Determining the Detection Threshold for Perception of Selected Textural Attributes

Tugba Aktar

Submitted in accordance with the requirements for the degree of
Doctor of Philosophy

The University of Leeds
School of Food Science and Nutrition

August 2015

The candidate confirms that the work submitted is her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others. Details of the jointly-authored publications are outlined on the next page.

Further details of the work from jointly-authored publications and the contributions of the candidate and the other authors to the work are included below:

Chapter 3

Aktar, T., Chen, J., Ettelaie, R. and Holmes, M. (2015) 'Evaluation of the Sensory Correlation between Touch Sensitivity and the Capacity to Discriminate Viscosity', Journal of Sensory Studies, 30(2), 98-107

Details of authorship contributions:

Aktar: conducted the experimental designs, data analysis, method validation, laboratory work and sensory evaluation tests, data interpretation, contributed to answer the reviewer's comments and primary authorship.

Chen, Ettelaie and Holmes: guidance, supervision, data interpretation, contributed to answer the reviewer's comments.

Chapter 4 and Chapter 5

Aktar, T., Chen, J., Ettelaie, R. and Holmes, M. (2015) 'Tactile sensitivity and the capability of soft-solid texture discrimination', Journal of Texture Studies, in-press (DOI: 10.1111/jtxs.12142)

Details of authorship contributions:

Aktar: conducted the experimental designs, data analysis, method validation, laboratory work and sensory evaluation tests, data interpretation, contributed to answer the reviewer's comments and primary authorship.

Chen, Ettelaie and Holmes: guidance, supervision, data interpretation, contributed to answer the reviewer's comments.

List of Publications and Awards

Aktar, T., Chen, J., Ettelaie, R. and Holmes, M. (2015) 'Evaluation of the Sensory Correlation between Touch Sensitivity and the Capacity to Discriminate Viscosity', Journal of Sensory Studies, 30(2), 98-107.

Aktar, T., Chen, J., Ettelaie, R. and Holmes, M. (2015) **'**Tactile sensitivity and the capability of soft-solid texture discrimination**',** Journal of Texture Studies, in-press (DOI: 10.1111/jtxs.12142).

Aktar, T., Chen, J., Ettelaie, R. and Holmes, M. (2014), Foods with Feeling, The 5th annual University of Leeds, Postgraduate Research Conference, 3rd Research poster of the year.

List of Accepted Conference Abstracts

Aktar, T., Chen, J., Ettelaie, R., Holmes, M., 'Little influence of tactile sensitivity on one's capability of viscosity discrimination' (2014), 3rd International Conference of Food Oral Processing - Physics, Physiology, and Psychology of Eating, Wageningen, Netherlands.

Aktar, T., Chen, J., Ettelaie, R., Holmes, M., 'Little influence of tactile sensitivity on one's capability of viscosity discrimination' (2014), University of Leeds Food Science and Nutrition, PhD Conference.

Aktar, T., Chen, J., Ettelaie, R., Holmes, M., Foods with Feelings (2014), The 5th annual University of Leeds, Postgraduate Research Conference, Leeds, UK.

Aktar, T., Chen, J., Ettelaie, R., Holmes, M., Foods with Feelings (2015), 2nd Food Industry Networking Conference, Leeds, UK.

Acknowledgements

I would like to give my acknowledgements and appreciation to many people who helped me on my rocky and long PhD journey. They all deserve a lot more than this page and should highlight it would not be possible without them. Firstly, my biggest thanks for my lovely family. My very much beloved mother Yuksel and father Yusuf, I am very glad to be your daughter and thank you for all the support, motivation, encouragement and belief you provided to me with all your heart. I love you more than anybody else in this world. Best sibling ever Tugce Aktar, I am not sure if you are aware but you are an awesome sister, I am very lucky to have you. You always encourage me to stand back whenever I am down. I love you very much.

Another big contribution to my work came from my three supervisors: Professor Jianshe Chen who provided me with lots of personal and professional guidance, help, advice, support even though he was miles away for most of my time; Dr. Rammile Ettelaie with all the knowledge, brainstorms and support when I needed the most; and Dr. Melvin Holmes, who has supported me wholehearted regardless the situation despite all the technical support he has given. I was very lucky and it was privilege to work with all of you, and I want you to know that I will admire and respect you for my entire life. Additional thanks for helpful discussions and guidance to Dr. Brian Henson who provided me lots of knowledge and help from a new perspective, which made my work stronger. In addition, Dr. Laura Laguna Cruanes, Dr. Mahmood Akhtar and Ian Hardy deserves to be mentioned in this page with all the help, support and moral they have given to me.

I am indebted to my sponsor, Turkish National Ministry of Education, for the financial support for my higher education. I am also grateful to my colleagues; especially to Woroud Alsanei who has been the most supportive, helpful, wholehearted friend to me and will be in my life forever. Also special thanks to Linda Pravinata, Fairuz Che Othman, Didem Sanver, Lilynorfeshah Mohd Shah and many more who gave me a chance to be in their life.

Abstract

Texture perception and appreciation was found to be one of the determinative factors for preference, which lead to business success. Moreover, it was claimed to be vital for safe consumption in some cases for the vulnerable population (i.e. elderlies, babies or dysphagic patients). To create more desirable, preferable or safer foods it is necessary to understand the perception limits of the textural attributes and investigate if there are any correlations between other possible sensation systems. This study is motivated with the aim of finding thresholds for the selected attributes of texture (liquid viscosity, soft-solid firmness, soft-solid elasticity and solid surface roughness) and explore whether there is any correlation between texture sensation and tactile sensation systems, which was claimed to be responsible for texture sensation. Current study was examined with sensory tests on the fingertip and tongue for the textural attributes perception thresholds. Tactile sensation limits were observed with touch sensitivity tests and two-point discrimination tests. For each attribute, correlations with the tactile sensitivity were tested. Results revealed that the tactile sensation was not directly determinative in texture discrimination and correlation between texture discrimination and tactile sensation was not possible to be established for those attributes. Another approach was comparing the sensitivities between the fingertip and tongue. These two parts of the body seemed to have similar texture sensitivity, excluding the fluid viscosity. Due to this general similarity in discrimination of texture, we suggested that one could use fingertip texture discrimination threshold to predict the tongue threshold. Findings of this study have implications in the food industry and can contribute to the general understanding of the sensory scientists. For industry, obtained thresholds for particular attributes could be used as guidance for creating desirable food products. Moreover, if the same approach could be followed, thresholds for the vulnerable groups can be obtained and used for medical food production for creating safe to consume foods. On the other hand, methodologies and findings of this study could provide information to sensory scientists to map the full image of the texture sensation thresholds.

