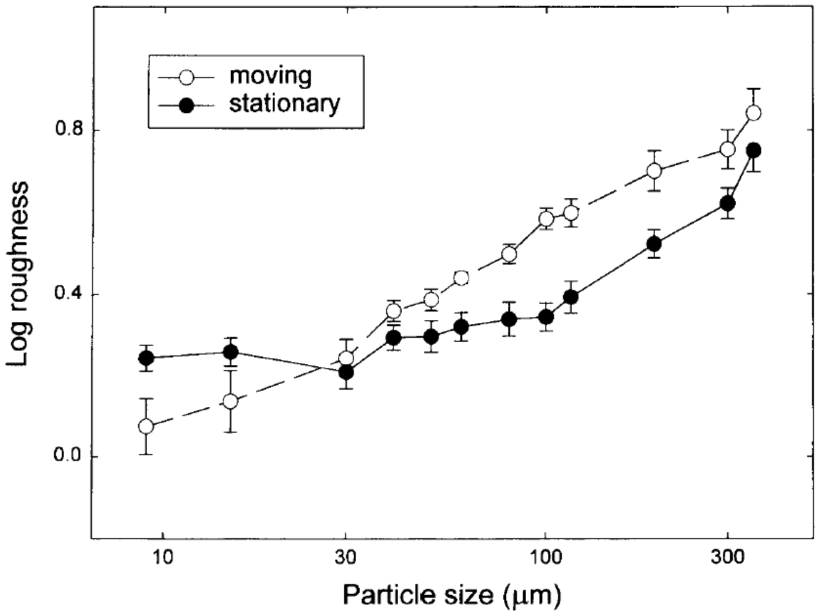

Figure 11 Log estimated roughness as a function of the particle sizes on abrasive surfaces [53]**.**

This difference below 100μm can be explained by considering the role of vibrations in roughness perception. In the dynamic condition both pressure and vibration cues are available, whereas in the static condition, only pressure cues are available. Not having any vibration cues is sufficient for coarser textures (>100μm), but for the perception of finer textures, vibrations are necessary and no difference in roughness is perceived for these fine textures without them. This was confirmed in an experiment by Hollins et al. [**58**] Pacinian receptors are nerve endings in the skin, responsible for sensitivity to vibrations and pressure. In the experiment these were desensitised in participants through adaptation with a 100Hz vibration. This adaptation was found to impair the discrimination of fine but not coarse textures, showing that the perception of coarse textures does not depend exclusively on vibrations.

4.1.4 Materials with ridges and grooves

In the studies mentioned so far, the authors used sandpaper-like materials as stimuli for roughness perception experiments. Because sandpaper varies within a number of factors, including the diameter of particles (texture elements) and the particle shape (jagged or smooth) it is difficult to pinpoint what aspect, or what combination of aspects, affect the perception of roughness [**59**] [**60**].

Some authors manufactured surfaces specifically for their experiments in order to overcome this potential limitation in the analysis of the results by giving them more control over the parameters to vary. Lederman and Taylor, for example, used aluminium plates with rectangular grooves [**59**] for their experiments on roughness perception (see Figure 12).

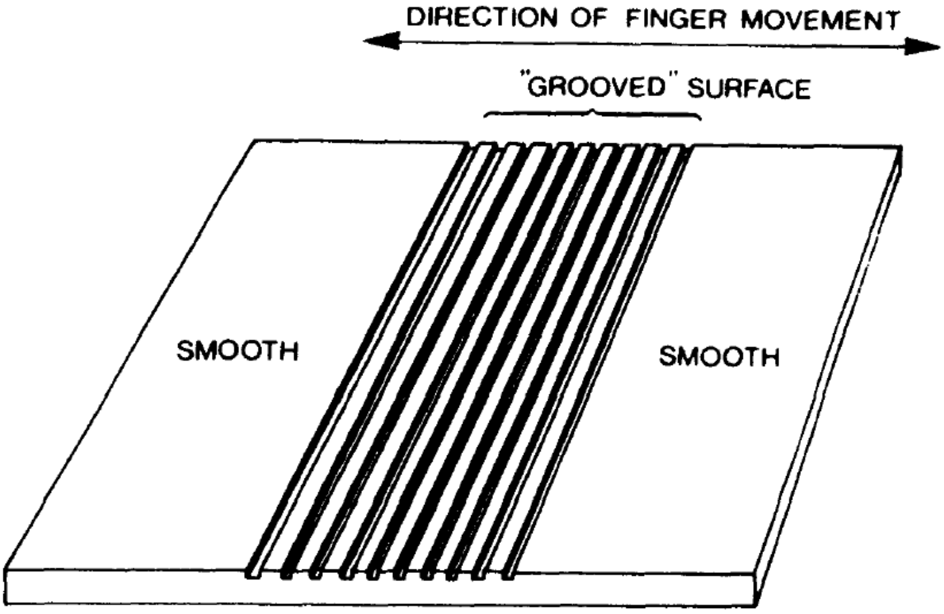

Figure 12 A grooved aluminium plate. The outer thirds of the plate are smooth; the inner section has parallel linear grooves cut along the width of the plate [61].

These experiments led to the conclusion that the perceived roughness increase rapidly with increasing in groove width (see Figure 13a) but less rapidly with decreasing distance between the grooves or "land width" (see Figure 13b).

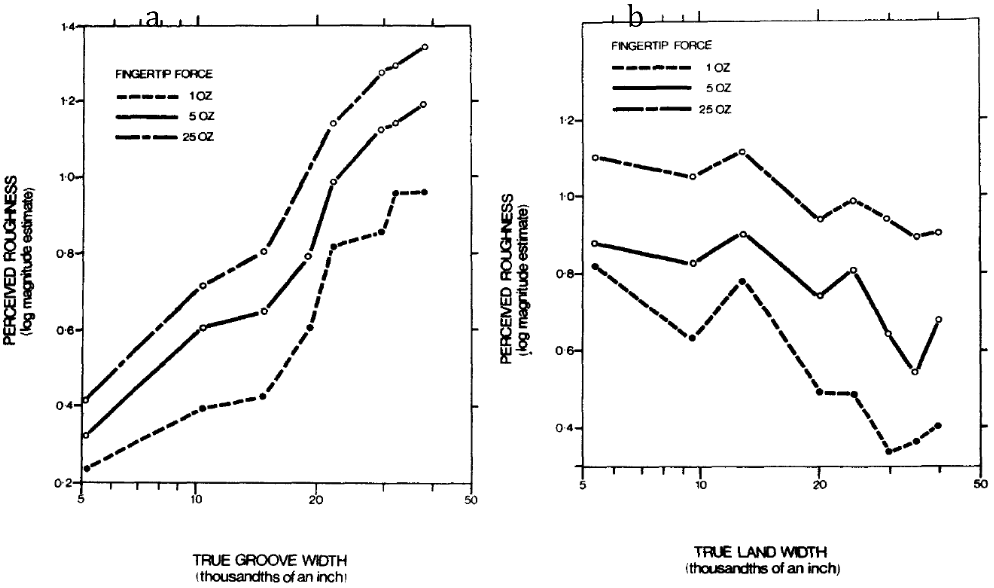

Figure 13 (a) Magnitude estimate of roughness as a function of groove width and fingertip force. (b) Magnitude estimate of roughness as a function of land width (space between grooves) and fingertip force.

4.1.5 Finger Pressure

Lederman and Taylor [**61**] also reported an effect of the fingertip force on perceived roughness. This effect shows that the perceived roughness decreases for both groove width and land width as the force increases.

The perceived roughness could therefore be predicted as a function of groove width, fingertip force and groove distance using a model based on the amount of depression of the fingertip into the groove [**62**]. In other words, Lenderman and Taylor [**61**] [**62**] found that the instantaneous pattern of indentation of the skin produced by a given texture determines the perceived magnitude of its roughness. More specifically, they proposed that perceived roughness is a function of the volumetric displacement of skin from its resting configuration while touching a given surface.

4.1.6 Fingertip speed

Fingertip speed – the rate of movement over the surface – has also been investigated. Katz [**32**] and Ekman et al [**63**] found that speed has a very small effect on perceived roughness, that it has the effect of making smooth surfaces feel slightly smoother [**64**]. They conclude that this is because of it affects the instantaneous skin indentation.

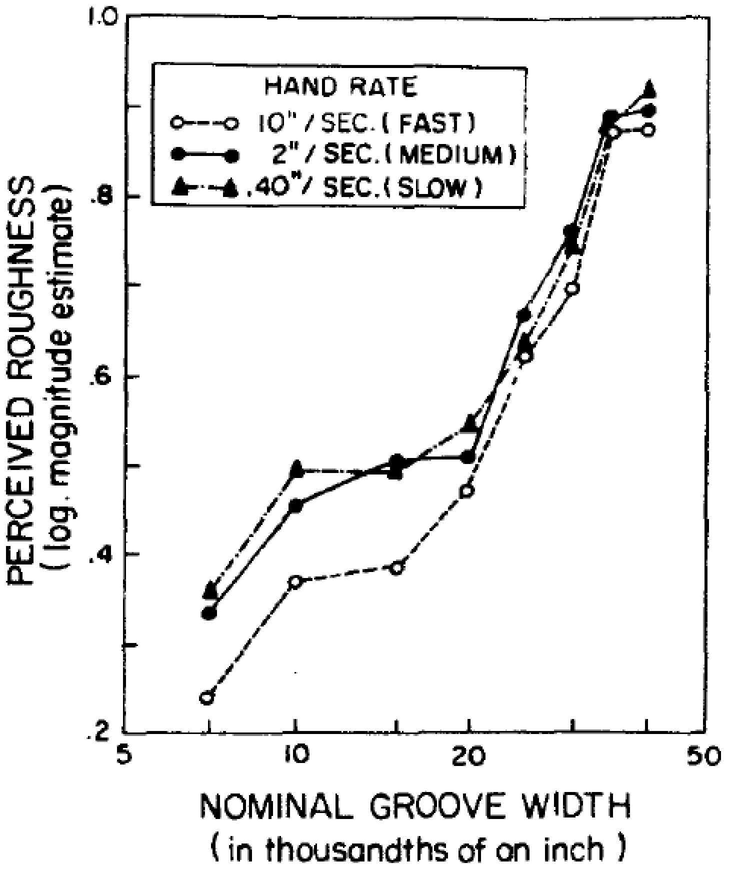

Figure 14 Perceived roughness as a function of groove width and rate of hand motion. Force at fingertip was kept constant at 10z or ~28g.

4.1.7 Friction

With regard to the friction coefficient, the evidence is contradictory. Taylor et al. [62] found that the friction coefficient component of texture has no important role in roughness perception. They used aluminium plates similar to those discussed above, reducing the friction coefficient from about 0.6 to something less than 0.15 by application of liquid detergent. This was found to have a negligible effect on the perceived roughness of the plates [62] when the groove width was varied. The perceived roughness in the two friction conditions showed more variation when the land width was varying but still can be considered negligible [62] (see Figure 15). They concluded that a large increase in the friction coefficient tends to cause a negligibly small decrease in the values of perceived roughness. This implies that perceived roughness should be essentially independent of the friction coefficient, or even that it might decrease slightly as friction increases.

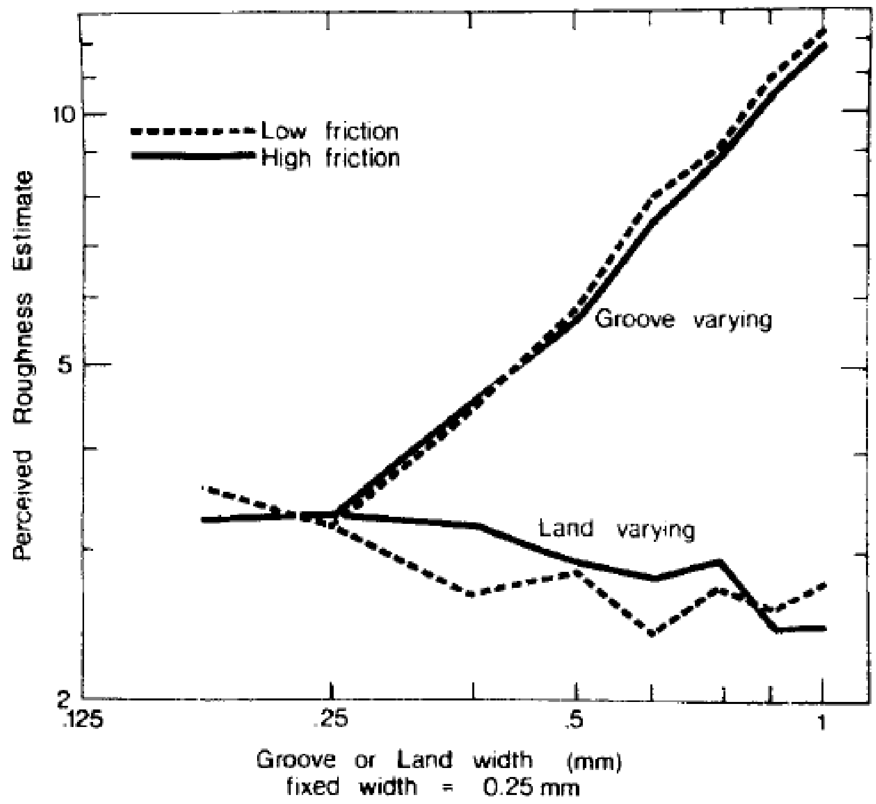

Figure 15 Perceived roughness as a function groove and land width for different levels of friction [62].

4.1.8 Context

In addition to the way a surface is explored and the physical properties of the said surface, spatial and temporal context also affect the way a surface roughness is perceived [**64**]. A surface felt just after a smooth surface feels rougher than when felt right after a rough one. This phenomenon was explored and found that it is also true in the reverse condition, where a surface is perceived as being rougher when felt right after a smooth one. Since this works both ways, it cannot be a result of fatigue or adaptation in the receptors, but a higher-level process happening in the brain with neurons adapting to the roughness of the scanned surface [**64**].

When a surface is felt with one finger at the same time another rougher surface is felt with another finger it will be perceived as rougher than if the other finger was feeling a smoother surface. This shows that information coming from more than one finger is integrated and also processed at a higher level [**64**].

4.1.9 Indirect texture roughness perception

Another way of perceiving surface roughness is from exploration with a tool, such as a rigid stylus or probe held in the hand. With this type of exploration (also referred to as indirect touch), the reported subjective roughness magnitudes reported show a relation between roughness and element spacing which is roughly quadratic in form. This quadratic function peaks near the point where the diameter of the tool can fit through the space between the elements on the surface. This indicates that roughness percept is highly sensitive to the physical interaction between the probe and the elements [**33**].

As mentioned above, the relationship between the perception of roughness and the space between the texture's elements was found to be roughly quadratic, with the function reaching a peak near the value where the space between the texture's elements was equal to the diameter of the probe. This is the point at which the perception of maximum roughness is reached for a surface (i.e. the surface feels roughest at that point). This is the point where the probe is also able to drop between the elements and ride on the substrate below them indicating that roughness perception is highly sensitive to physical interactions between elements and probe. Once this maximum is reached, the roughness estimation begins to drop, forming an inverted "U" quadratic shape function [**33**] [**65**] (see Figure 16).

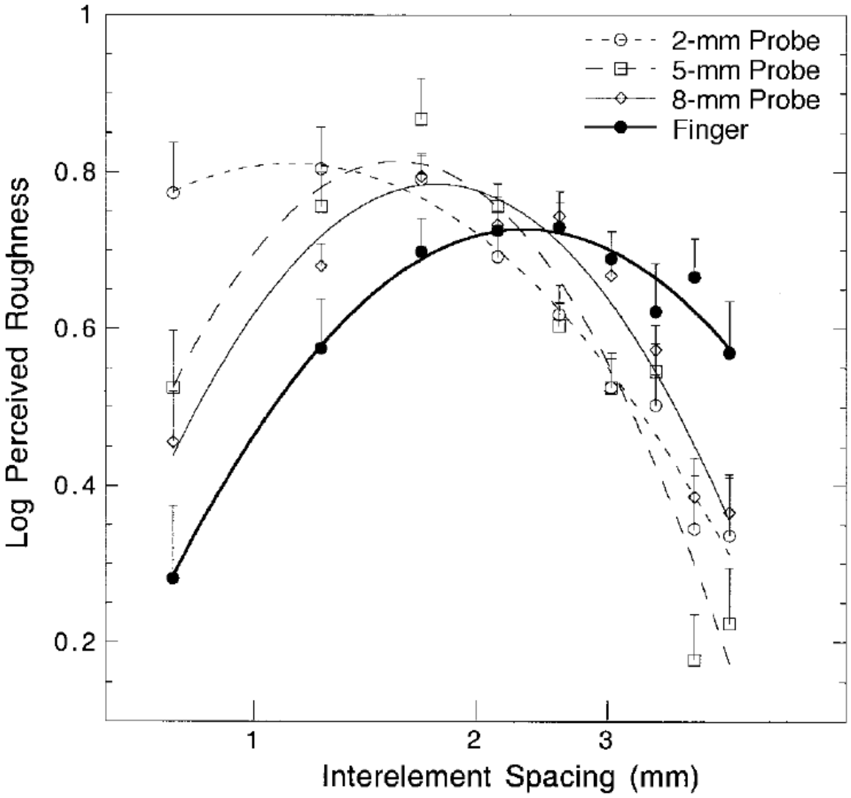

Figure 16 Log roughness magnitude against inter-element spacing width for the finger and the three probe sizes [33].

It is also worth noticing at this point that a similar quadratic shape exists for the graph where exploration was done directly with the finger and without using a probe.

These results indicate that roughness perception is mostly dependent on the ratio between the probe diameter and the space between the texture's element spaces, Klatzky et al. developed a geometric model of probe-texture interaction. This way, the perception of roughness could be predicted by changing the probe size, based on the texture's geometry [**33**].

Therefore, this model shows that, if a probe with a circular tip, or point of contact, traveling over a texture with small element spacing, in respect to the probe tip, the probe travels along the tops of the elements, having a very small distance of penetration. This will cause a very small vertical movement and consequently very small forces are transferred to the user's hand, hence the perception of roughness is also small. On the other hand, as the element spacing increases, the probe tip will penetrate deeper between the gratings. In order to maintain constant velocity, the user will start applying more force to overcome the gratings while moving in and out of them, causing an increase of force variation (see Figure 17).

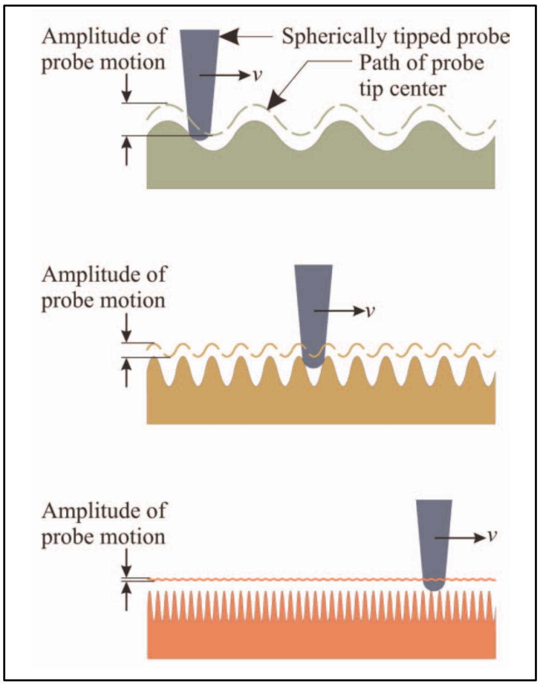

Figure 17 The effect of texture spatial frequency on probe motion amplitude [2].

Moreover, as discussed above, the speed of exploration showed a very small effect on roughness perception [**66**]. With this information alone we can conclude that the frequency of vibrations created during exploration also has no important role in the perception of roughness magnitude. The amplitude of the vibration does however play an important role in roughness perception. Therefore, an increase in amplitude, combined with an increase of the force needed to move forward, subsequently, causes changes in how the texture is perceived, with roughness estimations increasing with force and amplitude.

In addition, the sensation of roughness is not perceived only by pressure (static touch) and the combination of pressure and vibration (dynamic touch), but can also be perceived using only vibration. This was tested using a rigid probe between the skin and a surface [**65**], where only vibrations were transmitted through the probe, masking any pressure information. In this condition, the discrimination between different levels of roughness was found to be worse than the bare skin condition since less information was available. On the other hand, this condition (with the small probe) produced greater perceived roughness for the stimuli with the smallest inter-element spacing (see Figure 18). This may be because the probe could enter the narrow space between the elements on the surface that the finger could not, proving once more that vibrations are very important when exploring smoother surfaces than when you explore coarser ones.