Table of Contents

List of Figures

List of Tables

List of Equations

(2.1)	Newton's law of viscosity	$\sigma = \eta\dot{\gamma}$
(2.2)	Deborah number calculation	$De = \frac{\tau}{t}$
(2.3)	Hooke's law	$G = \frac{\sigma}{\gamma}$
(2.4)	Elastic modulus	$E = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0}$
(2.5)	Storage modulus	$E' = \frac{\sigma_o}{\varepsilon_o}\cos\delta$
(2.6)	Loss modulus	$E'' = \frac{\sigma_o}{\varepsilon_o}\sin\delta$
(2.7)	Weber's law	$S = \frac{\Delta I}{I}$
(2.8)	Fechner's law	$S = k\ log\ I + C$
(2.9)	Steven's power law	$S = k\ I^a$
(6.1)	Coefficient of Friction calculation	$\mu = \frac{F}{N}$
(6.2)	Hertz law of friction	$F = \mu_{1.}L$
(6.3)	Friction difference between two surfaces	$\Delta F = (\mu_{2-}\mu_1)\ .L$

Abbreviations and Symbols

Abbreviations

Acrylonitrile-Butadiene-Styrene	ABS
Alternative forced choice	AFC
Body Mass Index	BMI
Exploratory procedures	EPs
Force load	F_L
Gravitational force	g
Iowa Oral Performance Instrument	IOPI
Just noticeable difference	JND
Maximum Isometric Tongue Pressure	MITP
Rapid adapting	RA
Rapidly adapting sensors in dermis	RA2
Rapidly adapting sensors in epidermis	RA1
Semmes-Weinstein Monofilaments	SWM
Slow adapting	SA
Slowly adapting sensors in dermis	SA2
Slowly adapting sensors in epidermis	SA1
Texture profile analysis	TPA
Two-Point Discrimination	2PD
World Health Organization	WHO

Symbols

%	Percentage (concentration)
Ω	Ohm
$\dot{\gamma}$	Shear stress
±	Minus-plus (indicates standard deviation)
Δ	Change
μ	Coefficient of friction
A	Area
a	Power exponent
c	Constant of integration
De	Deborah number
E	Elastic modulus
E'	Storage modulus
E''	Loss modulus
F	Force
G	Shear modulus, rigidity
Hz	Hertz
I	Stimulus value
l	Length
p-value	Calculated probability
R^2	Coefficient of determination
R_a	Roughness
S	Sensation magnitude
t	Observation time
δ	Phase lag
ε	Extensional strain
η	Viscosity
σ	Shear stress
τ	Response time
γ	Strain
3-D	Three dimensional

Chapter 1
Aims and Objectives

1.1 Aims of the Research

Food is essential for survival but it is also a source of pleasure. It plays an important role in our celebrations and gatherings as a 'medium' to catalyse conversation and as an effective 'stimulator' to elevate our mood. Unfortunately, for some people, eating is not easy and straightforward, particularly for vulnerable individuals such as babies and some elderly and mentally disadvantaged people and patients suffering from dysphagia. For these people, the properties of foods, such as texture, if not properly controlled, can cause choking and may even prove to be fatal. As food scientists, it is our social duty to establish the link between texture perception and tactile sensation to provide food to these individuals. Alongside this, the food industry, particularly food quality controlling units, urgently needs a better knowledge of texture sensation so it can produce safe and tasty foods with a deeper understanding of consumers' needs. For this, the first step should be to gain a better understanding in healthy individuals of the perception limits of textural attributes, which might be used as determinative factors for safe food consumption.

Food oral processing is a newly developing science focusing on the structural and textural changes of food while eating and an individual's associated physiological and psychological responses. Various approaches have been used for food oral processing studies, including taste panel sensory analysis, instrumental characterisation (both in vitro and in situ) and computer simulation. Although studies reported in literature had different purposes and aims based around either meeting pre-designated needs or solving specific concerns and problems, most of them focused either on the correlation between food structure and sensation or on the instrumental prediction of the consumer perception of food sensation and preference. The former aimed to improve our understanding of controlling structural factors for the design and manufacture of enjoyable as well as healthy food, while the latter aimed to use food physics to predict the outcomes of sensory responses. Both were driven by the desire for a fundamental understanding of food texture and even more so by the urgent need of the food industry for practical solutions. Progress and achievements in these areas have been reported by several authoritative reviews (Chen 2013, Kilcast and Clegg 2002, Guinard and Mazzucchelli 1996, Pascua et al. 2013, Chen and Stokes 2012, Lenfant et al. 2009, Chen 2007, Harker et al. 2002, Prakash et al. 2013, Foegeding 2007). Despite these achievements, one aspect missing from such studies has been the role of individual oral physiological factors, both in determining physiological factors involved in an individual's capability for sensory perception and in the variation in sensory response among populations. A general assumption has been that an individual's tactile sensitivity is the most important physiological factor that determines one's capability of texture sensation. Although this assumption seems reasonable, very little experimental evidence is available in literature to prove or disprove it. Despite these achievements, one missing links of such studies is the role of individual oral physiological factors, both in terms of the determining physiological factors of one's capability of sensory perception and the sensory variation among populations.

The tongue is probably the most important organ for food texture sensation (Chen, 2009). It functions as a mechanical device for moving and transporting food, mixing food in the mouth and bolus swallowing. In relation to food sensation, densely distributed taste buds on the tongue surface detect five principal tastes and their combinations. Although it is certain that mechanoreceptors on the tongue surface are the main responding receptors for food texture sensation, the detection thresholds of these mechanoreceptors are still not fully understood and will be a main concern of this present work. Fingers provide another major source of textural information through the touching and handling of food materials either directly or indirectly. The tactile sensitivity of fingers has been better studied than that of the tongue as it is much easier to access. Despite this, many questions still remain on tactile and texture sensations both for fingers and, especially, for the tongue, such as how various mechanoreceptors differ in their functions in determining texture, how the tactile sensation interprets textural features of widely differing natures (e.g.

viscosity for a fluid and hardness for a solid material) and the minimal contact needed to initiate a texture sensation.

With this in mind, the present study aimed to fill the gap in the research area by seeking insight into the limits of perception of certain textural attributes using the fingertip and tongue in particular. These attributes were viscosity, firmness, elasticity and roughness, which were chosen because they are commonly referred to textural properties in daily life in both food and other materials as well as less complicated than the others such as creaminess or crunchiness. Perception thresholds were obtained for these attributes using sensory tests as well as instrumental characterisation. Instrumental methods involved in the present study were as follows:

1. Kinexus rheometer (Malvern Instruments Ltd., Worcestershire, UK)
    a. Double gap geometry (DG25) was used to measure the dynamic viscosities of food samples as a function of concentrations, shear rate and temperature (Chapter 3).
    b. Cone-and-plate geometry (CP2/60) was used to measure the dynamic viscosities of samples as a function of concentrations, shear rate and temperature (Chapter 6).
2. A texture analyser (Stable Micro Systems Ltd., Surrey, UK) was used to perform compression tests to characterise the mechanical/textural properties (firmness and elasticity) of gel samples (Chapters 4 and 5).
3. A touch sensitivity kit (North Coast Medical, Gilroy, CA, USA) was used to measure the absolute touch threshold on the fingertip and tongue (Chapters 3, 4, 5 and 6).
4. A two-point discriminator (North Coast Medical, Gilroy, CA, USA) was used to measure the spatial acuity on the fingertip and tongue (Chapters 4, 5 and 6).
5. The Iowa Oral Performance Instrument (IOPI Medical, Carnation, WA, USA) was used to measure tongue muscle strength (Chapter 4).
6. A JAMAR hand-held dynamometer (Patterson Medical Ltd., Nottinghamshire, UK) was used to measure the maximum hand grip capability (Chapter 4).

7. A flexi-sensor connected to a multimeter was used to measure the maximum finger grip capability (Chapter 4).
8. An NPflex 3D surface metrology system (Bruker Ltd., Tuscan, USA) was used to measure the surface roughness value (Chapter 6).
9. An artificial fingertip was used to measure the perceptible coefficient of friction (Chapter 6).

On the completion of this thesis we aim to answer the following three key questions:

1. Is texture perception determined by tactile sensation for the selected attributes?
2. Do the fingertip and tongue have similar texture perception and tactile sensation? And
3. Can the perception limits of the fingertip be used to predict oral perception dynamics?

As a general overview Chapter 2 presents a literature review outlining the background to the project and the reasons behind conducting it. The following chapters then present results as well as a discussion on viscosity discrimination (Chapter 3), firmness discrimination (Chapter 4), elasticity discrimination (Chapter 5) and roughness discrimination (Chapter 6). Overall conclusions and a summary are given in the final chapter (Chapter 7).

Chapter 2
Introduction and Literature Review

2.1 Introduction to Food Texture

Texture has taken a long time to develop and reach its current format due to many opposing ideas, difficulties and misunderstandings. The Oxford English Dictionary defines texture as ‘the disposition or manner of the union of the particles of a body’ (Shorter Oxford English Dictionary 2007). From this definition, it is clear that texture is a material property that can apply to anything from fabrics and furniture to cosmetics to describe the visual and tactile properties (Guinard and Mazzucchelli 1996). In particular, in material science, texture has been defined as the surface characteristics and appearance of an object, given by the size, shape, density, arrangement and proportion of its elementary parts (Urdang 1968). The evolution of the concept of texture progressed into other areas, including foods (Richardson and Booth 1993). In the 1920s, the task of defining food texture as a sensory food quality arose with sensation starting to be seen as a major part of the quality assurance process (Szczesniak 2002, Kramer 1973). This increasing emphasis on food texture was due to its effect on individuals’ acceptance of and preference for products (Kramer and Szczesniak 2012, Liu et al. 2005).

2.1.1 Classification

Texture was identified as a quality property, and its component attributes were listed in the mid-1940s by Smith (1947) as nine parameters: size, viscosity, thickness, texture, consistency, turbidity, colour, succulence and flavour. A few years later, Kramer (1955) suggested another perspective by introducing texture for the sensory quality of foods, classifying it according to the following attributes sensed by different modalities:

1. Appearance (sensed by the eye),
2. Flavour (sensed by the papillae of the tongue and the olfactory epithelium in the nose) and
3. Texture (sensed by nerve endings and mechanoreceptors).

This classification was used as a basic definition, and it was extended in 1965 by the US Department of Agriculture's standards for Quality in the Canning Trade Almanac list, in which appearance was listed as having two different attributes, flavour with 25 different attributes and texture with 57 different attributes including character, consistency, tenderness and maturity. Until 1963, sounds created during the oral processing of foods were not listed as a separate sensation modality of texture (Drake 1963, Kramer 1973). While this list of the specific properties of textural quality was developing, Kramer and Twigg (1959) added an update about viscosity and consistency by classifying them as appearance factors rather than texture. They defended this hypothesis with examples of drinks and semi-solid foods they considered to be visually judged for their consistency and viscosity. Later, researchers understood that viscosity and consistency could be classified as texture as well as appearance (Kramer and Twigg 1970).

While the classification of texture was in progress, researchers were also questioning the terms 'rheology' and 'texture'. These terms could be differentiated according to the properties of food, with 'texture' for solid foods and 'rheology' for liquid foods, but there was no corresponding terminology for semi-solid foods, which could be considered to be the most common type of food (Kramer 1964). Later, Kramer proposed another way of differentiating the two terms according to the force required for flow initiation. He suggested that rheology would apply to smaller deformations that only involved forces up to gravity force, whereas if deformation required greater forces, this was to be considered as texture (Kramer 1973). This can be seen in Table 2.1.

Table 2.1 Classification of texture and rheology terms, according to the force required to initiate flow, shown with the main modalities of sensation, appearance, flow behaviour and taste and smell (Kramer 1964, Kramer 1973).

	Rheological or Physical Terms (Gravitational force = G, Newton)		
Psychological or sensory terms	**Up to gravitational force (<G)**		**Greater than gravitational force (>G)**
	Newtonian	**Non-Newtonian**	
Appearance	Viscosity	Consistency	Texture
Flow behaviour			
Taste and Smell	Flavour		

Table 2.1 illustrates the importance of the force a sample requires for deformation. For example, when sauce needs a greater force than gravity to flow, it would be more precise to consider its physical properties as ‘texture’ (a larger deformation), whereas if lower forces are sufficient to cause it to flow, then it would be more appropriate to consider this as ‘rheology’ (a smaller deformation).