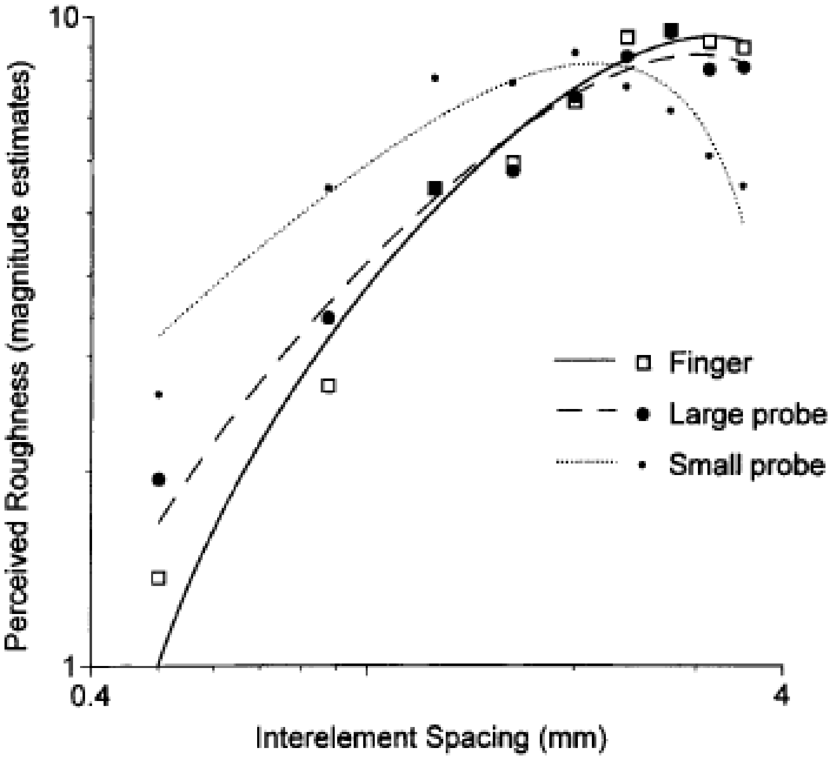

Figure 18 Perceived roughness magnitude estimates against inter element spacing for two probe diameters and fingertip exploration [65].

Overall this series of experiments showed that participants can judge surface roughness through their finger and through the probe at an acceptable and similar level of accuracy. Therefore, this proven viability of vibratory coding of roughness through a rigid link has very important implications for haptic displays and virtual-reality haptic systems.

4.1.10 Virtual texture perception of roughness

New possibilities are created for the study of texture perception with the introduction of haptic devices capable of rendering virtual textures. Parameters found from experiments in the real environment (such as surface ridge width) can be accurately and rapidly changed, allowing researchers to investigate human perceptual responses to a wide range of textures [**2**]. This allows haptic textures to be rapidly simulated at less cost than their physical counter- parts.

Despite the advantages this new technology has, early findings from roughness perception estimation studies performed in virtual haptic environments produced substantial differences in roughness perception for virtual versus real textures [**2**].

The reason for these discrepancies is mainly due to the way virtual interface interaction was performed in these early studies.

Unger et al. in their work for [**2**] note that some of the early work on roughness perception (e.g. k [**49**]) used a virtual point-probe on sinusoidal grating textures (SGT) for their experiments (see Figure 19), which may be the cause of these inconsistencies.

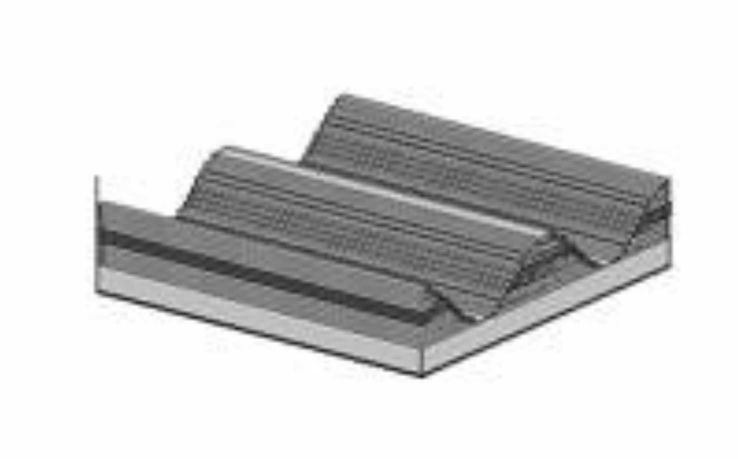

Figure 19 Artistic impression of a sinusoidal grating texture.

The SGT is the simplest of the virtual haptic simulations and was often preferred due to hardware limitations (processing power and haptic device resolution) in the early days of virtual haptic research.

SGT maps the haptic interaction point (HIP) as an infinitely small probe and when the probe is in contact with the surface, a force is generated proportional and opposed to its penetration depth into a virtual sinusoidal surface along the z-axis, and when the probe is not in contact with the surface, it is allowed to fly freely, with gravity (acting on the end effector of the force feedback device) being the only force acting upon it.

Klatzky et al. on a more recent study used a spherical probe on a dithered conical texture (DCT) of truncated cone-shaped elements, finding a different psychometric function that better represented that found in real texture environments.

This difference in probe geometry meant that the HIP at the probe centre could not follow texture contours exactly, but instead had to follow a surface determined by the interaction of probe shape and texture geometry, as seen in Figure 20.

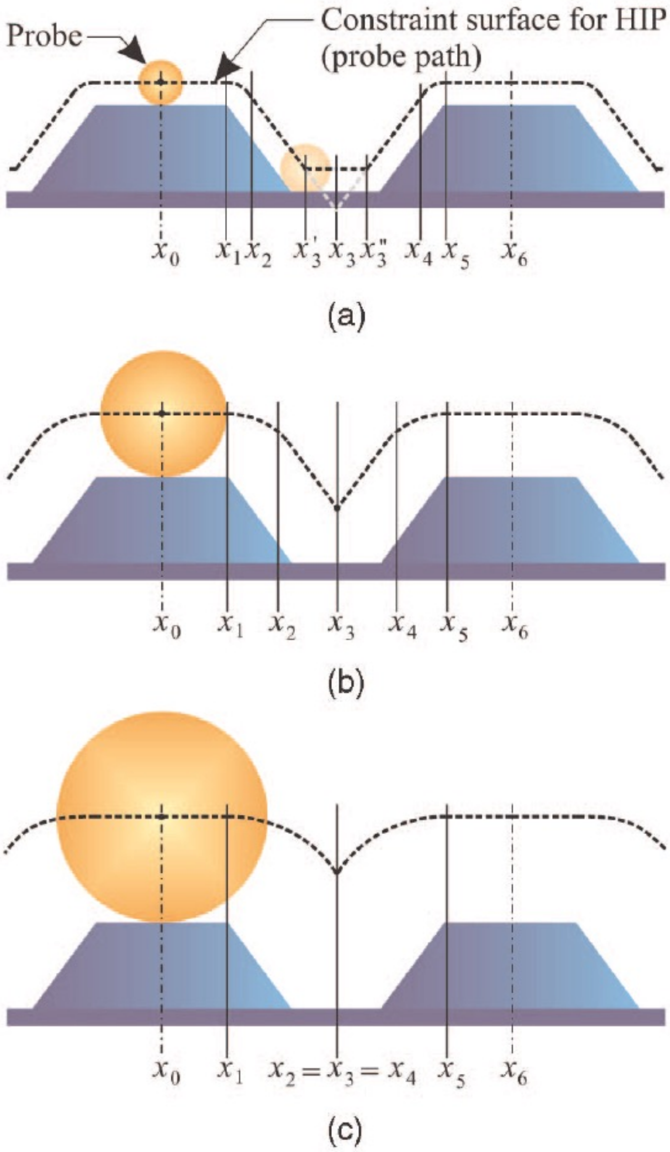

Figure 20 Cross-section of trapezoidal grating texture with inflection points: (a) small probe, (b) larger probe, and (c) very large probe

Unger et al. [**2**] established that initial differences in results were due to the way the interaction was designed and rendered when they repeated Kornbrot's experiment using a higher fidelity magnetic levitation haptic device, and an SGT. The results they obtained from that experiment showed almost identical results to that of Kornbrot et al. with a long plateau of high roughness, followed by a linear decline (see Figure 21). The slope of the declining portion was -0.82, virtually identical to that found by Kornbrot et al. (-0.80) [**49**].

Some variation was observed between subjects in Unger's experiment but the low standard error (0.13) of the function did not make it significant [**2**].

Another interesting point is the plateau of high roughness values Unger et al. found before the slope declining. This was attributed to the much higher fidelity of the hardware used by Unger et al. in comparison to what Kornbrot et al. used [**2**].

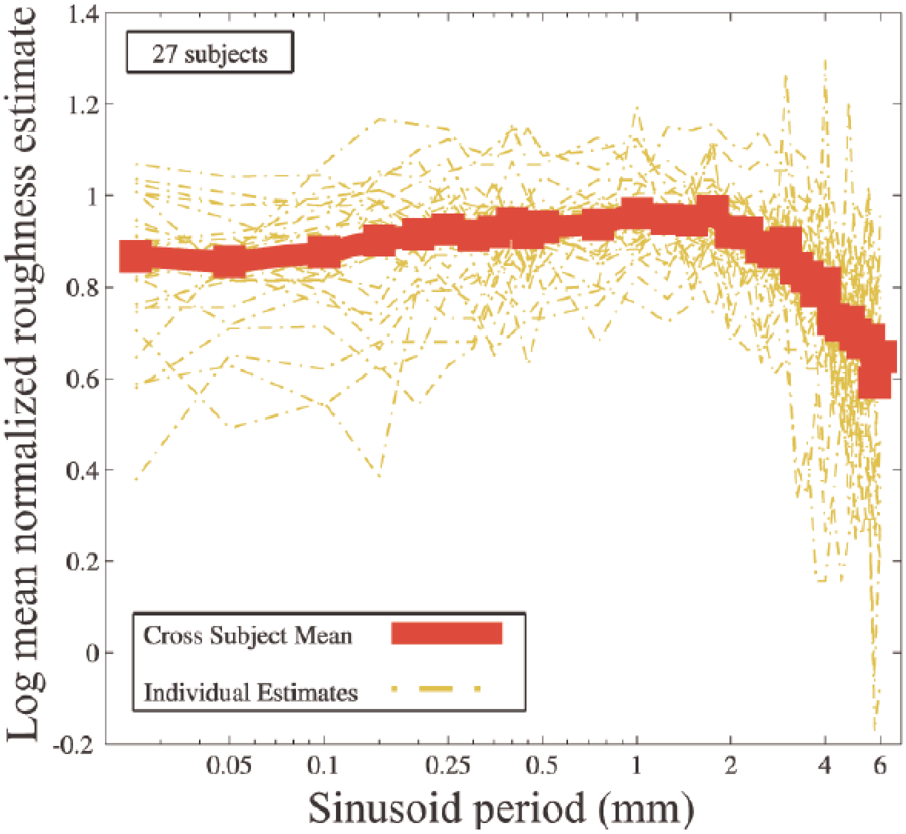

Figure 21 Log-log plot of individual normalized roughness psychophysical functions, superimposed on the cross participant mean for SGTs [2].

The shape of the psychophysical function for roughness clearly reflects the relationship between the geometry of the probe and the geometry of the texture (or as Unger et al. call it in [**2**], the probe-texture geometry), and not hardware capabilities or some fundamental difference between virtual and real texture perception. Therefore with careful simulation of the geometry of probe-texture interaction using a high-fidelity haptic device, virtual roughness perception is essentially equivalent to real roughness perception [**2**] (see Figure 22).

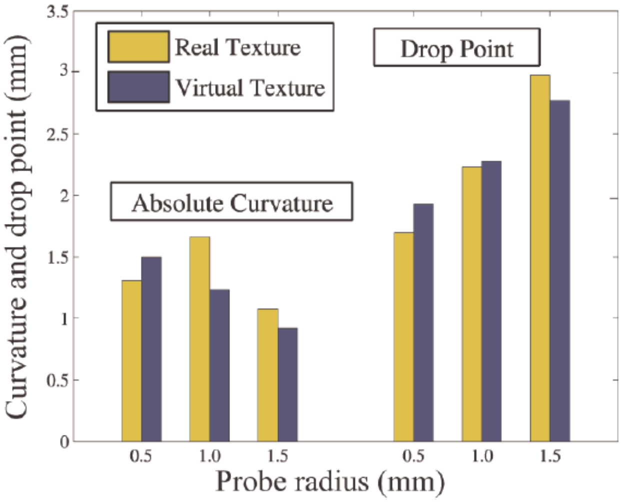

Figure 22 Comparison of the curvature and maxima location of the psychophysical function for roughness for real and virtual spherical probes on DCTs. Real data are taken from Klatzky et al. in [33]. Figure taken from [2].

4.2 Perception of hardness

4.2.1 Introduction

When referring to “softness” or “hardness” of a material we refer to the subjective perception people have when handling compliant materials. It is very important to make and emphasise this distinction between percept and stiffness values [**67**]. The perception of compliance results from contact with the surface continuum of an object. In the case of direct contact, the finger pad (skin located around the tip of the finger) changes the contact profile/pressure distribution, of the finger and the object [**68**]. This produces both a cutaneous and a kinesthetic sensation.

Thus, the *harness* of an object depends partly on its *stiffness*, and stiffness (K) is given in Equation 9 as the ratio between the *force* (F) exerted upon an object and the resulting *displacement* (Δl). This formula is also known as *Hooke’s Law.*

$$K = \frac{F}{\Delta l} \qquad (7.)$$

Therefore, if two objects are pushed on their surfaces with the same amount of force, but one object shows higher displacement than the other, that object is considered to be softer (lower K).

Softness and hardness can also be perceived indirectly, through a probe or a tool [**69**] giving rise to only kinesthetic and vibration cues during pushing or tapping [**70**].

4.2.2 Magnitude estimation

One way the relationship between physical attributes and perceived hardness can be calculated is by using magnitude estimation [**71**]. In these magnitude estimation experiments, participants are instructed to squeeze different types of rubber. This produces a power function relating perceived hardness and physical attributes with an exponent of around 0.8; therefore, subjective hardness grows with the physical "hardness" in a power function [**71**]. The same function, but with a negative exponent is obtained for perceived softness (see Figure 23), showing that hardness and softness are opposite to each other in a similar way as smoothness and roughness are opposite to each other [**56**] (4.1.1 Sandpapers and sandpaper-like materials, p.34)

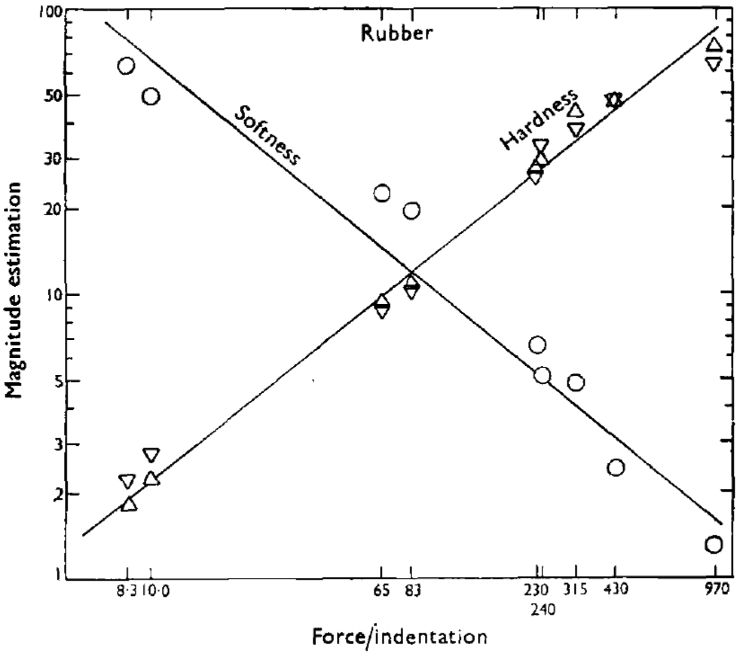

Figure 23 Magnitude estimations of subjective softness and hardness plot against physical hardness. Inverse triangles show results from a repeat experiment [71].

The discrimination between soft and hard objects have also been found to be better when samples are pressed down with one finger, compared to being pinched between the thumb and the index finger [**72**].

No difference between active pressing and tapping with the finger [**73**] was found on the softness perception but it was observed that when more force was used during active exploration, participants reported lower perceived softness (harder surface) than those who used less force. This suggests that softness could depend on the force used during exploration (see Figure 24). The perceived softness came to be of equal magnitude at high values of compliance, where the force a participant used during exploration did not seem to play an important role any more (see Figure 24).

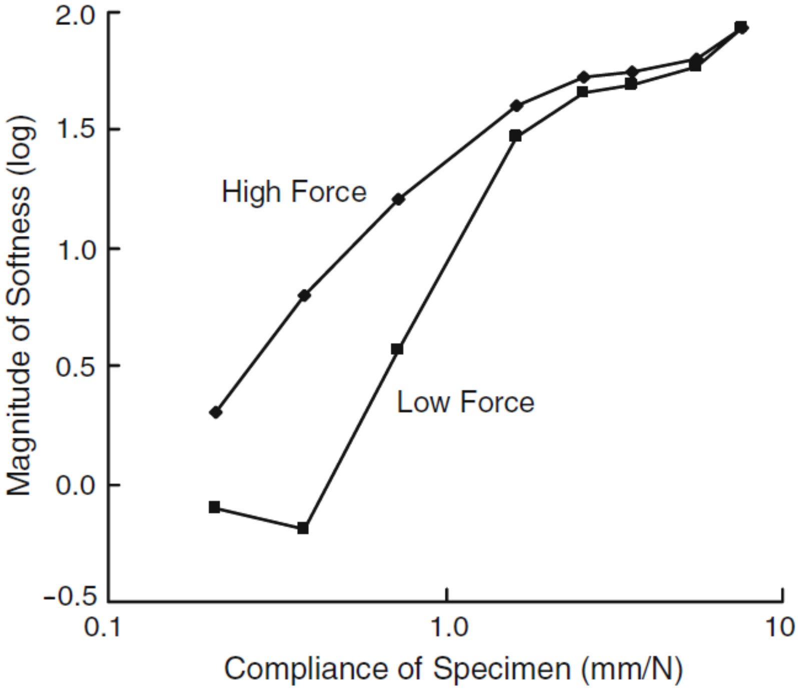

Figure 24 Effects of compressional force on the perceived softness of specimens actively pressed with the fnger pad [73].

Nevertheless, no link between softness and force used in the passive condition was found. This may be accredited to the fact that during passive exploration (where the stimuli were pressed against the finger pad via a force-controlled tactile stimulator), only cutaneous information was available since kinesthetic information was suppressed. Therefore, even though softness perception is not entirely dependent on kinesthetic information, it can be influenced by it [**68**] [**73**].

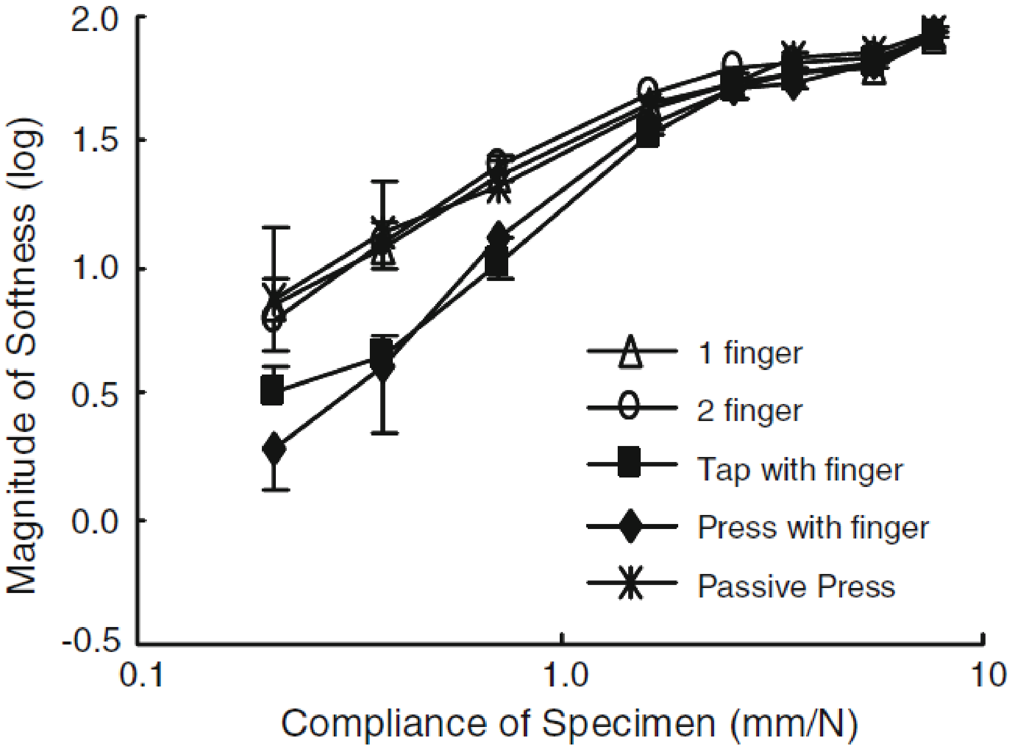

Figure 25 Mean magnitude estimates of softness for five different modes of contact. 1 and 2 finger refers to a situation where the surface is actively tapped with a stylus controled by one or two fingers [73].