During the 1960s, this classification and list of attributes continued to evolve. Szczesniak (1963) and Bourne (1966) developed textural properties related to solid food, while Sherman (1969) utilised state (liquid, semi-solid or solid) in his classification on the masticatory properties of foods. In the 1970s, Mohsenin (1970) conducted a comprehensive investigation relating the textural properties of solid food to the properties perceived by human sensations. A few years later, in 1973, Kramer published a book on measuring the texture of foods, providing a main reference source in this field. Current researchers of food texture are still using the same physical concepts proposed by these earlier researchers.

2.1.2 Definition

One of the earliest definitions of food texture was provided by Szczesniak (1963) as ‘sensory manifestation of the structure of food and the manner in which this structure reacts to the forces applied during handling and, in particular, during consumption’. Another widely accepted definition was provided by the International Organization for Standardization, defining food texture as ‘all the rheological and structural attributes of the food perceptible by means of mechanical, tactile, visual and auditory receptors’ (International Organization for Standardization 1981). These standard and other definitions of texture make it clear that tactile sensation provides the most valuable information, yet this has hardly been investigated in literature with regard to the sensation of food texture (Ross and Hoye 2012). The only report on this has been that tactile sensation engages with perception during an individual’s manipulations of a food sample by hand and oral tactile texture, where hand perception could involve direct or indirect touching (e.g. using cutlery) (Lawless and Heymann 1998). Additionally, sight, sound and the sense of movement and position also provide textural cues contributing to a judgement on the concept of total texture. Even though the definition of texture is subject to change according to conditions, the fundamental concern about texture is still to answer two basic questions:

How is texture observed?
What are the perception limitations and thresholds of the attributes?

It should be noted that any definition regarding food texture will not be comprehensive to be universal because an attribute will most probably overlap with other attributes; for example, crunchiness would be influenced by the sound of breaking and also the actual firmness value. Accepting the inevitability of this overlapping, the concept of texture perception should include kinaesthesis (the muscle sense, a sense of movement and position), haptaesthesis (the skin sense of touch) and the deformation or flow of matter, and it should at least be potentially possible to measure it by mechanical means in terms of mass or force (Kramer 1973). Kinaesthesis only refers to muscle sense and does not include cutaneous sensation, which creates the sense of the position of limbs and organs (Muller 1969). On the other hand, haptaesthesis is a concept that deals with the sensation of the mechanical behaviour of materials through the sense of touch (Muller 1969). As there is a gap in literature about the tactile sensation of texture, the present study aimed to observe haptaesthesis perception limits for selected attributes. Cutaneous sensation will be discussed further in section 2.5.

2.1.3 Characterisation

As proposed by Szczesniak (2002), texture is a sensory property of food; therefore, it is only perceivable by an individual. For that reason, direct measurement can only be made by subjective assessments in a sensory test (Stevens 1966). The instrumental assessments of texture provide indirect physical values that cannot be considered as being precisely correlated to human sensations (Harker et al. 2002, Kramer 1973). Ideally, a scientist would want to see a correlation between sensory and instrumental evaluations, but in most instances, this relationship remains unknown or is complex. Investigating such relationships could provide a substitute for expensive and time-consuming sensory measurements.

2.2 Instrumental Evaluation of Texture

As discussed earlier, instrumental texture assessments are considered to be objective and reliable, even though it can sometimes be difficult to establish the relationship with the actual textural experience of the consumer. Szczesniak (1973) listed the basic elements of an instrumental texture evaluation as follows:

1. a probe contacting the food sample,
2. a driving mechanism for imparting motion and stress,
3. a sensing element for detecting the resistance of the foodstuff (the strain) and
4. a readout system.

Szczesniak (1973) also classified the types of texture measurement instruments as:

1. penetrometers,
2. compressimeters,
3. shearing devices,
4. cutting devices,
5. masticometers,
6. consistometers,
7. viscometers,
8. extrusion measurements and
9. multi-purpose units.

The instrumental assessments of texture provide consistent and objective measurements that are more economical in terms of time and investment than those of equivalent sensory assessments. However, their outcome in product development or texture sensation studies gives only estimation about the real perception and it is still necessary to conduct a sensory test. Instrumental measurement of texture is done based on the mechanical properties of the foods.

2.2.1 Mechanical Properties of Foods

2.2.1.1 Characterisation of Textural Properties

The characterisation and construction of an adequate terminology for textural properties has been a popular area of research that has received plenty of interest in literature. Usually, the terminology was developed according to the state of the food (liquid, semi-solid or solid).

Semi-solid and solid food characterisation was completed by Szczesniak and Kleyn (1963), as seen in Table 2.2.

Table 2.2 Textural characterisation of semi-solids and solids (Szczesniak and Kleyn 1963).

	Primary parameters	**Secondary parameters**	**Popular terminology**
Mechanical characteristics	Firmness		Soft, hard, firm
	Cohesiveness	Brittleness Chewiness Gumminess	Crumbly, crunchy, brittle Tender, chewy, tough Short, mealy, pasty
	Viscosity		Thin, viscous, gummy
	Springiness		Plastic, elastic
	Adhesiveness		Sticky, tacky, gooey
Geometrical characteristics	Particle size and shape		Gritty, grainy, coarse
	Particle orientation		Fibrous, cellular, crystalline
Other characteristics	Moisture content		Dry, moist, wet, watery
	Fat content	Oiliness Greasiness	Oily Greasy

The characterisation of fluid foods was also conducted by Szczesniak (1979), as shown in Table 2.3. Even though other terminologies have been suggested by Jowitt (1974) and Sherman (1969), Szczesniak's remains the most comprehensive list.

Table 2.3 Classification of textural properties for liquid foods (Szczesniak 1979).

Category	Popular terminology
Viscosity related terms	Thin, thick, viscous
Feel on soft tissue surfaces	Smooth, pulpy, creamy
Carbonation-related terms	Bubbly, tingly, foamy
Body-related terms	Heavy, watery, light
Chemical effect	Astringent, sharp
Coating oral activity	Mouth coating, clinging, fatty, oily
Resistance to tongue movement	Slimy, syrup, pasty
After feel-mouth	Sticky
After feel- physiological	Clean, drying, lingering, cleansing
Temperature related	Cold, hot
Wetness- related	Wet, dry

The number of textural terminologies accelerated following the introduction of textural profile analysis (TPA), which made it possible to assess textural parameters with instruments (Bourne 1978, Friedman et al. 1963, Szczesniak and Kleyn 1963). Despite studies in that area, the terminology introduced by Szczesniak and Kleyn (1963) is still considered to be the most comprehensive list; it also includes the definitions of textural properties as shown in Table 2.4.

Table 2.4 Definitions of physical and sensory terminologies of textural characteristics (Szczesniak and Kleyn 1963).

	Terminology	Physical definition	Sensory definition
Primary properties	Firmness	Force necessary to attain a given deformation.	Force required to compress a substance between the molar teeth (in the case of solids) or between the tongue and palate(in the case of semisolids)
	Cohesiveness	Extent to which a material can be deformed before in ruptures.	Degree to which a substance is compressed between the teeth before it breaks.
	Viscosity	Rate of flow per unit force.	Force required dropping a liquid from a spoon over the tongue.
	Springiness	Rate at which a deformed material goes back to its undeformed condition after the deforming force is removed.	Degree to which a product returns to its original shape once it has been compressed between the teeth.
	Adhesiveness	Work necessary to overcome the attractive forces between the surfaces of the other materials with which the food comes in contact.	Force required to remove the material that adheres to the mouth (generally the palate) during food oral processing.
Secondary properties	Brittleness (Fracture ability)	Force with which a material fractures: high degree of hardness and low degree of cohesiveness.	Force with which sample crumbles, cracks or shatters.
	Chewiness	Energy required to masticate a solid food to a state ready for swallowing: hardness, cohesiveness and springiness.	Length of time (in second) required to masticate the sample, at a constant rate of force application, to reduce it to a consistency suitable for swallowing.
	Gumminess	Energy required to disintegrate a semisolid food to a state ready for swallowing: low degree of hardness and a high degree of cohesiveness.	Denseness that persists throughout mastication: energy required to disintegrate a semisolid food to a state ready for swallowing.

Another interesting topic in the field of texture has been the effect of language and culture on the characterisation of texture terminologies. Lawless et al. (1997) characterised approximately 70 texture and mouthfeel terms in English and Finnish and found that the terminologies in these two languages were not significantly different. However, Hayakawa et al. (2013) investigated a total of 455 Japanese texture terms; these showed some similarities to other languages, but most of the terms were unique to Japanese, including synonyms for particular terms that had no direct meaning in English (Rohm 1990, van Vliet 1999, Szczesniak and Kleyn 1963). As culture and language greatly influenced textural terminologies, it is noteworthy that in the present study, we had to select the test attributes among those commonly used across most cultures, such as the firmness of a gel or the thickness of a fluid.

It is necessary to consider the mechanical properties of foods according to their state (liquid, semi-solid or solid). The following subsections discuss the mechanical properties of different types of foods.

2.2.1.1.1 Structure of Liquid Food

For a clearer understanding of the instrumental measurement of mechanical properties, it is necessary to first consider Newton's law on the flow of liquids (Barnes et al. 1989). Newton's law of viscosity states that the shear rate of simple fluids is proportional to the shear stress, with the constant of proportionality giving the viscosity, as follows:

$$\sigma = \eta\dot{\gamma} \qquad (2.1)$$

where σ is the shear stress (Pa), $\dot{\gamma}$ is the shear rate (s^{-1}) and η is the viscosity (Pa.s).

This law is the simplest constitutive model for the flow properties of simple fluids. It applies to most gases and some simple fluids such as water, syrup and honey, which are described as 'Newtonian fluids' (Stokes 2012). Most Newtonian fluids have a low molecular weight (Rao 2007). The behaviour of Newtonian fluids is shown in Figure 2.1a.

Unfortunately, most fluids do not comply with this linear relationship and are therefore said to be 'non-Newtonian'. Non-Newtonian materials are those whose viscosity depends on their prior shear and thermal history (Stokes 2012). Often, non-Newtonian fluids display viscoelastic properties due to their ability to behave as liquid-like and solid-like, depending on the time course of the deformation process. A constant coefficient of viscosity cannot be defined for non-Newtonian fluids; instead, the term ‘apparent viscosity’ is used to describe the viscosity value at a given shear rate. Most food samples display non-Newtonian flow behaviour. Non-Newtonian fluids are classified according to their time dependency, as seen in Table 2.5. However, being time-dependent or time-independent is not a clear classification. For example, yogurt is considered to have time dependency due to its tendency to exhibit syneresis (the separation of a liquid from a gel), but also it shows time independent character by being shear thinning.

Table 2.5 Properties of non-Newtonian fluids according to their dependency on time (te Nijenhuis et al. 2007, Garay 1996, Rao 2007, Schramm 2005).

	Term	Property	Example
Time dependent viscosity	Rheopecty	Apparent viscosity increases with duration of stress	Printer ink
	Thixotropic	Apparent viscosity decreases with duration of stress	Yogurt, xanthan gum solutions, gelatin gels
Time independent viscosity	Shear Thickening (Dilatant)	Apparent viscosity increases with increased stress	Corn starch solution
	Shear Thinning (Pseudoplastic)	Apparent viscosity decreases with increased stress	Ketchup, whipped cream, blood, yogurt

However, because in most instances, experiments on the flow behaviour of a sample are not controlled for time and ageing effects, it is more appropriate to focus on the sample’s time-independent properties, unless the aim of the project is to investigate time dependency.

Shear-thickening or dilatant fluids increase their apparent viscosity under increased shear stress. A good example of this is a solution of corn starch in water. Fortunately, most foods do not belong to this class, which would make them very difficult to swallow and digest, especially during mechanical breakdown in the stomach. The behaviour of shear-thickening fluids is shown in Figure 2.1b.

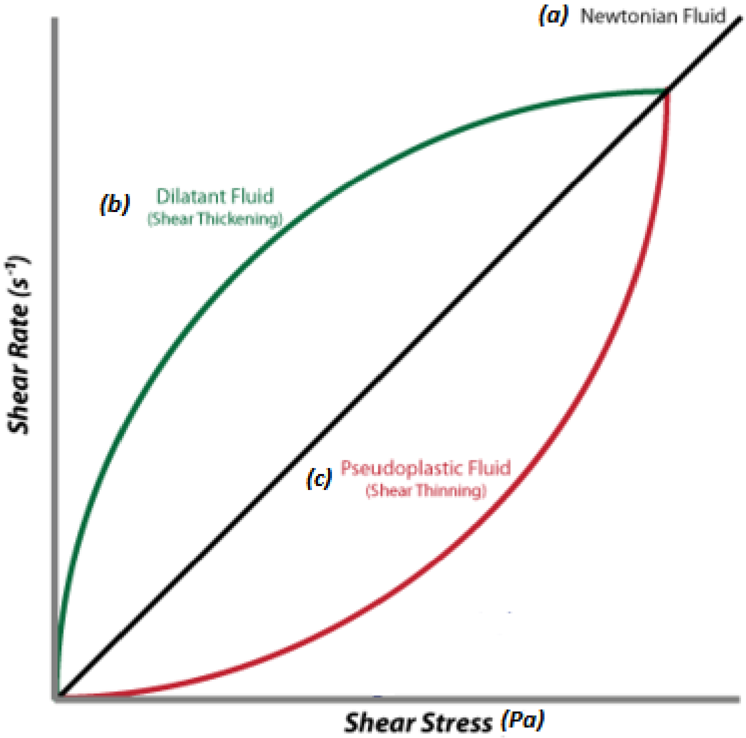


Figure 2.1 Examples of flow behaviours including, Newtonian (a), non-Newtonian shear thickening (b) and non-Newtonian shear thinning (c) (Rao 2007).