When using a tool for exploration and softness estimation, stimuli at the "low compliance" end were found to be perceived as softer than during direct touch, showing a less steep relationship between perceived softness and physical stiffness (see Figure 25), leading to the conclusion that the direct cutaneous contact mainly intensifies the perceived hardness of relatively soft materials [**73**].

4.2.3 Discrimination

Experiments have been carried out on hardness perception through tapping with a tool [**69**]. These showed that in addition to cutaneous cues provided by the deformation of the surface, the ratio between force and displacement, meditated through kinaesthetic information, can be used for hardness discrimination [**67**]. Experiments with discrimination thresholds with and without surface deformation showed that 90% of the information comes from surface deformation cues and 10% from stiffness (force/displacement) cues [**67**].

In addition, during active palpation (tapping or pressing), differences in stiffness were apparent equally well with a probe and through direct contact with the finger

[**69**]. There was slightly better discrimination of stiffness though when participants were asked to explore an object by *tapping* as opposed to *pressing* with a probe [**69**] (see Figure 26).

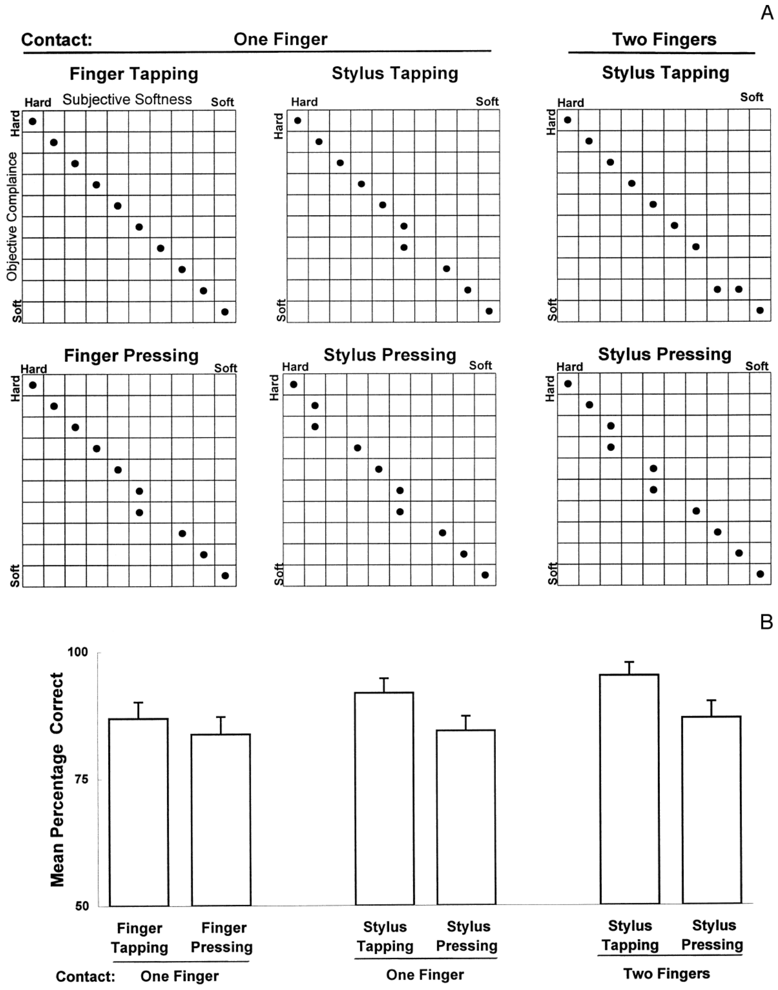

Figure 26 Accuracy of ranking softness under different methods of contact. In (A) a perfect correspondence between subjective and objective ordering of compliance follows a diagonal from top left to bottom right [69].

This shows that regardless of the mode of touch (direct or indirect with a probe) stiffness can be accurately judged in terms of softness (or hardness). Also, in the case of indirect touch the method of exploration was found to have an important effect on the results obtained, with tapping motion yielding more accurate results than pressing. No significant difference was demonstrated between these two exploratory motions in softness estimation for direct contact.

4.2.4 Perception of rendered stiffness

As discussed above, hardness (or softness) is a very important perceptual property of objects. Consequently, in order to produce realistic haptic experiences in the virtual world a good and accurate rendering of these perceptual properties is essential.

Interaction with a haptic display or device is usually done through a rigid interface such as a stylus or a probe or via thimbles that slide onto the fingertips. This means that the actual surface that is in direct contact with the skin does not show any deformation, even though the rendered visual interface might. Thus, even though forces relevant to the interaction may be available to the user, other cues that may be associated with the interaction with a compliant (soft or hard) object may not be present. These cues as discussed above come from tactile and kinesthetic information.

Bergmann and Kappers [**74**] tried to quantify the information streams that come from these two cues (tactile and kinesthetic). During their experiments, they found a *Weber fraction* of 0.12. This Weber fraction value is considerably lower than other results from earlier experiments that reported fractions as high as 0.3 [**72**]. Bergmann and Kappers argue that the reason for the better performance in their experiment was the fact that they did not impose any restrictions on their participants (i.e. with regard to time taken or access to reference stimuli). Therefore, their experiment better mimicked “real life” interactions [**74**].

When Bergmann and Kappers removed the surface deformation from their model, they found that the Weber fraction would increase, going up to 0.23. This 0.23 value is very close to the Weber fraction values obtained by experiments with rigid surfaces [**75**] [**76**] and it is almost twice as high as when a surface has deformation cues available. This provides support that for optimum hardness perception, both tactile and kinesthetic information is necessary as previously stated by [**68**].

These parallel information sources (tactile and kinesthetic) are then quantified by taking the Weber fraction from cutaneous information only (found to be 0.14) and comparing it to the Weber fraction for kinesthetic information (0.23). Bergmann and Kappers used these values and came up to the conclusion that the perception of hardness comes 73% from cutaneous and 23% from kinesthetic information [**74**].

The importance of surface deformation to compliance perception has implications for the way compliance should be rendered. When a haptic device that can only render force/displacement (stiffness) information is used, perceived hardness does not correlate directly with the rendered stiffness. Instead, a different measure, called *rate-hardness*, seems to be better correlated with perceived hardness [**77**]. This rate-hardness measure is defined by the initial force rate of change (in N/s) divided by the initial penetration velocity (m/s) [**77**], with "*initial*" referring to the point of first contact.

$$H_r = \frac{initial\ force\ rate\ of\ change\ (N\ /\ s)}{initial\ penetration\ velocity\ (m\ /\ s)} \tag{8.}$$

The unit for rate-hardness derived from this equation is N/m (Newtons per metre), which is the same as the unit for surface stiffness (see Equation 9.). Even so, the numerical values for rate-hardness may be larger than those of surface stiffness. This difference in value magnitude comes from the fact that rate-hardness is measured by recording force and position data while a user produced series of "taps", in contrast with stiffness, which is determined by the static relation between measured position and force applied in a linear way [**77**].

This suggests that the perceived hardness of such devices is mainly based on the immediate response when tapping a virtual surface, measuring only the point of impact, instead of the longer-term response when such a surface is pressed after the initial impact allowing some force to be absorbed (buffered) by the object.

4.3 Advantages of haptic displays

Haptic virtual environments are to haptic perception research what computer graphics are to vision research. They allow the investigation of haptic perception, the techniques used for exploration and any related phenomena. Further more, this can be achieved in novel ways that often include the creation of objects that do not exist naturally in the real world. Haptic virtual environments offer great flexibility over the control of mechanical signals, allowing the perception of these stimuli to be measured in a quantitative way; something that is extremely difficult to measure otherwise.

This close relationship between the research on haptic perception and haptic technology is a source of constant advancements in both fields. Evidently, human perception research greatly benefits from haptic technology and, equally, haptic technology benefits greatly from research on human haptic perception. Therefore, with all the current and future advancements in both fields, we are offered potentially with very important opportunities for understanding haptic perception. This may even highlight the profound importance of some haptic phenomena [**78**] like somesthesis[2] and proprioception[3].

By better understanding how we perceive touch in order to determine the characteristics of a physical object we are touching, haptic technology can be used to provide an enhanced interaction experience to the user. That may for leisure, simulating a fictional form of reality (force feedback in video games) or for simulating reality in real life situations (virtual training of doctors and surgeons, and machine operators).

Additionally, haptic feedback was recently used on a prosthetic arm to provide a patient who had lost his arm with the ability to touch and *feel* his environment again. With the new prosthetic arm the patient could judge the stiffness and shape of different objects by exploiting different characteristics of the elicited sensations in real time [**79**]. This is a significant step forward, towards directly improving a person's quality of life thanks to research on human haptic perception.

A number of reasons exist that have motivated research and use of virtual-haptic devices, both for research and commercial application reasons. For example, the aluminium plates Lederman used in her experiments on roughness perception [**61**] were reportedly extremely expensive and hard to produce and they may have had small imperfections that could have altered the results [**66**].

On the other hand, having a virtual simulator that could, in essence, replicate these aluminium plates, could allow research on that area proceed much faster and with costs; both money and time wise. Unger et al. in their more recent experiments on roughness perception [**2**] did exactly that, taking inspiration from these aluminium plates, as used by Lederman in 1972 and replicated them in a virtual simulator which used a high fidelity magnetic levitation force feedback device to feel them. Results from similar experiments on this simulator showed no noticeable

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[2] Somesthesis refers to the various sensory systems in the skin and other bodily tissues responsible for the sense of touch (e.g. pressure, warmth and coldness, pain, itch)

[3] Proprioception refers to the sense, which allows us to know where our limbs are in relation to our body.

difference between the results from this setup and the older setup used by Lederman.

4.4 Applications of haptic interaction

4.4.1 Message communication

With years of advancement in what technology is capable of and the progress made by researchers in the area of haptic and understanding how the sense of touch is perceived, better, more accurate and most important affordable systems can be designed. This advancement in both the technology available and the domain knowledge also helped the application areas of tactile displays to be expanded; with *Pressages* and *Tactons* being two very good examples of how domain knowledge can be applied on new technology.

Pressages [**80**] is one type of non-verbal messages. Users of pressages would apply pressure on their adapted mobile phone during a normal voice conversation whenever they wanted to send a pressage. Squeezing the phone triggeres the mobile phone of the other person in the conversation to vibrate in different patterns, depending on the level of pressure applied [**80**]. Hoggan et al. conducted an “in the wild” study where participants used pressages for a month in their everyday conversations with their partners (they both needed to have an adapted phone). During that period, participants used pressages for a variety of different purposes, ranging from greeting at the beginning of the conversation to nudges during silent periods. Overall, [**80**] concluded that an additional non-verbal, haptic channel of communication can be integrated in traditional voice calls to express greetings, presence or even emotions.

Another way by which non-verbal information can be communicated is through *Tactons.* Tactons, or tactile icons, can use parameters like frequency, amplitude, the duration of a tactile pulse, rhythm and even location on the body where a stimulus is received, to produce structured, abstract messages [**9**]. These messages can be used for non-visual communication, potentially improving the interaction in a range of different areas. These areas may include areas where the visual display is overloaded, limited in size or not available, such as interfaces for blind people or in mobile and wearable devices [**9**].

Brown et al. in [**81**] show in great detail how roughness can be used as a parameter for constructing Tactons, and how roughness can be combined with rhythm to create a new set of tactons. Roughness in [**81**] was simulated with vibrotactile actuators producing patterns of vibrations that map to different levels of roughness. In this experiment three magnitudes of roughness were used, described as "smooth", "rough" and "very rough". Both roughness and rhythm performed very well when considered on their own and as a combination of both.

In a follow up study by Brown et al. [**82**] the successful recognition rate of tactons decreased significantly when a third parameter was introduced. More specifically, the results of that study show that the identification rate for three-parameter Tactons drops to 48% from the 71% of the two-parameter tactons in [**81**]. Interestingly though, decreasing the number of roughness intensities from three to two significantly improves performance for absolute identification of Tactons encoding three dimensions of information to 81%. These results indicate that at least in the case of Tactons, two levels of roughness is the maximum that should be used when combined with spatial location and rhythm.

In addition, [**82**] show that, even though by reducing the available number of roughness less information can be encoded, more information can be transmitted giving a more beneficial use of a smaller set of tactons.

4.4.2 Medical domain

Medical simulators offer a venue where inexperienced physicians and medical students can train in potentially risky procedures such as invasive diagnostic and therapeutic interventions.

Through these simulators both training and evaluation on the physician's performance can be carried out before they can operate on human patients [**83**] or live animals [**84**]. Skills gained in training with simulators can be useful throughout a surgeon's career as they develop new skills for more advanced techniques without worrying of any consequences on the life or welfare of a patient in case of mistakes and experimentations.

Two of the main objectives a medical simulator has are for tool training and for improving clinical skills. A high fidelity is typically needed for the first objective, but a better overall environment providing a more realistic experience may be needed for the latter [**85**].

According to Klatzky et al. [**70**] only a few studies have looked in assessing the benefits of haptic feedback in surgical simulation training, and the results of studies that have, are mixed. Some studies, for example, show that the use of surgical simulators have long lasting effects on improving surgical techniques [**86**] while other studies report an improved initial performance that only lasts for the first five hours [**70**].

This lack of studies, the mixed results and, as Coles et al. [**85**] identifies, the lack of an appropriate simulator metrics for the effectiveness of a simulator can all be attributed to the variability with which individual practitioners may carry out the same procedure in a single department or between different hospitals causing conflicting requirements for the simulator designer.

4.5 Chapter summary

How an object feels when an individual touches it and what affects that feeling is something that intrigued researchers and psychophysicist since the early 1900s. Experiments with textured surfaces show that the perception of roughness vary predictably with changes on the surface properties and various models exist, describing how physical attributes of a surface affect the magnitude of perceived roughness.

Feeling the surface on a texture through a probe (indirectly) shows very similar results to those of direct touch. The perceived roughness depends on the physical attributes of a surface in an almost identical way it does for direct touch when felt indirectly through a probe (e.g. see figure 20 and figure 22).

Overall, studies have shown that it is possible to judge surface roughness through direct touch and through a probe at an acceptable and similar level of accuracy. The same results stand for virtual representations of textures where virtual roughness perception was found to be equivalent to that in the real world (see Figure 28).

Another important component of texture perception is that of physical stiffness that gives the perceived sense of “hardness” (i.e. how *hard* or *soft* a texture appears to be). Hardness depends on the stiffness value of the object, and as that is a physical property, it can be directly calculated using *Hooke's Law.* Studies show that an object is perceived to be “harder” as the stiffness value increases following a predictable mathematical model.

There are numerous practical applications for the knowledge obtained by studies exploring how surfaces with varying perceived “roughness” and/or “hardness” could be used. These applications vary from constructing and communicating messages in non-verbal way, non-visual way (i.e. using pressages and tactons) to life saving training of medical practitioners through medical simulators with haptic feedback.

Pressages illustrate how context-rich information representing greetings or even emotions can be send and received by squeezing a device and feeling different patterns of vibrations to enhance verbal remote communications (i.e. voice call through a mobile phone).

Tactons show that messages with different meaning can be constructed and correctly communicated by simply varying one haptic or tactile dimension (i.e. frequency of vibrations or perceived roughness). This can be linked to other aspects of haptics reviewed in this chapter similar to how groove width on a surface can affect the perception of roughness, or how two or more surfaces with different physical stiffness values can be differentiated from each other.

Revising the literature on the perception of roughness and hardness, and how that is affected by an object’s physical attributes helped with the identification of a gap in the current domain knowledge; and that is how physical stiffness affects the perception of roughness. The majority of literature to this day concentrates on determining the relationship between a physical dimension of an object and a quantifiable measure of the perception of that dimension. There is very little done on attempting to investigate the interrelationship between physical dimensions and perceived characteristics of an object’s a texture.

More specifically, the gap lies somewhere between the research on roughness and stiffness perception and has a link to the tactons and how they are created. The following chapter describes in more detail the motivation for the study carried out in an attempt to fill this gap.

CHAPTER 5 - MOTIVATION

In this study so far the huge advances on haptics and haptic research are discussed, from the early parts of 1900s [**32**] and within the classical psychology domain, all the way to the more cutting edge research of 2013 [**79**] where mathematical algorithms, computer science and electrical engineering came into play to produce the one of the first high fidelity prosthetic arm with force feedback capabilities allowing an amputee to feel the environment around him again with his missing limb.

During tis study so far, the knowledge that was carried forward from the early research and reapplied to the new domains of haptic technology was considered. Knowledge that could be reapplied and reused, either to reduce cost of experiments, improve accuracy and remove unwanted external parameters, or to simply reproduce situations and objects that are either too difficult or simply impossible to produce in the real world.

A review of the literature of any domain, on the other hand, cannot come without identifying some gaps, giving rise to unanswered or partially answered questions.

While going over the literature, it came to my attention that the majority of research to date concentrates on how changing one physical attribute affects its relative perception (e.g. physical stiffness with how "hard" it feels, or inter-element spacing with how "rough" it feels). Unger et al. note that: "*To understand the perceptual processes involved in perceiving texture by touch, a common approach relies on determining the relationship between a physical factor in the environment and a quantifiable measure of the perception of that factor as texture*" [**2**]. After examining the relevant literature, most specifically looking on roughness, the perceptual dimension described to be as *"[T]he perceived textural dimension most commonly studied*" [**2**] no studies could be found on how the physical stiffness of that same texture affects it.

As already discussed in Chapter 4 – Texture Haptic perception*,* page 34, the orientation and spacing of raised elements on the object's surface affects the way the object is perceived in terms of its roughness (e.g. [**21**], [**33**], [**36**], [**61**], [**65**], [**66**]), and physical stiffness values of an object affects how hard an object is perceived to be (e.g. [**67**], [**73**], [**69**]) are very thoroughly investigated, both in the real and in the virtual environment. Despite that, there is a lack of research on how physical attributes are linked to different perceived characteristics of a texture, such as a link between physical stiffness and perceived roughness. Creating such a link can be related to the work of Brown and Brewster (e.g. [**82**] [**9**]) where different tactile attributes are combined to produce sets of unique perceptions, creating what they describe as tactile icons, or *tactons* (see section 4.4.1 Message communication, page *57*).

The only relevant research found on how these two dimensions (physical stiffness and perceived roughness) are linked has been done by Unger, investigating the effects of probe stiffness has to the perception of roughness [**10**]. This investigation showed that the physical compliance of the probe does indeed affect the roughness perception of a texture. More specifically, Unger in [**10**], Chapter 7, page 169 notes: "[Probe] *Compliance is a significant confounding factor with regards to roughness perception. Increases in compliance lead to decreases in the magnitude of roughness perception* […]".

On the other hand, Unger in this study only investigated the effects of probe compliance to roughness perception and not what and how the physical compliance, or stiffness, of the object (instead of the probe) affects the perception of roughness.

The gap identified in the domain knowledge formed the base of this research.

Knowing how the stiffness of an object affects how rough that object is perceived to be when touched and/or manipulated can be of substantial benefit to both haptic display and medical simulator designers.

Haptic display designers can use the information regarding the relationship between the objects physical stiffness and its perceived roughness magnitude to produce a whole new dimension of haptic feel, in a similar way different haptic dimensions were used for the production and differentiation between different *tactons* [**9**]. Being able to adjust one parameter and predictably affect another can be of utmost important for designers who want to use as little resources possible on their system, or for haptic device designers who want to add the right level of realism to their application in order to mimic as closely as possible the interactions and the way the real world feel.