Shear-thinning or pseudoplastic fluids are the second type of time-independent non-Newtonian materials (Figure 2.1c). They show reduced apparent viscosity with increased shear stress. Shear-thinning behaviour arises from a structural change within the flow field, which includes the deformation and alignment of polymeric molecules, movement and rearrangement of particles and breakdown of aggregates due to the applied shear stress (Stokes 2012).

Materials can be divided into three categories of rheological behaviour:

1. Viscous materials,
2. Elastic materials and
3. Viscoelastic materials.

Viscous materials dissipate all energy supplied to them as heat, whereas elastic materials store the energy within the material. Viscoelastic materials have both solid-like and liquid-like structures, which show viscous and elastic properties at the same time. The degree of viscoelasticity will depend on the type of deformation applied and its duration (Stokes 2012). The property of viscoelastic behaviour is described by the Deborah number, which is obtained as shown in the equation below. At higher Deborah number values, a material exhibits a non-Newtonian regime increasingly dominated by elasticity and more solid-like behaviour (Reiner 1964).

$$De = \frac{\tau}{t} \tag{2.2}$$

where τ is the response time (s) and t is the observation time (s).

A typical example of a viscoelastic material is bread dough, which keeps its shape for a certain amount of time but quickly loses its shape at rest and eventually takes the shape of the container (Alcantara 2005).

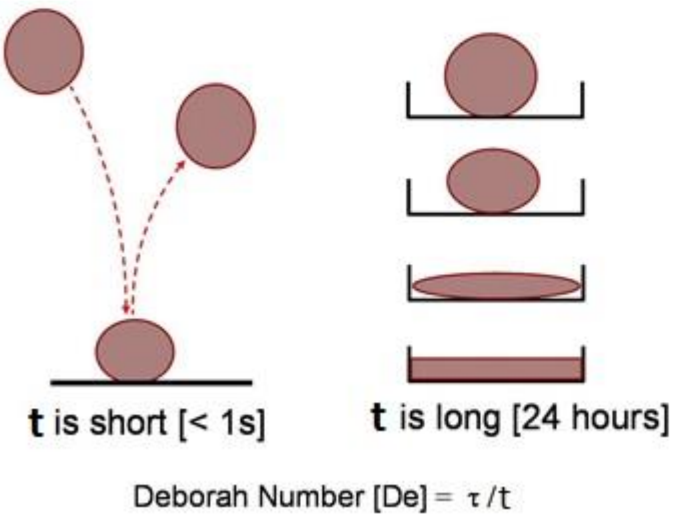


Figure 2.2 Illustration of viscoelastic material time according to the time (Alcantara 2005).

2.2.1.1.2 Instrumental Assessment of Liquid Foods

The rheological properties of liquid foods are usually measured with rheometers (Barnes et al. 1989). Rheology is the science of flow, with the term derived from the Greek word ‘rheos’ meaning flow. It determines the flow and deformation of materials under a given stress (Macosko 1994). Food rheology determines the flow behaviour of food products, which may be raw or in their intermediate or final condition (White 1970). Rheology focuses on viscosity measurements that include the shear stress and shear rate. Shear stress is the amount of force applied to the material and depends on the area over which force is applied (Jobling 1991). Shear rate is the rate of deformation and is measured in reciprocal seconds. The ratio between shear rate and shear stress gives the viscosity value, which represents the resistance behaviour of a sample against the deformation.

Rheometers work on a shearing principle between particular geometries. The sample is placed between the probe and a stand, where it is to be sheared under various temperatures (Hatschek 1928, Macosko 1994, Rao 2007). Depending on whether the sample is Newtonian or non-Newtonian, the test will characterise its viscosity or apparent viscosity. The use of rheometers for measuring flow properties is preferred to other techniques due to the rheometers' advanced system. A commonly used type of rheometer is the rotational rheometer (Schierbauni 1964, Mills 1999, Cichero et al. 2000), which, as its name suggests, incorporates a rotor and stator attached to the sensitive probe and stand (Barnes et al. 1989, Macosko 1994). Rotational rheometers can perform rheological tests, including the measurement of time-dependent viscosities, for all kind of fluids. They are also able to assess viscoelastic properties across a wide range of amplitudes and frequencies of applied strain (Steffe 1996). During rheology assessments, selecting a test geometry is critical for reliability. The most common geometries are cone-and-plate, parallel plate and concentric cylinder. Concentric cylinder geometry, also known as double gap geometry, is a standard geometry consisting of a cylinder that fits into a container stand with a narrow space and a larger area of contact, as shown in Figure 2.3a. However, it is unlikely that normal force measurements can be obtained with this geometry, especially for thicker liquids. This geometry is ideal for the characterisation of shear-thinning and Newtonian fluids at lower concentrations (Stokes 2012). Cone-and-plate geometry (Figure 2.3b) consists of a narrow-angled cone top plate and a flat-bottom plate (Stokes 2012). It has the advantage over other geometries of being able to measure the viscosity independent of the radius of the plates because of the angle on the top plate, which allows the same shear rate to be applied across the whole gap. This geometry is suitable for the measurement of fluids with moderate levels of shear-thinning behaviour.