The results of this study can also potentially be very important to designers of haptic medical simulators. Knowing how changes in the stiffness of an object affects how rough that object feels when felt through a tool (for example) can be of real importance when designing haptic displays capable of realistically simulating medical tasks a physician a surgeon or even a veterinarian may need to undertake in their professional life. An accurate haptic enabled simulator can allow both training and evaluation on a physician's performance can be carried out before they can operate on human patients [**87**] or live animals [**88**]. Skills gained in training with simulators can be useful throughout a surgeon's career as they develop new skills for more advanced techniques without worrying of any consequences on the life or welfare of a patient in case of mistakes and experimentations.

With this in mind, it is clear that it is very important to understand further how different haptic attributes interact with each other and the perception they produce this understanding will not only give a better insight to a designer when designing a new haptic enabled interface, but potentially also account towards adding to the realism factor of a haptic display, either if it is going to be used for recreational purposes, such as on mobile phones or on larger scale systems, such as the ones used for medical simulators for training doctors on how to save lives.

The next chapter gives an overview of the background knowledge concerning the force feedback device (FFD) used in this study, the methods it uses to implement and simulate stiffness and roughness, the rationale behind some important decisions during the experiment design and data analysis phases, and a preliminary experiment that was carried out to verify the fidelity of the FFD. A chapter descripting the experiment conducted to investigate the relationship between physical stiffness and perceived roughness follows this chapter.

CHAPTER 6 - EXPERIMENT PREFACE

6.1 Introduction

This chapter provides some technical background concerning the technologies used in rendering the virtual environment (both its haptic and visual aspect). In addition to this, it provides explanation and the rational behind some of the decisions taken during the design of the experiments carried out in this study along with the description of a preliminary experiment conducted, aiming to verify the expected fidelity of the hardware used.

6.3 How Geomagic Touch handles haptic rendering

The force feedback device chosen for the purpose of this study was a Geomagic® Touch™ (formerly known as Phantom® Omni™ by SensAble™). This is a haptic device, which makes it possible for users to touch and manipulate virtual objects. It has six degrees of freedom with positional sensing and uses an array of motor sensors attached on a mechanical, robotic arm to replicate haptic properties of virtual objects in the real world [**89**].

6.3.1 Rendering of Stiffness

One of the most common ways to render stiffness in virtual environments is using *Hooke's Law* (e.g. [**90**] and [**91**]). Hooke's law is an easy formula to implement that gives an accurate output of the reaction force proportional to the penetration depth of the user into the virtual object and normal to the surface of the object.

The equation through which physical stiffness can be rendered using Hooke's Law is:

$$F = -kx \tag{9.}$$

In this formula, the force F is calculated by multiplying the stiffness constant k by the displacement vector x. When simulating contact with a virtual object, forces that resist the device end effector from penetrating the virtual object's surface must be calculated.

The way virtual stiffness was simulated was through the concept of a cursor following the movement of tip of the device's arm in the virtual environment (see Figure 27, circled point). When the cursor comes in contact with a virtual object, the coordinates of this point of contact, or *surface contact point* (*SCP*) are recorded.

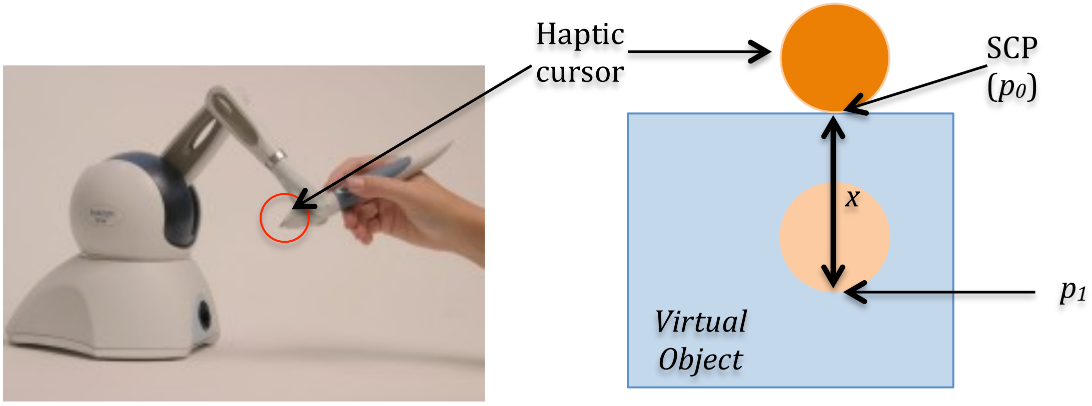

Figure 27 Rendering of stiffness using Hooke's law

The SCP is therefore a point that attempts to follow the end-effector position (point at the end of the arm) but is stopped by the surface of the virtual object.

The force is then calculated by simulating a spring stretched from the end-effector position to the SCP. Figure 27 shows penetration into the object.

More specifically, applying Hooke's law (see equation 15.), x is calculated by subtracting the SCP (p_0) from the end effector position (p_1), therefore $x = p_1 - p_0$ (Assuming p_0 and p_1 are in Euclidian dimensions). The constant k is defined for every object before the interaction and the stiffness force is calculated dynamically as the end effector moves inside the virtual object opposing the direction of motion (see Figure 27).

Rendering of stiffness can be done by using the hlMaterial() function. This function is part of the HL library of the OpenHaptics Toolkit [**92**] that comes with the Geomagic® Touch™ FFD. With hlMaterials(), a function that comes with the API, a programmer can very easily set haptic properties on virtual object by simply stating the desired attribute and physical constants. An example of using this function for setting the stiffness can be seen below:

```
hlMaterialf(HL_FRONT_AND_BACK, HL_STIFFNESS, 0.7);
```

After applying this function as seen above, the object will be haptically visible[4] both from the *front* and the *back* side, and the haptic attribute of stiffness is added with a Hooke's Law constant of 0.7 N/mm. Therefore the force produced will be: F=0.7 * x, where x is the distance from the SCP to the end-effector position (see Figure 27).

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[4] Haptically visible is defined as a surface that provides haptic feedback when the cursor comes in contact with it.

In the “real world” this opposition to the direction of motion is similar to the one explained above until a maximum value of *x* is reached, where no more penetration is allowed into the (assuming the object does not break or is punctured).

On the other hand, when dealing with virtual environments, the maximum force the FFD can produce limits this interaction. The limits of an FFD can mean they make the virtual objects feel less stiff (softer) than they actually are, just because they are unable to produce the necessary force to match the user input. Geomagic® Touch™ for example has a limit of around 3.3N [**89**]. Beyond that, the objects may feel “springy”, or even in some cases, going above this value, may cause the device to overheat and switch of as a precautionary, built-in safety feature.

6.3.2 Rendering of Surface Texture

There is a number of ways the surface texture can be altered in the haptic virtual environment. A virtual object for example can be rendered having a virtual “physical” micro-texture, with raised elements, simulating texture in a similar way as in the real world (e.g. [**2**]). The perception for roughness can then be altered by changing different attributes of that micro-texture as explained in Section 4.1.4 Materials with ridges and grooves, page 37 (i.e. altering groove-land width, element spacing etc.).

Another way of simulating surface texture for psychophysical experiments examining roughness perception is by using a friction model [**10**]. Even though a number of friction models exist ([**10**], page 190-193), for the purpose of this project, surface texture was simulated using stick-slip.

Stick-slip can be described as surfaces alternating between sticking to each other and sliding over each other, with a corresponding change in the force of friction. Typically, the static friction coefficient (a heuristic number) between two surfaces is larger than the dynamic friction coefficient. If an applied force is large enough to overcome the static friction, then the reduction of the friction to the dynamic friction can cause a sudden jump in the velocity of the movement. Figure 28 describes how stick-slip works.

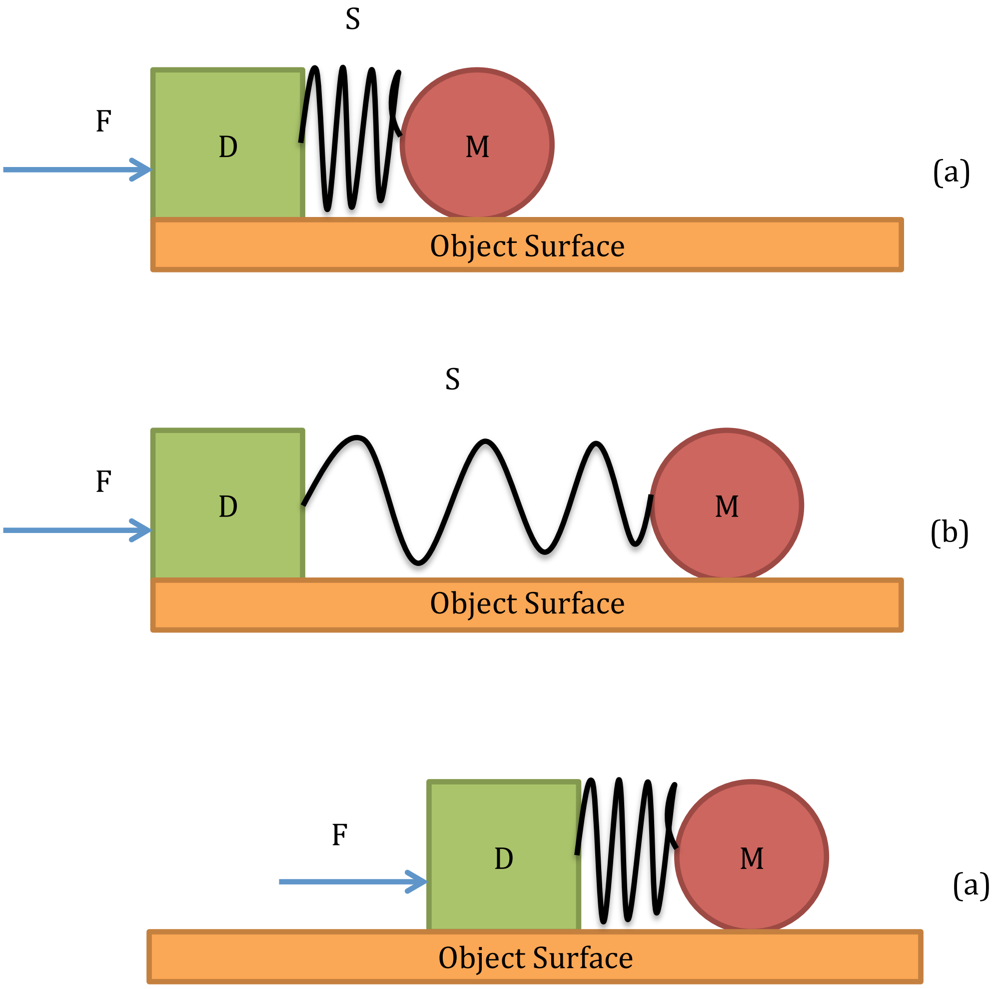

Figure 28 Graphical representation of the stick-slip motion

F is the force applied and D is a drive system used for controlling a virtual spring. The user supplies this force during the interaction. S is the elasticity in the system, and M is the load (cursor in our case, with a weight equal to the force the user applies perpendicular to the object's surface) that is lying on the object surface and is being pushed horizontally. When the drive system is started (stage (a)), the spring S is loaded and its pushing force against load M increases until the static friction coefficient between the load M and the surface in contact is no longer able to hold the load anymore. The load starts sliding and the friction coefficient decreases from its static value to its dynamic value (and from "stick" to "slip"). At this moment the spring can give more power and accelerates M (b). During M's movement, the force of the spring decreases, until it is insufficient to overcome the dynamic friction. From this point, M decelerates to a stop. The drive system however continues, and the spring is loaded again, going back to stage (a), ready to repeat the process.

This constant *sticking* and *slipping*, causes the user to perceive this motion as being equivalent to the motion over a textured surface, giving the perception of a "rough" surface.

Using a friction model to simulate "roughness" was also validated by a previous experiment (see [**93**]) in which a number of participants were asked to manipulate three haptic attributes of a virtual haptic object and try to replicate haptically a real object in the virtual environment. These haptic attributes were the virtual object's static friction, dynamic friction and stiffness, but the participants did not know how these properties were labelled; they just knew them as *A, B* and *C*. During the debriefing session, when the participants were asked what they thought they were changing when they changed the static friction, the majority of them responded that they thought they were changing the object's surface "roughness" (meaning how rough the object felt). More specifically, 12/24 participants described it directly as "roughness", 5/24 as "bumpiness", 1/24 as "texture" and 1/24 as "smoothness", which is the direct opposite of "roughness" [**56**] (See Figure 29).

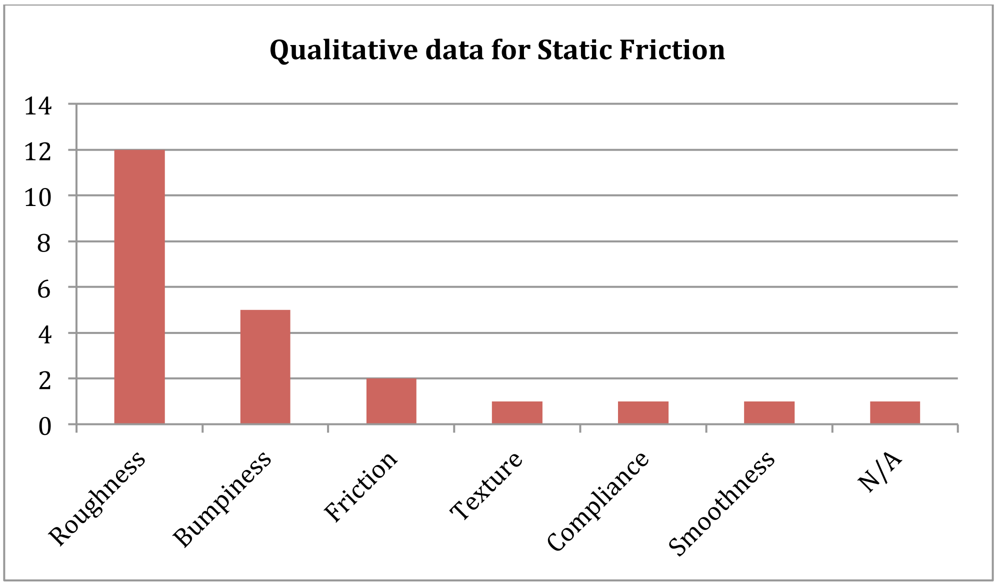

Figure 29 Qualitative data describing how participants perceived the rendered static friction from the Geomagic® Touch™ force feedback device.

Therefore, based on the evidence gathered, the ease of implementation, as well as the fact the Geomagic Touch API provides an easy and intuitive way of dynamically changing and handling the static and dynamic friction models of an interaction between two objects, stick-slip was chosen for simulating surface texture in the experiments described in this project, keeping the value of dynamic friction to 0.0 so that it will not interfere with static friction.

6.4 Haptic environment design

This section explains the way the Geomagic Touch API was used to design and implement the haptic environment as used for the purpose of these experiments, along with an explanation of the design decisions.

6.4.1 Implementing the haptic Interface

There are two main components of the graphical interface in the system, namely: the two flat surfaces onto which the haptic attributes are attached, and the haptic cursor, which visually represents the end-effector of the FFD (see Figure 30).

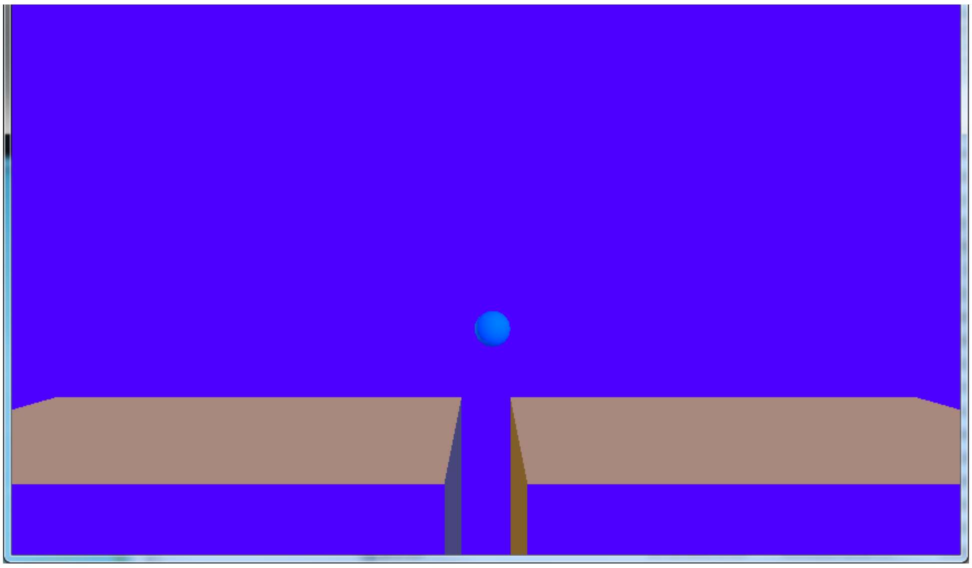

Figure 30 Two virtual flat surfaces as used for the two experiments.

Special consideration was made for participants who got "stuck" underneath the flat surface by designing both surfaces to be "haptically visible" only when the cursor was travelling from top to bottom and not from bottom up. Thus if a participant managed to go underneath the surface, the cursor would move freely back to the top without meeting any resistance from the surface.

6.4.2 The surfaces

The visual component of all of the surfaces (including the cursor), were drawn using OpenGl graphics. No visible changes (such as surface deformation) were implemented on the surfaces or the cursor when haptic values were changing during the experiment, keeping the visual and haptic component of the virtual environment parallel (one drawn on top of the other) but independent from each other.

The two surfaces were rendered as horizontal planes, at the same height with a small gap between them Figure 30. This gap prevented the participants from exploring both surfaces with one long motion. The importance of this feature is explained in the experiment methodology section (page 83).

6.4.3 Haptic cursor

A sphere was created to function as the visual representation of the cursor using OpenGL graphics. The x, y and z coordinates of the FFD were attached to this sphere and moved accordingly to the FFD's end effector movements. A blue sphere of a finite diameter represented the visual component of the cursor so that participants could see the cursor and navigate through the three-dimensional space more easily.

The haptic cursor was implemented on top of the visual cursor and had an infinitely small diameter. Since this experiment was not intended to investigate the effect of the point-of-contact area or diameter to the perception of hardness and roughness, implementing a cursor with a set diameter would only make this program more computationally "heavy". This haptic cursor was implemented to be in the centre of the sphere acting as the visual cursor.

6.5 Clearing up the definitions

Before going into a deeper explanation on how physical attributes are rendered haptically on virtual objects, it is important to state some definitions regarding these physical attributes and the haptic perceptions they generate.

There is even some ambiguity detected in the literature as regards the definitions given by various researchers on how different attributes are perceived. A simple example is the perception of "hardness". Some researchers choose to describe the physical aspect of this interaction as "stiffness" and how the perception of “hardness” changes (e.g. [**90**]), whereas other researchers describe hardness as a material property (e.g. [**74**]) and stiffness as a perception (e.g. [**94**]). In addition, other researchers choose to describe “hardness” as compliance (e.g. [**67**]), which just adds to the potential confusion when going over the literature.

One possible reason for this confusion of vocabulary may be because early research in the haptics started in the field of psychology and only (relatively) recently moved on to the computer science field, following the development of cheaper FFDs and more powerful computers. This gave rise to diversity in the field of haptics, with researchers from a number of different disciplines (computer scientists, psychologists, electrical engineers etc.) to work on the same field, trying to interpret and define the same phenomena.

Furthermore, Obrist et al. in [**95**] state that: “[*A*] *common problem with designing and developing applications with tactile interfaces is the lack of a vocabulary that allows one to describe or communicate about haptics*”. Even though the study in [**95**] is very thorough, it concentrates on direct touch and how different sensations mapped on skin neuro-receptors can be verbally translated.

In the experiments conducted for this thesis, participants had to explore the virtual surfaces through a probe, making it very difficult for the vocabulary suggested by [**95**] to be usable in this context. This is the reason Table 1 was constructed stating the definitions chosen to follow and use when describing the experiments carried out. Having a table describing explicitly the definitions in the context of this experiment helped in: (a) having a standardised way of explaining to the participants what each definition meant and (b) helped to make sure that participants understood the definition in the context of this study.

The words “hardness” and “roughness” were used to describe the sensation felt since both words are non-technical and are commonly used in the English language. A definition was given to the participants before each experiment, explaining what both “hardness” and “roughness” mean. Each participant was then asked to verify if they understood the definition, and no participant reported any difficulties in understanding these definitions. Therefore, an assumption can be made that all participants had a firm understanding on what “hardness” and “roughness” meant in the context of this experiment.

Physical attribute	**Rendered using**	**Creates the perception of /Described as**
Stiffness <u>Rationale</u>: *Term used by the Geomagic® Touch™ in its API*	Hooke's Law	"Hardness"
Surface Texture *<u>Rationale</u>: Texture is chosen for consistency purposes*	Static-dynamic friction (stick-slip)	"Roughness"

Table 1 Haptic attribute definitions

6.6 Preliminary Experiment – Obtaining a psychometric function for perceived hardness

6.6.1 Introduction

This experiment was designed to test how accurate people are in sensing differences in stiffness and how effective the force feedback device (FFD) being used is in rendering different stiffness values. Even though the perception of hardness (perception definition of physical stiffness) is well documented in the literature, it was prudent to pilot test it using the particular device and in the specific environment to be used in the main experiment. In this way it was possible to collect the specific value of PSE for this device, rather then relying on the documented values.

6.6.2 Aim

The aim of this experiment was to investigate what the minimum difference of physical stiffness values needs to be between two objects, in order for one to be perceived as "harder" than the other, in the majority of times it is tested. This helped with the better understanding of both the sensitivity of people in regards to to stiffness changes and how good the Geomagic® Touch™ device is at rendering physical stiffness.

To do this an experiment using the constant stimulus discrimination method (see 3.3 Method of Discrimination, page 21) was designed, with the independent variable being the physical stiffness of virtual objects and the dependent variable the participant perception of the object’s hardness. Other psychometric methods were considered and rejected based on its weaknesses, leaving this as the best suited for this experiment. A more thorough explaiantion on how this method was chosen can be found on section 3.4 Choosing a psychometric method, page 23.

During this experiment, ten participants were presented with a number of virtual object pairs using a Geomagic® Touch™ force feedback device and were asked to say which object of the two they thought felt “harder” in a series of trials.

6.6.3 Methodology

This experiment made use of the method of discrimination with constant stimuli. This psychometric method was chosen since the aim of this experiment was to find the points of subjective equality (PSE) between two stimuli with different physical attributes (levels of stiffness). A PSE value similar to the real value will indicate that the FFD used can accurately reproduce forces to simulate stiffness on a virtual object within the desired range.

This psychophysical method uses pairs of stimuli, (called the standard and the comparison stimuli), which are presented in a random order to the participants, making sure the participants had no indication as to which one is “harder” (the comparison or the standard) in every trial. The participants could only say which object of the two they thought was harder, either “left” or “right” (forced choice method). Since only two choices were available, a single psychometric function, which plots the proportion of “harder” responses against the value of the comparison stimulus physical stiffness, can be used to summarise the data.

In this experiment thirteen pairs of surfaces were used, with one object always having a stiffness value of 0.50 (standard stimulus) and the other varying from 0.20 to 0.80 in steps of 0.05 (comparison stimulus). This gave a total of 13 different stiffness levels.

The order in which the stimuli pairs were presented was randomised before the experiment started (using Excel’s rand() function) and then each participant received the pairs in the same order. This method of presentation aimed in avoiding introducing a new condition by having the participant’s answers being affected by the previous stimuli pair (i.e. like the condition in roughness related experiments where a smooth surface feels rougher when felt right after a rough one [**64**]).

Each stimuli pair was presented once with the constant stimulus to the left and once to the right in every trial set, giving a total of twenty-six comparisons per set. The experiment was split into four sets, each presenting the pairs in a different order, giving a total of eight repetitions per stimulus pair and an overall total of 104 comparisons (13*2*4=104). These pair values can be found in **Table 5** on page 108.

The stiffness values were rendered using the technique explained above which utilises Hooke's Law and the objects were represented graphically on screen by two flat surfaces (see Figure 30) implemented using OpenGl graphics. The experiment setup can be seen on Figure 31. The reason of using Hooke's law for rendering stiffness can be found in section 6.3.1 Rendering of Stiffness, page 64.

Figure 31 Experiment setup

Participants

A total of ten participants took part in this experiment; eight of whom were males and two females. All ten participants were right handed and nine out of the ten were native Greek speakers. Their average age was 27.3(±1.89) years and nobody reported any known disability that could affect the results of this study. Age demographics are summarised in (see Figure 32).

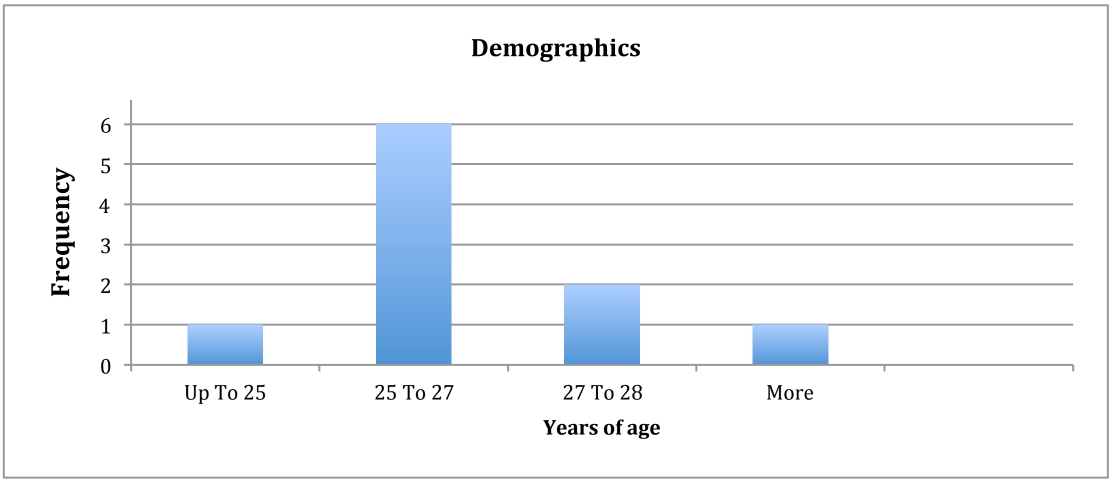

Figure 32 Age demographics histogram from first experiment (n=10)

Equipment used

Force Feedback device

For the purpose of the following experiments, a force feedback device was used. The force feedback device chosen for the purpose of this study was a Geomagic® Touch™. This is a haptic device, which makes it possible for users to touch and manipulate virtual objects. It has six degrees of freedom with positional sensing and uses an array of motor sensors attached on a mechanical, robotic arm to replicate haptic properties of virtual objects in the real world [**89**].

The Geomagic® Touch™ works in a virtual space, which measures approximately 160mm width x 120mm height x 70 mm depth (6.4 x 4.8 x 2.8 in). This makes it very compact and capable in working in space-limited environments such as a lab workbench. The device can generate a force of approximately 3.3N (0.75 lbf) [**89**].

Computer setup

The machine used was a computer system with an Intel® Pentium® 4 Core 2 Duo processor at 3.00 GHz and 4GB of RAM. It also had a Radeon™ graphics card, capable of supporting two screens. The use of two screens was essential to parts of the experiment where the facilitator had to monitor values, which the participants should not see.

Software used

The lab machine used was running a 64bit version of Microsoft Windows 7 operating system and the code used for controlling the Geomagic® Touch™ was written and compiled in Microsoft's Visual Studio 2010 with the OpenHaptics (Academic Edition) software development toolkit integrated into it.

6.6.4 Procedure

The participants were greeted and asked to fill in consent form (see Appendix 1). Then they were asked to make themselves comfortable and hold the FFD end effector (stylus shaped component) as they would hold a pen and start feeling the two virtual objects, trying to identify which one felt "harder". A brief description was given to them before the first trial, explaining what it is meant by "harder" using the example of the table as being "harder" than the silicon wrist rest (seen in Figure 31). The vast majority of participants in this experiment were native Greek speakers (9/10), and being native Greek speaker myself, Greek was preferred for the briefing session, using the term "Σκληρό" (skli̲ró) to describe hard. The one non-Greek speaker received the briefing in English.

After they confirmed they understood the definition of hard given to them, participants were then briefed about the procedures of the experiment. More specifically they were told that it will be about comparing pairs of virtual objects using an FFD and pointing out which one they thought to be the "*harder*" of the two. After this briefing, participants were asked again to confirm if they understood the definition of "hard" in the context of this experiment as it was given to them, and what they were meant to do. At this point were also asked to fill in a demographics questionnaire and state if they have any known disabilities that may affect the experiment. This demographics questionnaire can be found in Appendix 1. All forms and questionnaires were later handed to this study supervisor, Dr Edwards, who will store them in a safe location according to the University's rules and regulations for a period of time before destroying them.

Since the rendering of stiffness does not cause the FFD to produce any vibrations that could affect the outcome of the study in any way, the ambient noise was not controlled. The conclusion that stiffness rendering does not produce any mechanical sounds that needed control came through personal experience while using the devise and after comments from participants of previous experiments conducted. The values for both static and dynamic friction were set to 0.00 and remained at that value for the duration of the experiment.

Participants were asked to respond after every comparison by stating which surface they thought it was harder by saying either “left” or “right” (forced choice) with no “equal” option allowed. By having this forced choice method, participants are forced to choose between two responses; “left” and “right”, so, when a participant is uncertain, like when the two stimuli appear the same, the participant is assumed to choose equally between the “left” and “right” response, since statistically left and right have 50% chance to be picked (see section 3.3.3 Method of Constant Stimuli*,* page 21). There was no time limit set for each trial, therefore the participants were free to explore both surfaces as long as they liked before giving their answer. The decision for not having a time limit came after reading [**74**] where the authors argue that by not imposing limits to the participants (time wise or access to the standard stimuli), mimics closer real life interactions, giving more accurate results.

The only limitation given to the participants was that they had to use a tapping motion when feeling the two surfaces. This constrain was introduced primarily for two reasons. The first reason came from the literature where it suggests that tapping motion yields better results than pressing in discrimination two surfaces in order of their stiffness (see Chapter 4, section 4.2.3 Discrimination, page 52). The other reason came from one of the limitations of the FFD used. Press down on the surfaces for extended periods of time would cause the motors of the FFD to overheat and the device to shut down. The reason for this second constrain was explained to each participant and they were encouraged to use a taping motion for judging “hardness”. Once an answer was given, the answer would be marked down and proceed to the next trial. A debriefing session followed the completion of the experiment where participants had the chance to have any questions related to this experiment answered.

6.6.5 Results and analysis

Figure 33 shows a plot of the stiffness values (x-axis) against the probability that a participant will correctly identify the object as harder than the standard. This probability was calculated by dividing the number of correct identifications (i.e. a participant correctly identifying an object with higher stiffness value as harder), with the total number of repetitions. Hence, if the participants were presented with a comparison stimulus with stiffness value of 0.60, and described it as being *harder* an average of three out of the three repetitions, that comparison stimulus was said to have 0.75 (75%) probability of being recognised as being "harder" than the standard.

At the point where both objects had identical values for stiffness, the participants were still required to give an answer choosing between "*left*" or "*right*" (the forced choice method does not allow them to use "*same*" as an answer), and their answer was recorded. The participants ended up answering 40/80 (50%) that the left object felt harder and 40/80 (50%) that the right object felt harder. This agrees with the probability theory that states that when the comparison stimulus appears equal to the standard, the participants will call it larger (harder in this case) 50% of the time [**39**].

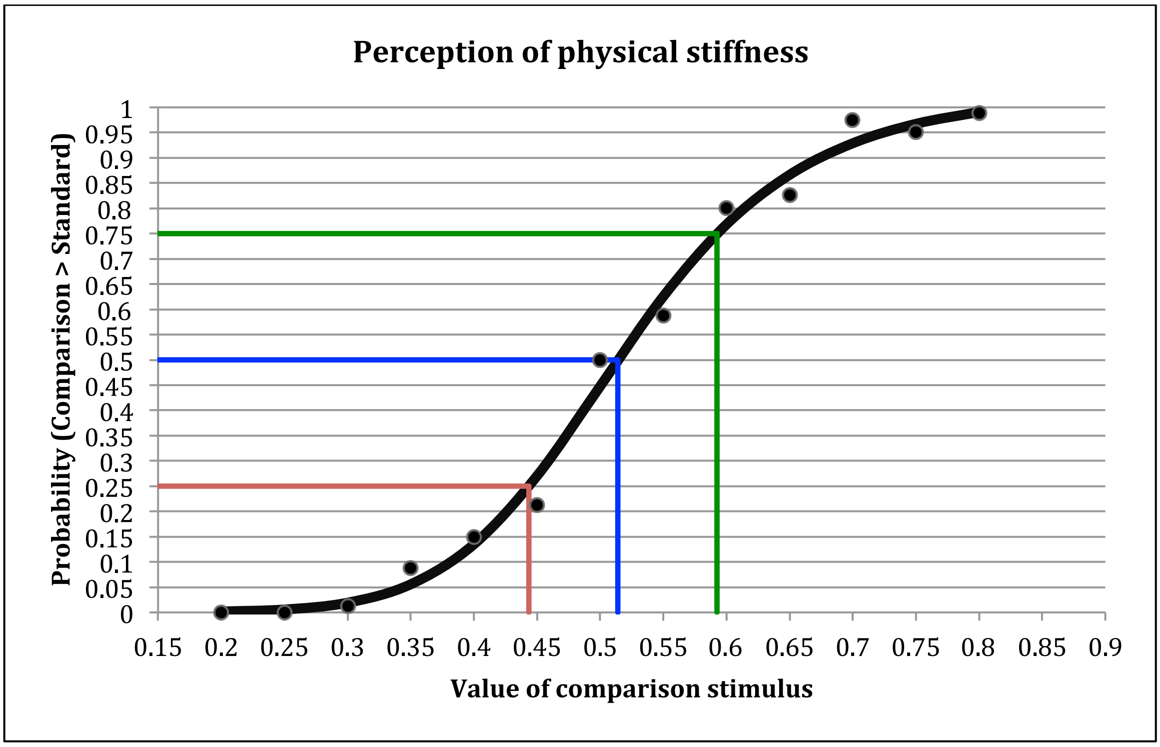

Figure 33 Psychometric function of stiffness perception. The standard stimulus had a stiffness of 0.5 throughout the experiment, while the comparison stimulus stiffness value was changing.

Each point on the plot in Figure 33 represents the average of eighty readings (eight repetitions per pair, ten participants). Once the points were plotted, a best-fit sigmoid curve was drawn through them using the logistic equation of:

$$y = D + \frac{A - D}{1 + \left(\frac{x}{C}\right)^{B}} \tag{10.}$$

In this equation, A is the initial or minimum y value; B is a power, C is the point in the x-axis where the curve changes direction, and D is the maximum value for y. These variables were adjusted to keep the sum of square differences at a minimum value (method of least squares) in Microsoft Excel using the *Solver* add-in These variable values had to be kept at a minimum in order to achieve a best fit through the points. For variable values and raw data, see Appendix 2 – Raw data, page 109.

In discrimination experiments, two statistics can be calculated: the difference threshold, or Just Noticeable Difference (JND), and the Point of Subjective Equality (PSE) [**42**]. The JND, as mentioned above in Chapter 3, is the minimum amount of physical change needed to yield a perceived change. The PSE is the point, where the comparison and standard stimulus have equal chances of being perceived as "harder" (middle black line in Figure 33). In this case, the PSE was found to be 0.51. The upper difference threshold is calculated by taking the difference between the PSE and the point where the comparison stimulus was judged to be harder 75% ($JND_{0.75}$) of the time (green line in Figure 33).

This was calculated to be 0.079. The same was done for the lower difference threshold at the 25% ($JND_{0.25}$) point (red line in Figure 33), finding a value of 0.071. The JND is then calculated by taking the average of the upper and lower difference thresholds. This was found to be 0.075.

The Table 2 below summarises these values.

Psychometric statistics	Equation	Value
PSE	Graph reading on figure 43	0.514
$JND_{0.25}$	Graph reading on figure 43	0.444
$JND_{0.75}$	Graph reading on figure 43	0.593
Lower threshold (LT)	$PSE - JND_{0.25}$	0.071
Upper threshold (UT)	$JND_{0.75} - PSE$	0.079
JND	Average of LT and UT	0.075

Table 2 Summary of psychometric statistics obtained from experiment

For a full method on how these values are calculated, refer back to section 3.3.3 Method of Constant Stimuli, page21.

6.6.6 Discussion

The data gathered from this experiment indicate a point of subjective equality (PSE) value of 0.51.This value is extremely close to 0.50 that was the actual point of equality. Also the points where the psychometric function indicates a point of just noticeable difference (JND values) are also very small. Therefore, the low JND value (0.075) and the PSE being so close to 0.50, signifies two important aspects of haptic interaction using this FFD within its middle stiffness values for judging "hardness" perception:

1. This particular FFD (both the model and the actual device) is very good at rendering stiffness at its middle range of values and,
2. Humans are very good at accurately detecting small changes in stiffness values.

In summary, the data obtained confirm the high fidelity and suitability of the FFD used for rendering stiffness and also indicates a high accuracy of detection by participants when asked to identify the “harder” of two surfaces.

Therefore, this experiment confirms that this FFD is of sufficiently high fidelity for the purpose of the next experiment, where the effect that stiffness has on the perception of roughness (how rough a surface feels) is explored.

The following chapter describes the experiment carried out to explore the relationship between physical stiffness and perceived roughness values. This investigation has an additional aim of defining numerically, using a power function, this relationship.

CHAPTER 7 – EXPERIMENT INVESTIGATING THE RELATIONSHIP BETWEEN PHYSICAL STIFFNESS AND PERCEIVED TEXTURE ROUGHNESS

7.1 Introduction

This chapter contains the experiment designed and carried out to elicit information regarding how one haptic attribute affects the perception of another. More specifically, this chapter describes how changing the physical stiffness of an object affects how “rough” it is perceived to be by a group of participants. The data obtained from this experiment is then analysed, identifying the relationship between physical stiffness and the perception of roughness it creates.

Once the fidelity and accuracy of the FFD device available had been established in the preliminary experiment, the investigation could start on the relationship between the physical stiffness values rendered via this device and how this stiffness affects the perception of surface roughness on a set of virtual objects.

The initial hypothesis that this experiment was designed to explore is that increasing the physical stiffness will cause an increase in the perceived roughness. This increase of perceived roughness should follow a power curve as defined by *Stevens’ Power Law* (see page 29).

To recap, the objective was to test how the perception of one haptic attribute is altered at different levels of intensity of another attribute. This lends itself to the method of magnitude estimation, as defined by Stevens [**47**] (and as discussed previously, on section Magnitude estimations and Steven’s Power Law, page 29)

The data was normalised, as proposed by Stevens [**47**], and magnitude estimation values for different levels of stimulus intensity were calculated. All these levels were then drawn on a graph and a power function passed through them, indicating that there is a strong relationship between the physical attribute of stiffness and the perceived value of roughness, and a power function can accurately describe this relationship.

7.2 Aim

Aim of this experiment was to investigate the relationship between physical stiffness and perceived roughness values. This aim lead to the formulation of the hypothesis stating that increasing the physical stiffness will cause an increase in the perceived roughness and should follow a power function curve.

7.3 Methodology

7.3.1 Participants

A total of thirty participants took part in this experiment; sixteen of whom were males and fourteen females. Twenty-eight of the participants were right handed and two left-handed. Their average age was 28.2(±6.3) years and nobody reported any known disability that could affect the results of this study. Age demographics are summarised in Figure 34.

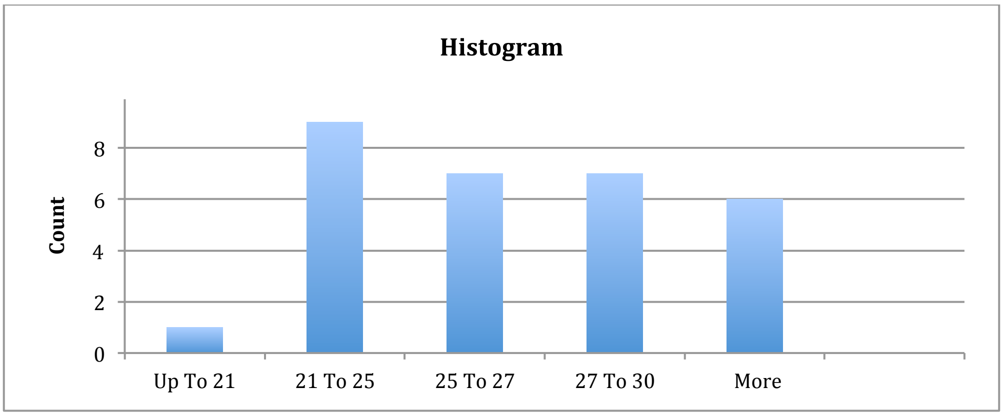

Figure 34 Age demographics histogram from second experiment

Nineteen of the thirty participants had used this FFD before either in the preliminary experiment (see previous chapter, page 72), or as part of [**93**].