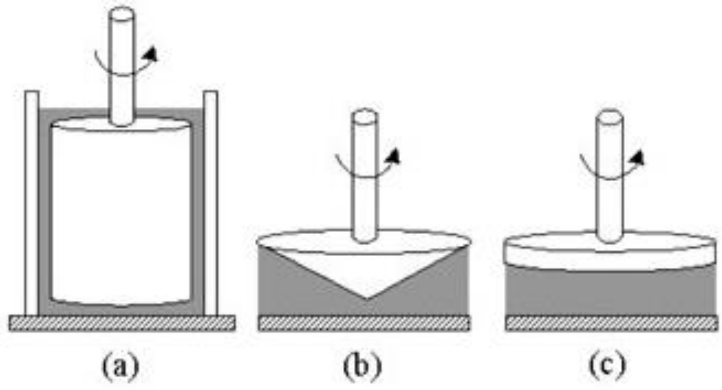


Figure 2.3 Geometries that are commonly used in rheometers to measure the mechanical properties of fluid samples. (a) concentric cylinder, (b) cone-and-plate, (c) parallel plate.

Parallel plate geometry consists of two flat plates (Figure 2.3c). The main disadvantage of this geometry is the variation in shear rate across the plate. At the outer edge of the plate, the shear rate will greatly differ from that in the centre (Stokes 2012). Even though it is not advantageous to use with non-Newtonian materials, if analysed correctly, the viscosity can be measured with a low level of error (Davies and Stokes 2005, Davies and Stokes 2008). This geometry can be used for the characterisation of fluids using very narrow gaps to extend the shear rate range above that obtained by cone-and-plate by two orders of magnitude to $10^5\ s^{-1}$; in addition, the narrow gap allows the use of a much smaller sample, which can be less than 100 µm (Stokes 2012). However, correct experiment requires care, especially when there are suspended particles in the fluid and measurement artefacts can occur when the gap is too narrow.

In the present study, Newtonian fluid samples were used, and their viscosity values were obtained with cone-and-plate and double gap geometries depending on the concentration levels.

2.2.1.1.3 Mechanical Properties and Structure of Soft Foods

Soft foods (semi-solid and semi-fluid) are considered to be the most common food type and are classified according to their elastic properties. Elastic properties are described by Hooke's law, which is as follows (Barnes et al. 1989):

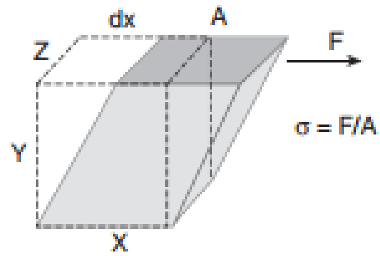


Figure 2.4 Schematic illustration of deformation process for elastic solid material by an applied force of *F* (Stokes 2012).

Figure 2.4 illustrates the deformation of elastic material under an applied force F. It can be seen that the material is able to absorb the force up to a yielding point and then remains as shown in the figure until the stress is removed. This property is calculated with Hooke's law for purely elastic solids:

$$G = \frac{\sigma}{\gamma} \qquad (2.3)$$

where Ɣ is the strain (mm), σ is the pressure (Pa) calculated as the force per area and *G* is the rigidity or shear modulus (Stokes 2012). This model assumes a linear relationship between the shear stress and strain rate.

The dynamic mechanical properties of soft materials are analysed under a force (stress) and a resulting displacement (strain) (Perkinelmer 2001). Important concepts describing these mechanical properties are the storage and loss moduli. The storage modulus measures the stored energy, representing the elastic portion, while the loss modulus measures the energy dissipated as heat and represents the viscous portion (Meyers and Chawla 2008).

Soft foods show solid-like properties, yet they are far more deformable than solids and can sometimes be liquid-like (Stokes and Frith 2008, Stokes 2012). Under small deformations, the material will show elastic properties that fit well with Hooke's law. During that stage, it is possible to measure these elastic properties. Young's modulus or the elastic modulus, describing the elasticity levels of a material, is given by the following equation:

$$E = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} \quad (2.4)$$

where *E* represents the elastic modulus, which is calculated as the ratio of tensile stress (σ) to extensional strain (ε). Tensile stress is calculated as the force per cross-sectional area and extensional strain as the change in length divided by the original length. In the present study, the elasticity of the gel samples was calculated from the initial slope of the force–displacement curves.

The storage modulus (*E′*) is the differential of the elastic modulus (*E*) and can be calculated as follows:

$$E' = \frac{\sigma_o}{\varepsilon_o} \cos\delta \quad (2.5)$$

where σ_0 is the original tensile stress, ε_0 is the original extensional strain and δ is the phase lag between stress and strain.

The loss modulus (E″) indicates the pronounced elastic properties of the material. It is calculated as shown in equation 2.6, where smaller values of phase angle are considered to indicate an elastic material and higher phase angles, a perfectly viscous material (Alcantara 2005).

$$E'' = \frac{\sigma_o}{\varepsilon_o} \sin\delta \quad (2.6)$$

where σ_0 is the original tensile stress, ε_0 is the original extensional strain and δ is the phase lag between stress and strain.

These equations will only be valid while there is a linear relationship between strain and shear stress. The linear regime no longer exists beyond a critical stress value, the yield stress. When a material reaches its yield stress, it cannot absorb any more energy; therefore, the structure breaks down (Stokes 2012). This yielding point is considered to be the firmness or breaking hardness of soft foods, and yield stress can be calculated from this value by dividing the force by the area. In the present study, the firmness of gel samples was obtained by finding the yielding points of the samples.

2.2.1.1.4 Instrumental Assessment of Soft Foods

The flow and deformation properties of soft foods can be determined using a rheometer or texture analyser. Texture is a complex material property that has more than one attribute. Features formed as a result of physical characteristic properties that arise from structural components which are perceived by touch and can be measured by the deformation, disintegration and flow properties under a force (stress) (Bourne 2002). Techniques to assess texture have been studied with the initial aim of understanding consumer behaviour and preferences in relation to texture (Wilkinson et al. 2000). Currently, the use of texture analysers is one of the most widely accepted and used techniques for research in this area and in industrial laboratories. A texture analyser applies a certain amount of force over a controlled distance on the sample and measures the resistance. The resultant data are used to plot force–displacement graphs (Rosenthal 2010). Texture analysers can measure many textural properties, as seen from the texture profile analysis shown in Figure 2.5.