Sixteen out of thirty participants were of Greek or Greek-Cypriot decent. This is mainly due to the way participants were recruited (either through the University of York Greek Society, or through personal relationships such as friends and friends of friends). This was important to note since all Greek speakers received the experiment briefing in Greek.

After the experiment, and when all the data were analysed, none of the groups identified in the demographics showed any significant difference over the other.

More specifically, one-way analysis of variance (ANOVA) test was performed between each group (male-female, experienced-not-experienced, Greek- not Greek speakers) giving a result of $p>0.05$ in all three cases, showing no significant difference in the data each group gave (more information in section 7.6 Discussion, page 90).

7.3.2 Setup

The setup and equipment used for this experiment was in a large degree identical to the preliminary experiment, as explained in the previous chapter. The Geomagic® Touch™ FFD was used for interacting with the haptic rendering of two flat surfaces that acted as the stimuli, and OpenGL graphics was used for the graphic (or visual) representation of these surfaces. The physical texture on each of the two surfaces was simulated using the stick-slip method (see Section *6.3.2 Rendering of Surface* Texture, p.66). This method was chosen after analysing the qualitative data collected during the debriefing session of a previous experiment. These data indicated that the sensation of "roughness" could be produced with stick slip. This method of simulating the physical properties on a virtual object is further supported in the literature [**10**]. More information on how surface texture was rendered and justification on decisions made can be found on Section *6.3.2 Rendering of Surface* Texture, p.66.

Simulating a "rough" surface this way has a number of advantages in the context of this experiment. First of all it is much faster to produce a number of different surfaces, all varying in their roughness level. The alternative would be to describe each surface with an algorithm similar to [**49**] or using 3D modelling software to produce a different wireframe mesh surface for every object used and alter each individual surface micro-texture. In addition, as seen from the literature, the probe size plays a significant role in how roughness is perceived, but simulating "roughness" on a surface using static friction, enables the use of probe with an infinitely small diameter. This is much easier and computationally lighter to implement and will not affect the outcome of the experiment. Lastly, the OpenHaptics Toolkit API [**92**] provides a method that enables the programmer to dynamically change an object's haptic parameters of "stiffness" and "static friction", so a tried and tested method could be used to assign these parameters on the haptic objects.

Both virtual surfaces were set to have a constant static friction value of 0.50. This value remained unchanged for both objects throughout the experiment. Also, the value of physical stiffness for the standard stimulus was set to 0.40 and remained unchanged for the experiment. These values were chosen because they are in the middle of the range this particular FFD can render with a high degree of accuracy, as proven by the last experiment. The stiffness value of the comparison stimulus was then changed in every trial within a range between 0.10 (minimum this FFD can safely produce) and 1.00 (maximum) in 0.10 intervals.

The order in which the stimulus was presented was randomised before the experiment started and then each participant received each stimulus in the same order. This method of presentation was preferred since it has been demonstrated that in roughness related experiments, a smooth surface feels rougher when felt right after a rough one [**64**]. This way, if unwanted conditions were presented, it was the same for all participants and had a major effect in the overall results of the study. The order then remained constant for the duration of the experiment.

Two repetitions per set per participant were performed, each in a different random order, but the same order for each participant (see Table 10 on page 114). As Stevens suggests, "*a good schedule should provide for one judgement, or at most two judgements per stimulus per subject* (participant)" [**47**].

The aim of this experiment is to measure how the physical stiffness of an object affects its perceived texture roughness, therefore all other parameters that may play a role in the perceived magnitude of roughness were controlled or minimised. One parameter that was found to affect the perceived values of roughness both during the pilot experiments and from personal experience was the audible noise produced by the FFD device. Because stick-slip (based on static friction values) is implemented by causing the virtual haptic cursor to stick and slip on the virtual texture (hence giving rise to the perception of roughness) the motors inside the FFD produce a mechanical noise every time they stop and start. This noise is then further amplified by the wooden desktop the FFD was sitting on. After some experimentation with placing different materials between the FFD and the desktop, it became obvious that the best way to mask this noise was by asking the participants to wear a pair of JVC headphones[5] playing pink noise[6]. The pink noise was chosen over white noise since after comparing the two, and founding it to be more comfortable to hear over long periods. Since both sounds can mask the motor noise equally well; pink noise was chosen. An assumption was made that any (now

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[5] Model: HA–D570B

[6] Pink noise obtained via http://simplynoise.com and played in a loop for the duration of the experiment.

inaudible) vibrations transferred on the table would not cause a change to what was under investigation.

On the other hand, vibrations coming from other equipment, such as the computer tower used for controlling the FFD, may had an effect on the perceived roughness, therefore, it was placed on a different table and special precaution was made so that the two tables would not touch on each other or on the wall behind them. The configuration of all the equipment used can be seen in Figure 35.

In addition to that, the participants were not restricted as to how much they could use exploring a surface. This was done since in earlier experiments conducted by Lederman and Klatzky, they found that people need more time when exploring a texture indirectly through a probe, to produce results of similar high accuracy to direct touch [**38**] (section 2.7 Comparing direct and indirect touch, page 11). Also, the speed and force of exploration was not controlled for the same reason. Each participant was free to use as much force and speed they felt they could obtain the best results with.

The virtual graphic environment participants could see was identical to the one in the preliminary experiment as described above (see Figure 30, page 69). As before special precaution was taken to release the cursor if and when trapped underneath a surface. This seamless release of the haptic cursor ensured that the experiment would flow more smoothly.

Haptic attribute changes did not result in any changes in the visual representation of the objects. Also, the two surfaces were implemented with a small gap between them, in order to stop participants from exploring both objects in one motion, something that might give them a clue that the stiffness of the two objects was actually different. The gap forced them to stop at the end of the object, raise the cursor and land it on the second object.

Figure 35 Experiment setup. Far left is the experimenter corner where participant responses were recorded in a MS Excel sheet and trial order was controlled. The right corner is where the participants made the magnitude estimations using the Geomagic® Touch™ FFD.

7.4 Procedure

Participants were greeted and asked to sit in front of the Geomagic® Touch™, facing the device and the computer screen at a 90-degree angle. Then they were asked to make themselves comfortable, adjusting the distance of the FFD from them to a point they found it most comfortable. At this point the participants thought that the experiment would be about manipulating the haptic texture of the virtual objects and measuring their perception of "roughness".

Before starting the experiment, each participant was given a brief explanation, of what is meant by "roughness" in the context of this experiment. This was done by saying to the participant that "*for example, if we feel the rug of the room with a probe, it will feel rougher than when feeling the top of the desk with the same probe*" while demonstrating with the back end of a pen. In some cases this definition and demonstration was carried out in Greek, describing "rough" as "τραχύ" (trachý). After the definition of what is meant by "rough" was clarified and the participants confirmed that they understood the definition and had no further questions, I would move on to explain what they had to do. Immediately after that they were asked to fill a consent and a demographics form (see Appendix 1). At that point, participants were also asked if they had any disabilities that may affect their performance in the experiment. None of the thirty participants reported any disabilities.

Participants were informed that they would be presented with two flat surfaces on the computer monitor in front of them, which they could feel using the FFD. As mentioned above, this was a magnitude estimation experiment. The procedure followed was identical to the one proposed by S. S. Stevens' paper [**56**]. Both stimuli were presented simultaneously to the participant and they were asked to say how rough they felt by assigning numbers to them. They were informed that the surface to the left was to act as the standard stimulus and therefore would remain unchanged throughout the experiment. The first thing they were asked to do was assign a number (*modulus*) to this standard stimulus. Stevens notes that allowing the participants nominate a number for the standard has no difference from giving a number at the beginning during the briefing, but on the contrary he claims that his experience show that it is usually better to let the participants designate the standard [**47**]. The only limitation given to the participants was that the number they would nominate had to be more than zero. Then their task in each trial was to assign numbers to the comparison (right) surface proportional to their subjective impression of roughness. They could use whatever numbers seem appropriate (fractions, decimals, or whole numbers) as long as they were not zero and not negative numbers. For example, if they assigned 10 as the modulus to the standard at the beginning, and a surface felt 3 times as rough as the standard they had to say 30; if it felt half as rough they had to say 5; if they thought it was one fifth as rough, they had to say 2, etc. Participants were also informed not to worry about being consistent, but to try to give the appropriate number to each surface regardless of what they might have called some a previous surface. Each response was recorded in an MS Excel sheet as a *ratio* to the modulus (response/modulus) before going to the next pair.

After the last trial, every participant was debriefed, informing them that the attributes responsible for "roughness" was actually constant throughout the experiment and what was actually changing was the value of stiffness for the comparison stimulus. Then any questions they might have were answered.

7.5 Results and analysis

Once a participant finished both repetitions, the mean of the magnitude estimation ratios of the two repetitions per pair was calculated. Stevens then suggests using the geometric mean (GM) when calculating the average of magnitude estimation for every pair across all participants [**47**]. The use of a geometric mean instead of an arithmetic mean is necessary since every participant was free to use any value for the modulus they wanted, potentially having different numeric ranges for every participant. Therefore, the slope determined by the geometric mean is not affected by the fact that every participant was free to use a different unit for the modulus.

The equation used for calculating the geometric mean of a number n of arithmetic means, a, is:

$$GM = \sqrt[n]{a_1 * a_2 * a_3 * \dots * a_n} \tag{11.}$$

The geometric means were then plotted on a graph of roughness estimation ratios against the physical stiffness value for the comparison stimulus in N/mm (see Figure 36).

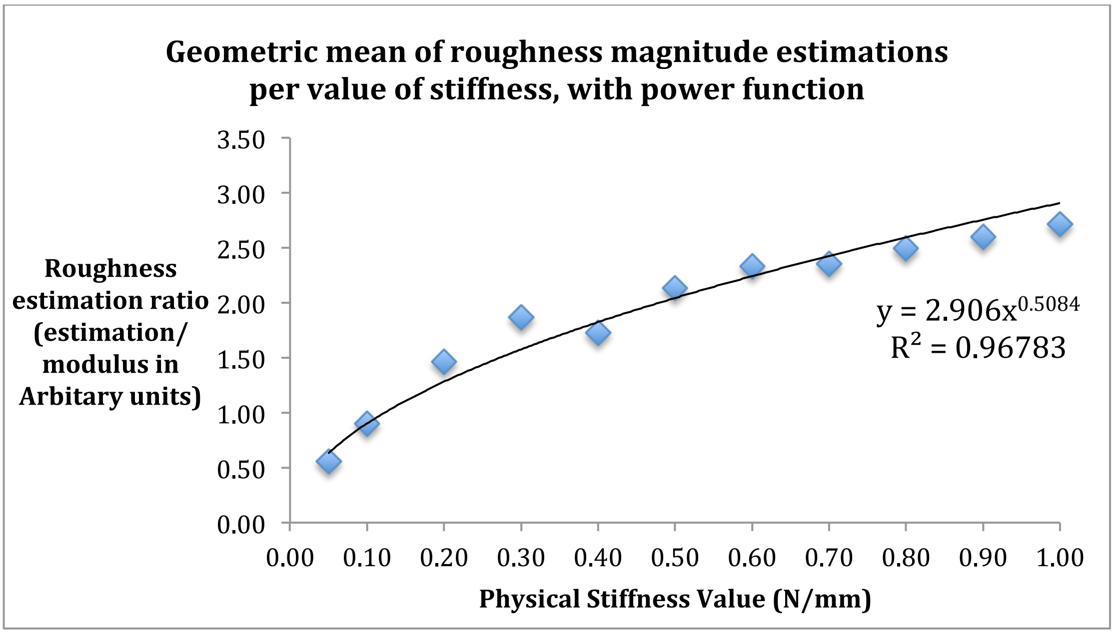

Figure 36 Plot showing the relationship of physical stiffness and perceived roughness. The plot also contains a power function used to describe the data points with a very high percentage of deviation (R^2) of 0.968.

A power function was then calculated and plotted using these data. This function shows an extremely high percentage of deviation that can be explained by this relationship ($R^2 = 0.968$). This shows that there is indeed a very strong relationship between the physical stiffness values and the perceived magnitude for roughness, hence proving the initial hypothesis. More specifically, the data confirm the existence of a relationship between stiffness and roughness, where the perception of roughness increases as stiffness increases (raw data can be found in Appendix 2 – Raw data, page 114.

In addition, the high R^2 value also shows that the power equation also stands and can be used to accurately describe the data gathered. The equation for this power function is:

$$\psi(I) = 2.906x^{0.5084} \qquad (12.)$$

This indicates that this relationship has a proportionality constant of 2.906 and an exponent of 0.5084, signifying that the perceptual magnitude grows more slowly than physical magnitude. Comparing these values and the shape of the graph, it can be observed that the relationship between stiffness and perceived roughness is comparable to the relationship between other sense stimuli with perceptual continua such as perceived brightness.

7.6 Discussion

It is clear from the graphs plotted using the data of this experiment that a strong relationship exists between the physical stiffness changes and the perception of roughness. More specifically, using the formula for *Stevens' Power Law* (Equation 5.) a power function is passed through the points obtained from the magnitude estimations with a high percentage of deviation that can be explained by this relationship ($R^2 = 0.968$).

Going back to *Chapter 3, page 29* we may recall that according to Stevens, the best way to show that the data obtained from a psychometric test following his power law is by plotting the data in log-log coordinates (see figure 37).

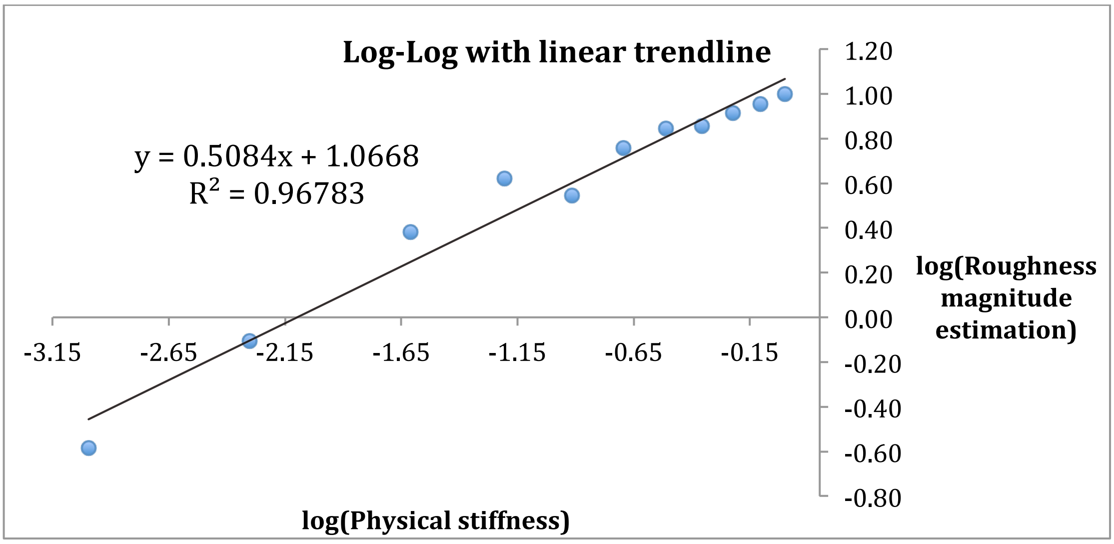

Figure 37 Roughness magnitude estimation against physical stiffness values in log-log coordinates

The power function has a very convenient feature of becoming a linear function, with a slope equal to value of the power exponent when a logarithmic transformation is performed on the data collected from the experiment and the values of the stimulus tested (different levels of stiffness in this case) [**46**].

The format of the resulting equation is:

$$\log \psi = a \log \phi + \log k \tag{13.}$$

The exponent calculated from the power law can then be calculated by plotting the logarithm of the psychological scale values ψ against the corresponding stimulus values ϕ and find the slope of the straight line fitted through the points using the method of least squares [**46**].

With this technique, the closeness of fit of the power law to the experimental data can also be evaluated [**46**]. Any systematic deviation of the data points from the straight line an indication that the psychophysical magnitude function is not a power function.

If no systematic deviation is shown by the data points, the method values from the straight line equation as calculated via the method of least squares can be used to determine the values of the exponent and for the constant of proportionality.

In this case (see figure 46) the constant of proportionality was calculated to be 2.906 (log 1.0668 = $e^{1.0668}$ = 2.906) and the exponent (slope of plot) 0.5084. These values are identical to those calculated by the power function, therefore the equation obtained from the power law can be considered valid.

Therefore, since there is no observed systematic deviation of the data points that would suggest inaccuracies in the power function as Stevens suggests [**97**], and after proving the validity of the experimental results we can start looking on what these result mean.

Data collected from this experiment indicate that the sensation of roughness grows at a slower rate than the physical stimulus (stiffness) increases, with, as mentioned above, an exponent value indicated by *Stevens' Power Law* to be 0.5084.

This exponent value is a lot smaller than the exponents measured by Stevens for a number of relevant continua. More specifically Stevens found an exponent value for vibration continuum of 0.95 when a vibration stimulus of 60 Hz was applied to the finger and 0.6 when the frequency was increased to 250Hz.

When tactual roughness was tested by rubbing emery cloths, as the stimulus condition, an exponent of 1.5 was calculated and 0.8 for tactual hardness when squeezing rubber [**96**]. If anything, one can say that the relationship of stiffness in the perception of roughness can most closely relate numerically to the relationship between lumens and the perception of brightness (exponent of 0.5) linking the levels of brightness and the size of the point source [**96**].

At the moment of writing, there is no literature of how stiffness affects the perception of roughness in real, physical objects and what the value of the exponent of such relationship is to compare these data against.

There is, on the other hand, some literature that suggests that when considering individual psychometric functions there might be some diversity (e.g. [**49**]). Having that in mind, data from each individual participant was considered and plotted independently, giving each participant a unique exponent value.

Twenty-eight out of the thirty participants had positive exponent values and a linear fit with an R^2 value greater than 0.75 (mean 0.87±0.07). This indicates linear growth of the roughness perception magnitude with the physical stiffness value, as exponent translates to the graph's gradient in log-log coordinates.

The magnitude estimations from two participants on the other hand did not follow a linear fit (see figure) and the R^2 was under 0.50 (0.29 and 0.47). Interestingly, these two participants were the oldest two participants involved in this study; both were over 40 years old. One participant was male and the other female and both were white British. This may indicate that age plays an important role in magnitude estimations for roughness and can be something worth investigating in the future.

This means that the data from this study do not show the high diversity other studies have shown, and all individuals exhibited an increase in magnitude estimations as the physical stiffness was increasing. A table of all exponents and R^2 values can be found in Appendix 2.

Even though Steven's Law is often criticised for not taking into consideration individual differences of the participants and only taking into account the group average, it is not uncommon for the shape of the psychophysical functions to be consistent between subjects (e.g. [**70**]).

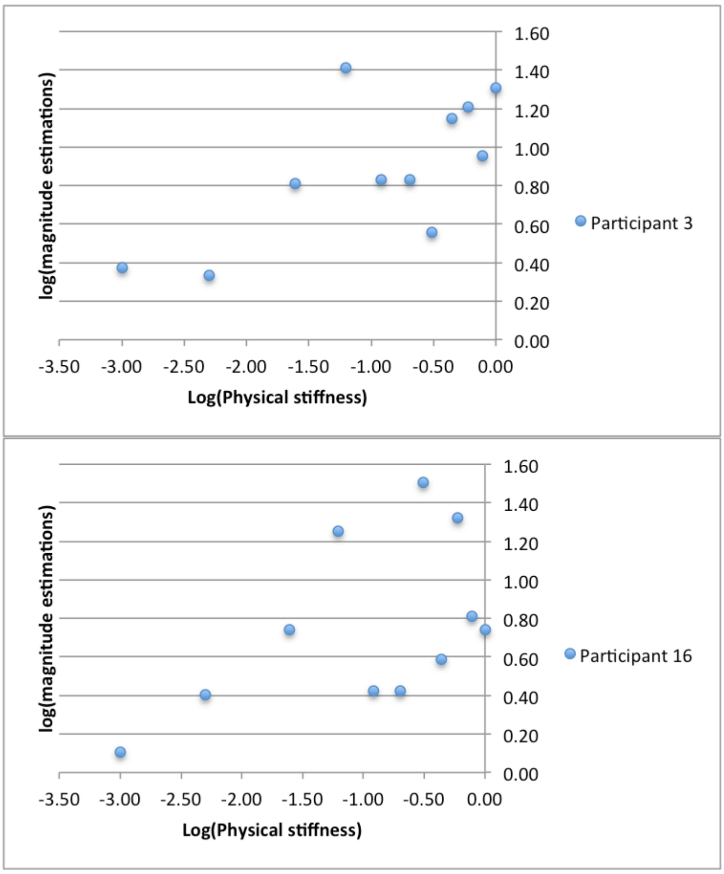

Figure 38 log-log graps of participants 3 and 16

	Group size		*Sum of squares*	*Degrees of freedom*	*Mean Square*	*F*	*p-level*
Gender (M/F)	16	14	0.00265	1	0.00265	0.10986	0.74277
Experience (with/without)	19	11	0.00026	1	0.00026	0.01069	0.91838
Language (Greek/non-Greek)	17	13	0.01428	1	0.01428	0.60279	0.44402

Table 3 Results of a one-way ANOVA test between: a) genders, b) Experience with the FFD, c) Language the briefing was given in.

Lastly, demographics data from the participants of this study showed that a number of them had participated in previous experiments using this FFD for the studies in [**93**]. Also, as mentioned in 7.4 Procedure section, page 87, the briefing for Greek speakers was given in Greek. To make sure the participant expertise with the FFD or the language in which the briefing was given to them had no effect on the data, a one-way analysis of variance (ANOVA) test was performed between each group (experienced vs not-experienced, Greek vs non-Greek speakers) and between genders. That gave a result of $p>0.05$ in all three cases, showing no significant difference in the exponents given by each group. Full data of the ANOVA results is given in table 3 above.

CHAPTER 8 – CONCLUSION

8.1 Conclusion

Haptics and the sense of touch has been a very explored area of research for a number of decades. Recent advancements in technology and the proliferation of haptic enabled devices in the market means it is an area that is still growing and expanding. Psychologists began exploring haptics during the early part of the twentieth century, defining haptics as being any form of nonverbal communication involving touch. During the later part of twentieth century, advancements in technology and electronics meant that researchers began to look at novel ways of interaction with machines involving touch. Instead of devising a new name for this new discipline, they decided to redefine the pre-existing term for haptics, broadening its definition and hence its domain to include all aspects of information acquisition and object manipulation through touch by humans, machines, or a combination of the two. This made haptics a massively wide domain, including not only psychologists but also other scientific fields, like electrical engineers, computers scientists and even medical researchers.

Studies exist that explore how a rough surface is perceived and what physical attributes affect the perceived level of roughness. When talking about sandpapers and surfaces with raised elements, like emery cloths the perceived roughness was found to relate to the grit number[7] by a power function [**56**] while, both the inter-element space and the radius of each element play an active role to the perception of roughness [**1**].

When exploring surfaces with ridges and groves carved into them (instead of raised elements) the perceived roughness is found to depend in both the width of the grooves and the space between each groove, with the perception increasing at a steady rate until the groove width approaches the diameter of the finger and then the roughness magnitude is perceived to drop [**66**]. Lederman and Taylor [**61**] also reported an effect of the fingertip force on perceived roughness with the perceived roughness decreases for both groove width and land width as the force increases.

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[7] Grit number refers to the number of openings per square inch in the sieve used for applying the abrasive powder on the cloth. Therefore, it is equal to the number of sharp particles per square inch.

The perceived roughness could therefore be predicted as a function of groove width, fingertip force and groove distance using a model based on the amount of depression of the fingertip into the groove [**62**].

When the exploration is performed indirectly through a probe, a surface feels rougher as the space between the surface elements or the width of the ridges approach the diameter of the tool which allows it to fit through the space between the elements on the surface before it drops to form a graph of quadratic shape. This indicates that roughness percept is highly sensitive to the physical interaction between the probe and the element configuration [**33**].

With advancements in technology, haptic displays became available for researchers to use in their experiments. Studies aiming to replicate the results of previously conducted experiments indicate that with careful simulation of the geometry of probe-texture interaction haptic device, virtual roughness perception is essentially equivalent to real roughness perception [**2**].

Similar research is also done in the area of stiffness and virtual stiffness and how it affects the perception of hardness with the overall conclusion being that subjective hardness grows with the physical stiffness value in a power function [**71**].

While reviewing the literature of haptic perceptions, a gap emerged in the domain knowledge between the studies for hardness perception (linked to the physical stiffness of an object) and that of roughness perception (linked to the physical microstructure of a textures surface).

Most of the research to date concentrates on exploring how humans perceive touch one characteristic at the time, leaving one main question unanswered: how does one physical characteristic affects the perception of another? More precisely, this study was set to explore how the physical stiffness of an object affects how rough that object is perceived to be.

Before attempting to answer this question, a preliminary experiment was carried on, in order to test and verify the fidelity of the force feedback device (FFD) available for the purpose of this study. In this study a comparison experiment was conducted using the method of discrimination. The results of this experiment showed that human participants are very accurate in identifying very small changes in physical stiffness, rendered via the FFD available, within the value range chosen to use for the main experiment. Also, with this experiment I had verified that this particular FFD (both the model and the actual device) is very good at rendering stiffness at its middle range of values.

Having verified the fidelity of the FFD available for this study, I proceed to answer the question whether one physical characteristic affect the perception of another. To do this an experiment was carried out where a group of participants was asked to give magnitude estimations regarding their perception of roughness for a set of surfaces compared to a standard. Even though, the participants of this study were asked to report how "rough" the surface of the virtual object felt in every trial, the physical attribute actually changing was the object's physical stiffness. This stiffness value has been demonstrated in the literature to affect the object's perception of "hardness" and not "roughness" (see section 4.2 Perception of hardness, page 49). Therefore what this study was investigating was how their perception of "roughness" was changing with varying the physical value of stiffness.

The results showed a close relationship between physical stiffness and perceived roughness. More specifically, the average roughness magnitude estimation showed an increase with increasing physical stiffness in a rate that can be very closely described by a power function with a constant of proportionality equal to 2.906 and an exponent of 0.508 (see Figure 36). Plotting the same data in log-log coordinate gave a straight line, further indicating the existence of this relationship (see Figure 37).

Analysing the data from every individual participant also showed a linear increase when plotted in log-log coordinates with a high coefficient of determination (R^2) value for the majority of them (28/30). Two participants gave inconclusive data, which followed no specific trend line with a strong fit. Both of these participants were British and 40 years of age. Further investigation is necessary to determine if their age had a link with the results they produce or if they were just outliers.

The increase demonstrated in roughness perception with increase in physical stiffness can be compared to the increase in the magnitude of roughness with increasing ridge width, increase between the inter-element spaces or the element radius previous experiments have shown. Exactly how it compares remains to be answered in the future.

Therefore, based on these results the conclusion that physical stiffness plays a very important role in the perception of roughness can be made, making harder[8] objects feel rougher than softer[9] objects in a predictable way, even though their texture characteristics may remain constant.

This means that simply changing the physical stiffness of an object in a haptic display, we can *predictably* change the perceived roughness level it can give to its user. This new information, and more importantly the predictability given by the power function, gives a, potentially useful insight to the haptic display interface designer. This insight can be especially useful, for example, if hardware limitations only allow the designer to alter the stiffness levels of the haptic interface. Changing the stiffness, the level of roughness can be changed *predictably*, creating unique sensations and allowing the designer to utilise a whole new dimension to the haptic display.

In addition to that, this relationship can be of utmost important to medical simulator designers, where they need to be able to predict how roughness perception may change while an object becomes more or less stiff and incorporate that to their simulation.

Having in mind the existence of this relationship is a small step forward to a better understanding of touch as a sense that will help us move to the creation of better and more accurate haptic interfaces in the future, producing even more accurate representations of virtual haptic objects, as they exist in the real world.

8.2 Limitations

8.2.1 Hardware used

The first and, maybe, most obvious question one may ask is why only one point of subjective equality (PSE) was tested for the physical stiffness values (see page 72). As mentioned in that section, the main aim of that experiment was to identify the level of accuracy that specific device could render stiffness and how accurate humans are in detecting small changes in stiffness within a specific range of stiffness values. Therefore, for the purpose of the current study, only that PSE range value was needed.

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[8] Perception of hardness depending on stiffness

[9] Softness defined in literature as the opposite of hardness [**56**]

On the other hand, that does not mean that the restricted hardware capabilities of the Geomagic® Touch™ was not one of the limitations in this study. As mentioned in section 6.6 Preliminary Experiment – Obtaining a psychometric function for perceived hardness, page 75, the maximum force this particular FFD can produce is 3.3N. This low force value means that it is not possible to render a surface with very high or even infinite stiffness (e.g. surface made out of granite), causing even the "hardest" surfaces to feel springy.

Another device related limitation is the way interaction takes place with the device. Having a stylus as its end effector forces the user to interact with a virtual surface as if the user is holding a probe. This may not lead to "natural" interaction in some cases since, except for few tasks (outlined in Section 2.6 Indirect touch, page 9), we do not often use a probe to explore the texture of an object. Modifications can be made to the device to simulate direct touch (e.g. [**97**] and [**98**]) but these need careful design and manufacturing which may be both costly and time consuming.

8.2.2 Participants

The way participants were recruited for this study can also be a limiting factor. As mentioned in the demographics section 7.3.1 Participants, page 83, the majority of participants were under 35 years of age (27/30). Only three participants were over the age of 40 and 2 of them gave inconclusive data (did not follow a linear trend). This may indicate that magnitude estimations of roughness when stiffness changes is affected with age. With only three out of thirty participants being over 40, there is not enough evidence for a conclusion to be made.

9.2.1 Expanding the stiffness range

One way to extend and expand the work started in this project can be by repeating the roughness perception experiment (see Section Chapter 7 – Experiment investigating the relationship between physical stiffness and perceived texture roughness, page 82) using a wider range of values for the constant stimuli of physical stiffness. Then the relationship of physical stiffness and perceptual roughness will be established in a wider, or even the entire range of values of stiffness for the haptic human computer interaction that can be rendered via the Geomagic® Touch™.

9.2.2 Better stiffness rendering

This further work suggestion comes from one of the limitations of the current study. More specifically, the low maximum force the FFD can produce may cause even the "stiffer" objects feel "springy" (see section 8.2.1 Hardware used, page 98).

The most obvious way to overcome this limitation is by using a higher fidelity FFD, like the Magnetic levitation haptic device Unger, Hollis and Klatzky used for their experiments [**2**] [**97**].

This, on the other hand may not be the best solution due to availability of such device and the high cost. Karadogan et al. [**98**], managed to overcome this limitation of the Geomagic Touch by applying the law of moments on the device end effector (tip of the device arm). They modified the device's stylus, moving the point of application of the force away from the FFD's original pivot (the distal end of the arm) to the finger stylus shown in Figure 39. This modification allowed their participants to feel higher forces for stiffness.

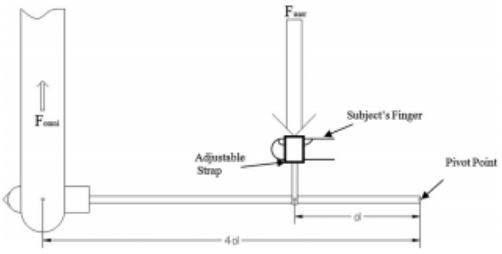


Figure 39 Diagram showing the modified stylus of the Geomagic Touch FFD as used in [98]

After achieving better stiffness rendering, the experiment on how physical stiffness affects perceived roughness can be repeated to investigate the effects a change in stiffness fidelity can have on the power function shape.

9.2.3 Investigate more haptic rendering techniques

It is also worth investigating how other techniques for simulating physical attributes that produce the perception of roughness can be used to investigate the relationship between physical stiffness and roughness. In this project, the method of stick-slip was chosen for simulating roughness. As a future work, three dimensional models of objects with a micro-texture rendered on them can be used, for example, and again alter their stiffness values, repeating the experiment to find the relationship of physical stiffness and the perception of roughness. These micro-textures can be either raised elements (similar to the surface of sandpaper) or a texture of ridges and lands as used by Lederman et al [**66**] in their experiments regarding the perception of roughness.

A comparison can then be made on the points where the roughness level perceived is equal to changes in physical stiffness and to other texture properties such as ridge width, inter-element spacing and radius of raised elements (i.e. "changing the physical stiffness value by X units has the same effect in the perception of roughness as changing the ridge width of the grooves on the surface by Y units").

9.2.4 Investigate the relationship between more physical haptic dimensions

Other relationships can also be investigated between physical dimensions of an object and the perceptions it affects. For example, the relationship between physical roughness and the perceived hardness (opposite of what is presented in this study) can be investigated, or how a "sticky" surface may affect the perception of hardness. This investigation of how one physical attribute affects one or more perceived haptic dimensions can subsequently used for constructing something like a haptic pallet for a haptic display designer, where altering one physical attribute can in turn change a whole array of perceived haptic dimensions in a clear and predictable way.

Furthermore, after further exploring the area of physical attributes and their effects on all perceptual dimensions, it may be possible to implement a tool, where even non-programmer designers can use to construct the haptic scenes that they need.

9.2.5 New group of participants

Participants in this study were recruited through advertising within the Department of Computer Science at the University of York and The University of York Greek society (section 7.3.1 Participants, page 83). This introduced a limitation regarding the age group of the participants (see Limitations in section 8.2.2 Participants page 99). This limitation can be considered in future work to investigate if its existence played a significant role to the results of this study.

The majority of participants (27/30) were under the age of 35. Results from this study showed that 2/3 of the participants who were over the age of 40 could not give conclusive data (section 7.6 Discussion, page 90). The small number of participants in this study who were over the age of 40 did not allow a definite conclusion that age plays a significant role in roughness magnitude estimation when stiffness changes. Therefore, this study can be repeated with a number of age groups and investigate the results, both within each group and between groups to see if any significant differences are introduced because of the participant's age.

APPENDIX 1 – FORMS

P.N.:________.

Participant consent

Your participation in this experiment is entirely voluntary; there will be no remuneration for the time you spend evaluating it. All data gathered from this study will be treated in a confidential fashion: It will be archived in a secure location. When your data are reported or described, all identifying information will be removed. There are no known risks to participation in this experiment, and you may withdraw at any point. Please feel free to ask the researcher if you have any other questions; otherwise, if you are willing to participate, please sign this consent form and proceed with the experiment.

Full Name ____

Signature: ____________________

Date: ____________________

Researcher's contact details:

Name
Theodoros Georgiou

Email address
tg633@york.ac.uk

Supervisor's contact details:

Name
Alistair Edwards

Email address
alistair@cs.york.ac.uk

Demographics Form

Age:________________________.

Sex: Male / Female

Left-Right handed: LEFT / RIGHT

Any known disabilities related to the experiment? Yes / No

Comment:

Ever used a haptic device before? Yes / No

If "Yes", when, how and why?:

____

Country: ____

Ethnicity:

White

- ○ White - British
- ○ White - Irish
- ○ Other White background

Asian or Asian British

- ○ Indian
- ○ Pakistani
- ○ Bangladeshi
- ○ Other Asian background

Chinese

- ○ Chinese

Information refused

- ○ Information refused

Black or Black British

- ○ Caribbean
- ○ African
- ○ Other Black background

Mixed ethnicity

- ○ White and Black Caribbean
- ○ White and Black African
- ○ White and Asian
- ○ Other mixed background

Other ethnic background

- ○ Other background

Please specify:

____

APPENDIX 2 – RAW DATA

Preliminary experiment

Demographics

Participant number	Age	Sex
1	26	Male
2	26	Male
3	32	Male
4	25	Male
5	27	Male
6	27	Female
7	27	Male
8	28	Male
9	28	Male
10	27	Female
Average	27.3	
Stdev	1.888562063	

Table 4 Age and sex demographic data (n=10)

Values for stiffness as used in the experiment

	Stiffness Values							
Set No.	**First Set**		**Second Set**		**Third Set**		**Fourth Set**	
	Left	**Right**	**Left**	**Right**	**Left**	**Right**	**Left**	**Right**
1	40.00	50.00	50.00	30.00	70.00	50.00	50.00	45.00
2	50.00	25.00	30.00	50.00	50.00	55.00	50.00	20.00
3	30.00	50.00	35.00	50.00	55.00	50.00	60.00	50.00
4	75.00	50.00	50.00	75.00	50.00	20.00	50.00	25.00
5	80.00	50.00	50.00	35.00	50.00	75.00	50.00	65.00
6	50.00	65.00	40.00	50.00	35.00	50.00	25.00	50.00
7	50.00	45.00	50.00	65.00	50.00	35.00	20.00	50.00
8	20.00	50.00	50.00	70.00	50.00	40.00	80.00	50.00
9	50.00	30.00	65.00	50.00	50.00	45.00	50.00	75.00
10	50.00	60.00	20.00	50.00	45.00	50.00	40.00	50.00
11	70.00	50.00	50.00	45.00	50.00	50.00	50.00	60.00
12	50.00	35.00	50.00	50.00	50.00	70.00	50.00	50.00
13	60.00	50.00	50.00	20.00	25.00	50.00	50.00	70.00
14	50.00	70.00	50.00	55.00	50.00	30.00	65.00	50.00
15	55.00	50.00	80.00	50.00	20.00	50.00	50.00	55.00
16	50.00	75.00	50.00	60.00	50.00	50.00	45.00	50.00
17	50.00	50.00	50.00	40.00	50.00	25.00	55.00	50.00
18	50.00	40.00	75.00	50.00	75.00	50.00	50.00	50.00
19	50.00	80.00	50.00	50.00	65.00	50.00	50.00	30.00
20	50.00	20.00	55.00	50.00	50.00	80.00	50.00	40.00
21	45.00	50.00	70.00	50.00	40.00	50.00	75.00	50.00
22	50.00	55.00	25.00	50.00	50.00	60.00	70.00	50.00
23	50.00	50.00	50.00	80.00	50.00	65.00	50.00	80.00
24	35.00	50.00	50.00	25.00	60.00	50.00	50.00	35.00
25	25.00	50.00	45.00	50.00	30.00	50.00	30.00	50.00
26	65.00	50.00	60.00	50.00	80.00	50.00	35.00	50.00

Table 5 Values for stiffness as used in every trial of every set during the hardness discrimination experiment

Raw data from participants

Average values from four trials per participant per pair are presented here
Full raw data are available from the author upon request.

Standard	Comparison		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10		Average	Probability	
															Standard > Variable	Variable > Standard
50.00	20.00		1	1	1.00	1	1	1	1	1	1	1		1	1	0
50.00	25.00		1	1	1.00	1	1	1	1	1	1	1		1	1	0
50.00	30.00		1	1	1.00	0.875	1	1	1	1	1	1		0.9875	0.9875	0.0125
50.00	35.00		1	1	0.88	0.75	1	0.625	1	1	0.875	1		0.913	0.913	0.087
50.00	40.00		0.75	0.875	0.88	0.75	0.875	0.75	1	0.875	0.875	0.88		0.851	0.851	0.149
50.00	45.00		0.875	0.75	0.75	0.75	0.75	0.75	1	0.75	0.75	0.75		0.7875	0.7875	0.2125
50.00	50.00		0.50	0.50	0.50	0.50	0.50	0.5	0.5	0.5	0.5	0.5		0.5	0.5	0.5
50.00	55.00		0.625	0.75	0.63	0.25	0.625	0.625	0.75	0.625	0.5	0.5		0.588	0.412	0.588
50.00	60.00		0.875	0.625	0.75	0.625	0.875	0.75	1	1	0.625	0.88		0.8005	0.1995	0.8005
50.00	65.00		0.75	0.875	0.88	0.375	0.875	0.875	0.88	1	0.875	0.88		0.8265	0.1735	0.8265
50.00	70.00		1	0.75	1.00	1	1	1	1	1	1	1		0.975	0.025	0.975
50.00	75.00		1	1	0.88	0.75	1	1	1	1	1	0.88		0.951	0.049	0.951
50.00	80.00		1	1	0.88	1	1	1	1	1	1	1		0.988	0.012	0.988

Table 6 Raw data from preliminary experiment

Analysed data

Plotting the best-fit sigmoid curve using Equation A1 (next page).

The value of Stiffness for the standard is set to 0.5

Value of Variable	Probability of Variable > Standard (%)	Predicted value	Square difference
0.2	0	0.001792566	3.21329E-06
0.25	0	0.005738623	3.29318E-05
0.3	0.0125	0.019231672	4.53154E-05
0.35	0.087	0.055665755	0.000981835
0.4	0.149	0.134778612	0.000202248
0.45	0.2125	0.270220867	0.003331698
0.5	0.5	0.447728368	0.002732324
0.55	0.588	0.625572172	0.001411668
0.6	0.8005	0.76810417	0.00104949
0.65	0.8265	0.866406531	0.001592531
0.7	0.975	0.928893309	0.002125827
0.75	0.951	0.967299996	0.00026569
0.8	0.988	0.990774513	7.69792E-06
		sum	0.013782469

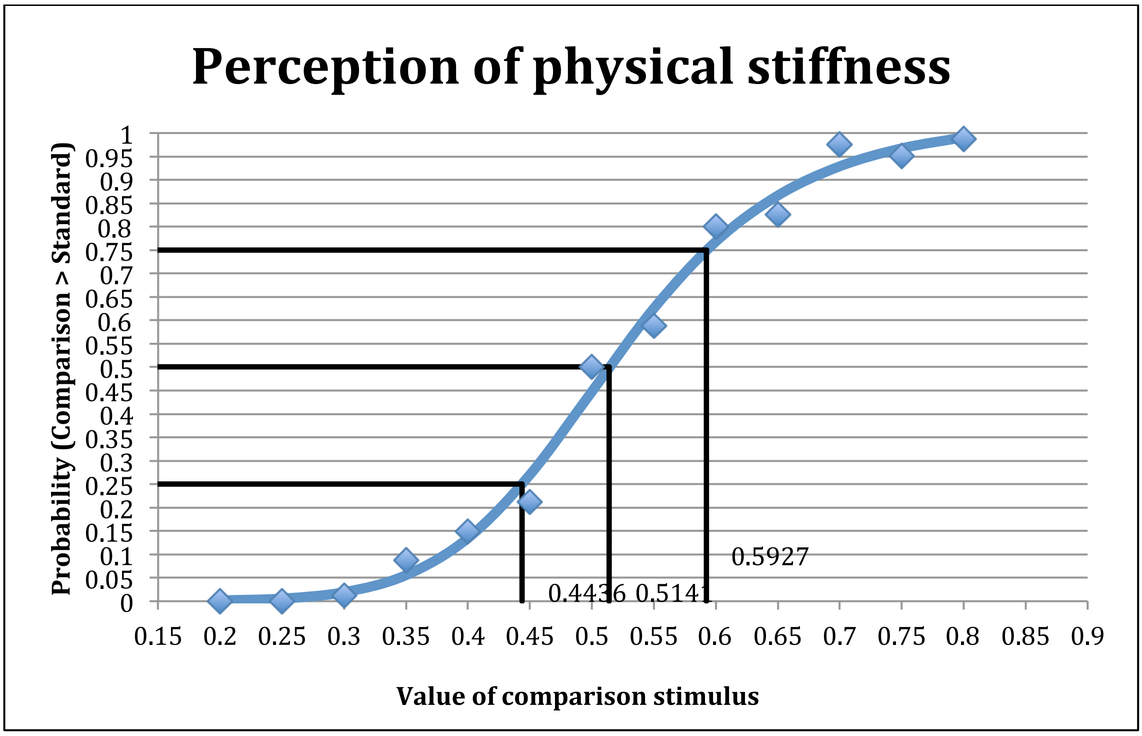
Table 7 Data used for plotting a best fit curve of the psychometric data from preliminary experiment

Equation Variables			**Psychometric Statistics**	
A	0.000830817		R^2	0.993017106
B	7.321141175		$\text{JND}_{0.25}$	0.443639549
C	0.518675444		PSE	0.514148953
D	1.032252098		$\text{JND}_{0.75}$	0.592655518
			Upper-JND difference	0.078506565
			PSE	0.514148953
			Lower JND Difference	0.070509404
			Difference threshold	0.074507985

Table 8 Psychometric statistics

$$y = D + \frac{A - D}{1 + \left(\frac{x}{C}\right)^B}$$

Equation A1 Equation used for plotting the best-fit curve of the psychometric data


Perception of physical stiffness
Probability (Comparison > Standard)
1
0.95
0.9
0.85
0.8
0.75
0.7
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.4436
0.5141
0.5927
Value of comparison stimulus

Experiment investigating the relationship between physical stiffness and perceived roughness

Demographics

Participant number	Age	Sex
1	27	Male
2	28	Female
3	42	Female
4	32	Male
5	28	Male
6	26	Male
7	21	Female
8	27	Male
9	22	Female
10	29	Female
11	26	Male
12	26	Male
13	31	Male
14	29	Female
15	27	Female
16	49	Male
17	30	Female
18	28	Male
19	32	Female
20	24	Male
21	25	Male
22	42	Female
23	23	Female
24	28	Female
25	25	Male
26	27	Male
27	23	Female
28	23	Female
29	23	Male
30	23	Male
Average	28.2	
Stdev	6.266495473	

Table 9 Age and sex demographics for main experiment (n=30)

Values for stiffness as used in the roughness magnitude estimation experiment

	Stiffness Values		
Trial	Standard Object	Comparison Object	
		First Set	Second Set
1	0.40	0.60	0.90
2	0.40	0.30	0.60
3	0.40	0.20	0.10
4	0.40	0.90	1.00
5	0.40	0.50	0.70
6	0.40	0.80	0.50
7	0.40	1.00	0.30
8	0.40	0.70	0.80
9	0.40	0.10	0.20
10	0.40	0.05	0.05
11	0.40	0.40	0.40

Table 10 Comparison object stiffness values as used in main experiment

Raw Data

Average values from four trials per participant per pair are presented here
Full raw data are available from the author upon request.

Comparison Stiffness		**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**	**P14**	**P15**
0.05		0.18	0.75	1.45	1.45	1.15	1.10	1.25	0.85	1.10	0.28	1.10	0.75	1.30	1.50	0.40
0.10		0.58	0.75	1.40	1.75	1.50	1.25	1.50	1.15	1.15	0.58	1.20	1.25	1.50	2.25	0.55
0.20		2.40	1.14	2.25	2.25	1.90	1.75	2.25	1.25	1.30	0.80	1.40	1.50	1.65	2.50	2.05
0.30		3.45	1.28	4.10	3.00	2.15	2.10	2.00	1.30	1.25	1.40	1.68	1.75	2.00	2.50	2.40
0.40		1.40	1.18	2.30	2.75	2.10	2.25	3.00	1.40	1.75	1.10	1.25	1.60	1.75	3.00	1.50
0.50		5.50	1.35	2.30	4.00	2.00	3.25	3.75	1.50	1.40	1.33	1.58	2.05	2.00	4.00	2.45
0.60		7.00	1.68	1.75	4.25	3.25	3.50	2.75	1.50	1.75	1.97	1.90	2.00	2.50	2.50	2.75
0.70		6.50	1.45	3.15	4.75	2.40	2.50	3.75	1.50	1.50	1.73	1.75	2.25	2.50	3.25	3.00
0.80		4.60	1.62	3.35	4.00	2.75	3.00	5.25	1.30	1.75	2.00	1.68	2.75	2.15	3.00	2.55
0.90		6.20	1.75	2.60	4.50	2.90	3.75	2.50	1.60	2.00	3.00	1.70	3.00	2.50	3.75	3.25
1.00		6.60	1.45	3.70	4.75	2.50	2.60	4.00	1.60	1.75	2.67	1.60	3.35	3.00	3.50	3.00
Comparison Stiffness		**P16**	**P17**	**P18**	**P19**	**P20**	**P21**	**P22**	**P23**	**P24**	**P25**	**P26**	**P27**	**P28**	**P29**	**P30**
0.05		1.11	0.75	1.25	1.03	0.02	0.60	0.65	0.15	0.50	0.08	0.37	0.35	0.45	0.30	0.50
0.10		1.50	1.00	2.00	1.05	0.11	0.75	0.85	0.40	1.05	0.20	1.00	0.65	1.35	0.45	0.85
0.20		2.10	1.50	3.75	1.15	0.35	1.40	1.50	1.00	1.35	0.85	2.10	1.23	1.35	1.00	1.00
0.30		3.50	1.50	4.00	1.25	1.38	2.05	1.40	1.65	1.55	1.15	2.80	1.25	1.65	1.50	1.25
0.40		1.53	2.50	2.75	1.35	0.85	1.45	1.50	1.70	1.30	1.75	3.50	1.20	1.65	3.00	0.95
0.50		1.53	2.75	3.50	1.35	1.58	2.45	1.55	1.60	1.85	2.25	3.80	1.35	2.50	2.00	1.24
0.60		4.50	3.00	4.00	1.35	1.60	1.80	1.45	1.35	2.05	2.50	4.50	1.50	1.75	3.00	1.55
0.70		1.80	2.38	4.75	1.55	2.05	2.05	2.15	1.45	2.10	2.50	5.00	1.35	2.25	2.50	1.45
0.80		3.75	3.25	4.50	1.45	1.48	2.60	1.85	1.85	2.10	2.75	3.95	1.50	3.75	3.00	1.30
0.90		2.25	3.50	5.25	1.45	1.70	1.80	1.70	2.00	2.20	3.25	4.00	2.00	3.00	3.50	1.40
1.00		2.10	3.00	6.00	1.43	2.05	2.10	2.05	2.50	2.15	3.50	5.45	1.75	3.75	4.00	1.48

Table 11 Raw data from main experiment

Analysed data

Comparison Stiffness	Geometric mean
0.05	0.56
0.10	0.90
0.20	1.47
0.30	1.86
0.40	1.72
0.50	2.13
0.60	2.33
0.70	2.35
0.80	2.49
0.90	2.60
1.00	2.72

Log(Stiffness)	Log(Geometric mean)
-1.30	-0.25
-1.00	-0.05
-0.70	0.17
-0.52	0.27
-0.40	0.24
-0.30	0.33
-0.22	0.37
-0.15	0.37
-0.10	0.40
-0.05	0.41
0.00	0.43

Table 12 Geometric means from raw data and their log values

Exponent values from individual participants

Participant number	Exponent	R^2
1	1.1614	0.8699
2	0.2859	0.889
3	**0.2599**	**0.4749***
4	0.4234	0.9479
5	0.2866	0.8464
6	0.3871	0.8523
7	0.3942	0.75997
8	0.1767	0.849
9	0.1825	0.7653
10	0.708	0.9449
11	0.1519	0.6893
12	0.429	0.9285
13	0.2436	0.8563
14	0.2504	0.7535
15	0.6845	0.8561
16	**0.246**	**0.2893***
17	0.519	0.9376
18	0.4382	0.8525
19	0.1358	0.9162
20	1.5117	0.9001
21	0.44	0.812
22	0.3501	0.875
23	0.8059	0.8718
24	0.443	0.9058
25	1.2697	0.9656
26	0.8139	0.9258
27	0.4829	0.8904
28	0.5747	0.8517
29	0.8765	0.9515
30	0.3191	0.8483

Table 13 Exponent values for every individual participant

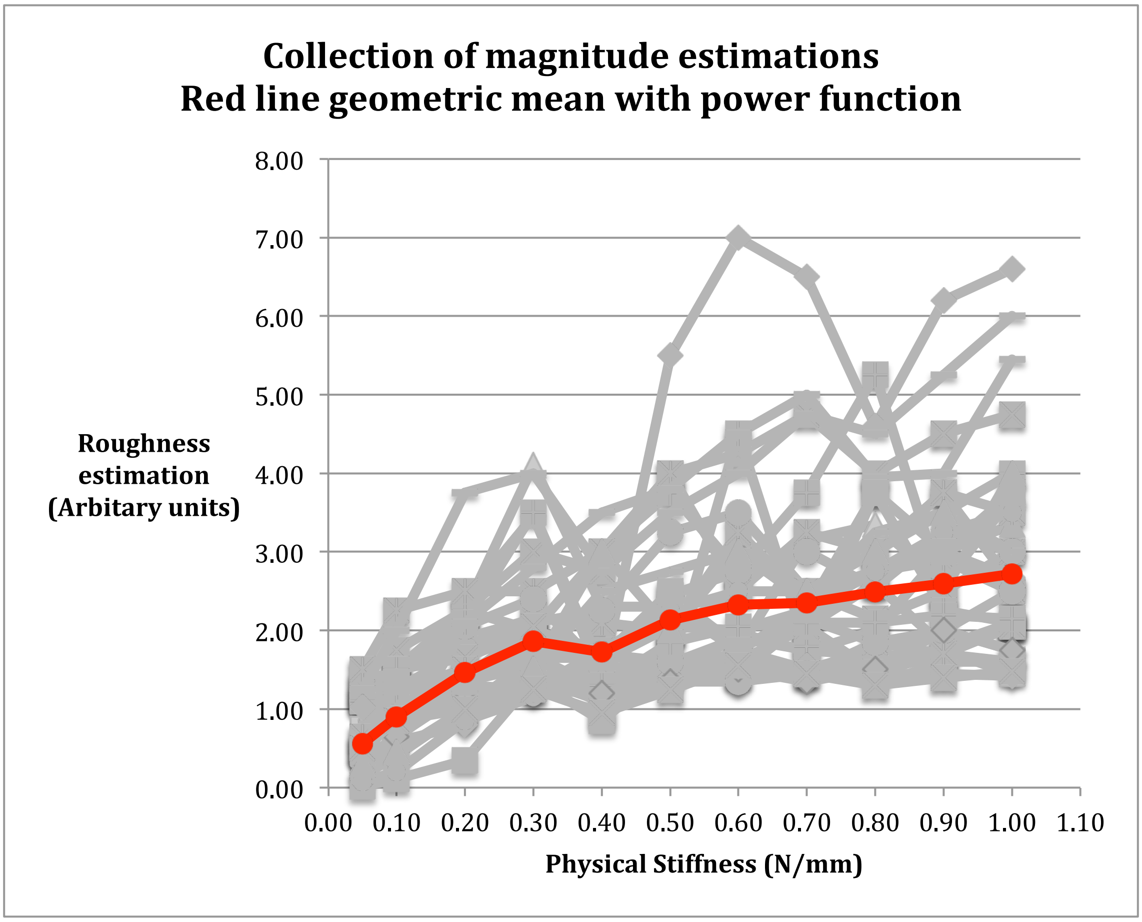
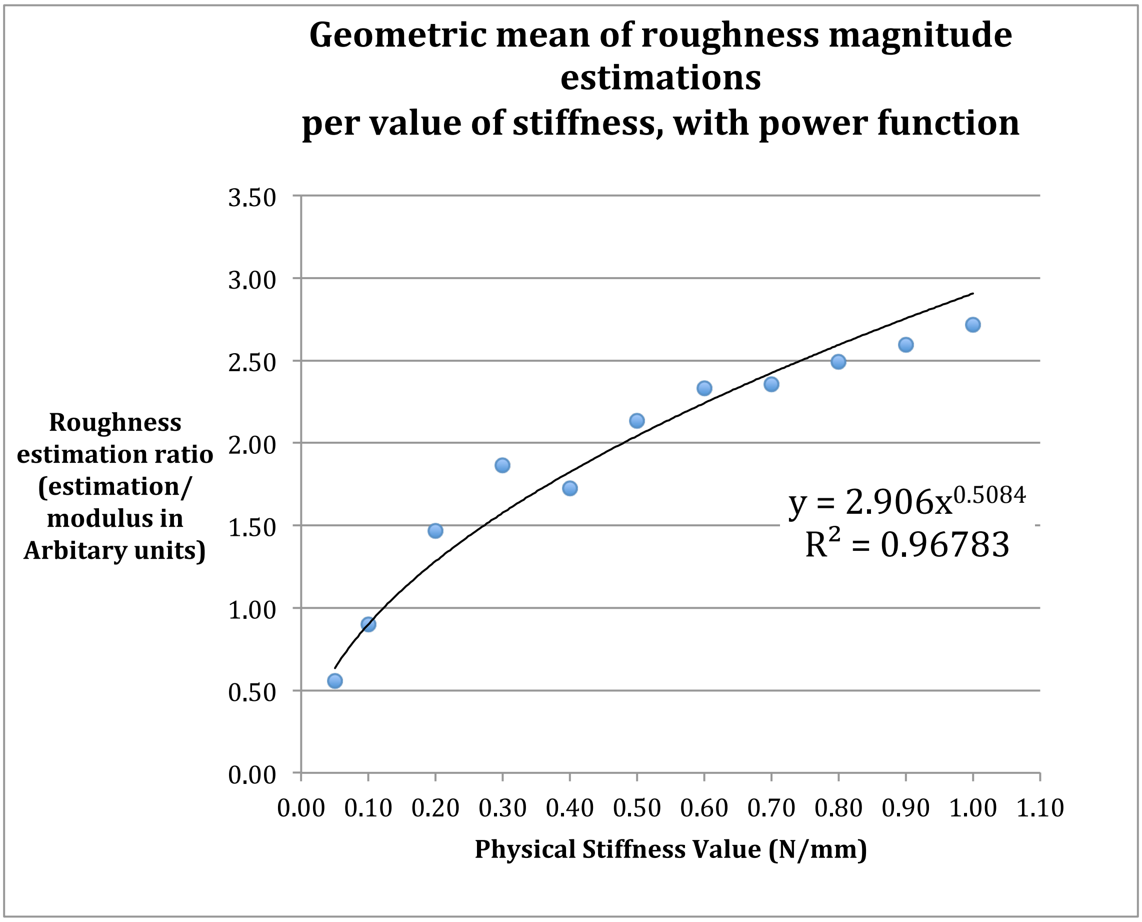
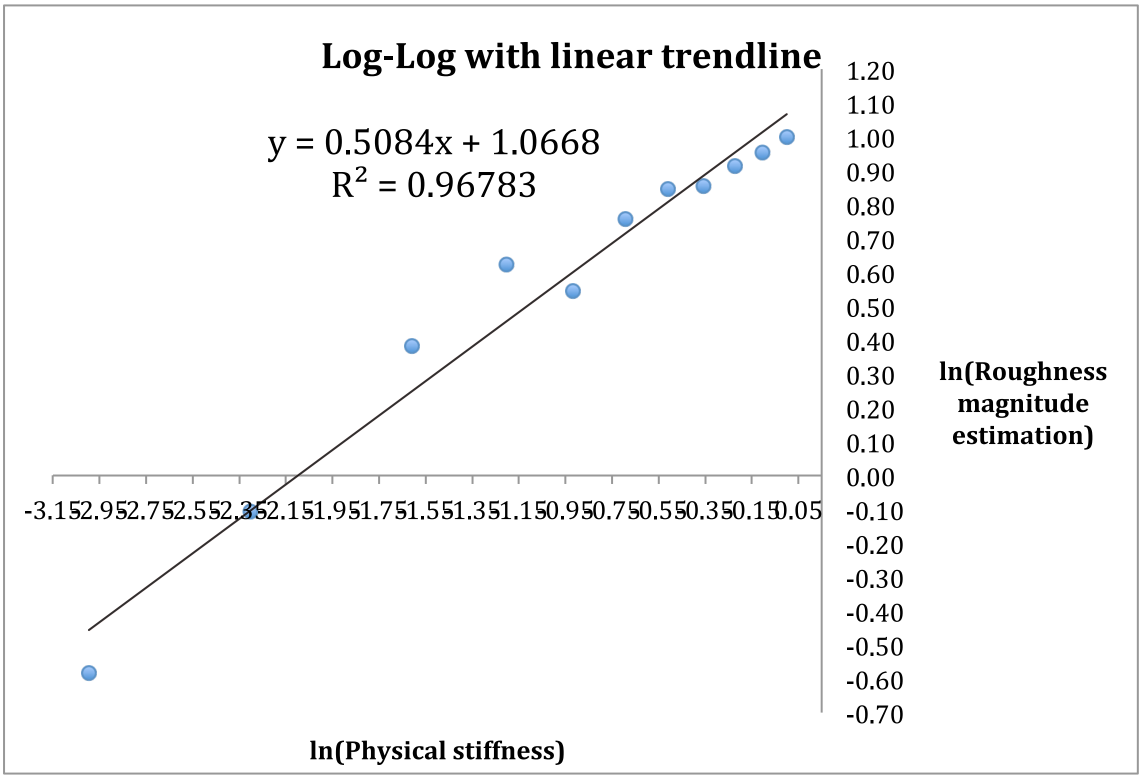


Figure 40 Data from all participants plotted together (gray lines) with their geometric mean (red line)


Geometric mean of roughness magnitude estimations
per value of stiffness, with power function
Roughness estimation ratio (estimation/ modulus in Arbitary units)
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
Physical Stiffness Value (N/mm)
y = 2.906x^0.5084
R² = 0.96783


Log-Log with linear trendline
y = 0.5084x + 1.0668
R² = 0.96783
1.20
1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
-0.60
-0.70
ln(Roughness magnitude estimation)
-3.15
-2.95
-2.75
-2.55
-2.35
-2.15
-1.95
-1.75
-1.55
-1.35
-1.15
-0.95
-0.75
-0.55
-0.35
-0.15
0.05
ln(Physical stiffness)

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