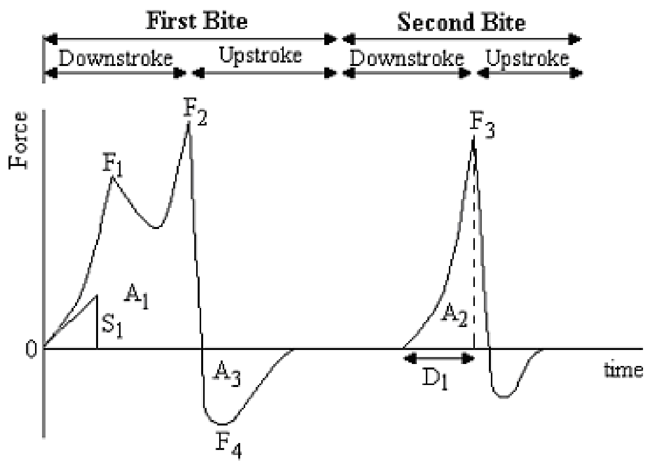


Figure 2.5 Force- time curve obtained from texture profile analysis (TPA) (van Vliet 1999).

The parameters that can be obtained from Figure 2.5 are listed below (Walker 2004).

F_1 = Fracturability,

F_2 = Hardness (firmness),

A_2/A_1 = Cohesiveness,

A_3 = Adhesiveness,

D_1 = Springiness,

Gumminess = Hardness × cohesiveness,

Chewiness = Hardness × cohesiveness × springiness and

S_1 = Slope of the first linear phase, representing the Elastic modulus.

The main limitation of the instrumental measurement of texture is a weakness in correlating results with sensory studies. Unfortunately, instruments cannot replicate the actual dynamic oral experience of texture (Alsanei and Chen 2014, Alsanei et al. 2015, Engelen and Van Der Bilt 2008, Gambareli et al. 2007). Therefore, since the 1950s, the main problem has been relating sensory and instrumental data to eliminate the need for sensory studies using the direct instrumental measurements in their place. However, there has not yet been good correlation and modelling of sensory and instrument data, and sensory tests still provide the most realistic results for the evaluation of food texture. These are time consuming and costly also questionable in terms of objectivity of results in relation to the research area (Boyar and Kilcast 1986). An additional limitation of the instrumental techniques can arise from conditions under which a test is conducted. For instance, temperature has a significant effect on textural properties, and the choice of probe could also affect results and may reduce the correlation with sensory studies (Kohyama and Nishi 1997, Peleg 2006, van Vliet 1999). Moreover, saliva can change the structure of food, but this condition must be ignored in most instrumental texture analyses, leading to definite differences in thermal reactions, chemical reactions and the mechanical effects of lubrication (Hutchings and Lillford 1988). The missing link between the sensory and instrumental texture assessments has been investigated and psychophysical studies showed some good correlations on particular materials under certain conditions and those correlations (laws of psychophysics) will be discussed in following sections.

2.2.1.1.5 Breakdown and Structure of Solid Food

Solid foods are those that require chewing and mastication when consumed. Mastication is linked to food's mechanical properties and its inherent microstructure (Stokes 2012). The texture of solid food is also instrumentally analysed using the texture analysers described in section 2.2.1.1.4. The process of breaking solid foods down in size depends on the shape and mechanical properties of the food (Chen and Lolivret 2011). The time of mastication certainly depends on the material type; for example it has been found to be 22 s for hard solids such as peanuts or biscuits and 9 s for soft-solid foods such as bananas, whereas low-viscosity liquids were found to remain in the oral cavity for approximately 1 s (Hiiemae and Palmer 1999, Cichero and Halley 2006). For breakable or brittle solid samples, the breakage function is important, indicating the distribution of fragments of broken particles formed per chew; it has been found to be related to the elasticity and toughness of food (Lucas et al. 2002). Even though structural and mechanical properties are important in the breakdown of solid foods, oral processing conditions are mostly determined by saliva. Saliva causes the aggregation of hard particles during mastication and changes the consistency of the bolus. It has also been found that orally processed foods are prepared for swallowing because of the contribution of the saliva (Cichero and Halley 2006, Agrawal et al. 1998, Prinz and Lucas 1997).

The texture of solid food samples dynamically changes in the oral cavity to a greater extent than for soft-solids and liquids; therefore, it is relatively hard to predict the textural properties of solid foods using the instrumental assessments. During oral processing, the texture of solid foods and sometimes also of semi-solid foods continuously changes, resulting in changing perception, which is referred to as dynamic texture perception. Therefore, in the present study, we avoided using solid foods not only because of their dynamic texture perception properties but also to avoid the saliva integration process.

2.2.2 Effect of Saliva

The stimulation properties and interactions of saliva with food cause changes in the food structure which directly affects textural properties and oral perception (Stokes 2012). The effect of saliva on texture and especially, the relationship of this with instrumental analysis is complex; as a result, there is still a lack of information about the effect of saliva on texture and the application of this to the instrumental tests (Stokes 2012). Saliva has numerous functions: cleansing, solubilisation of food, bolus formation, aid to mastication and swallowing, food and bacterial clearance, dilution and digestion of starches and mineralisation and lubrication of oral mucosa (Stokes and Davies 2007). It is naturally present in the mouth, but the levels of secretion increase in the presence of food. The levels of secretion have also been found to be influenced by stress, hormones, caffeine intake and hunger (Stokes and Davies 2007). While consuming food, the amount of secretion changes via neural reflexes according to the food’s mechanical and chemical stimuli (Stokes 2012). It is known that saliva is important for texture, mouthfeel and taste perception, as well as for oral health. Saliva contains amylase, an enzyme that initiates the digestion of starches. During digestion, it is known that the increased secretion of saliva reduces the perceived thickness of food and that the disruption of salivary proteins from oral surfaces is associated with the sensation of astringency with the loss of lubrication sensation (Janssen et al. 2007, Janssen et al. 2009, Rossetti et al. 2009). Additionally, saliva determines the sensation of texture and mouthfeel attributes as well as taste perception (Christensen

1981, Guinard et al. 1997, Ship 1999, Vingerhoeds et al. 2005, Dresselhuis et al. 2008, Benjamins et al. 2009, Silletti et al. 2008, Rossetti et al. 2008). Taste perception is influenced by saliva as saliva contains essential taste transporter molecules (Christensen 1981, Ship 1999).

Integrating saliva into the instrumental texture assessments is complicated and does not correspond to natural oral processing. In the present study, the effect of saliva was minimised by avoiding solid food samples and also by minimising the oral time during sensory tests.

2.3 Sensory Evaluation of Texture

Food is essential for survival due to the nutrients it contains, but it also provides a pleasurable experience that contributes to many social occasions (Warde and Martens 2000). If a food product does not correspond to what is needed or does not provide pleasure, it will ultimately result in failure and will most probably leave the market (Kilcast 1999). The importance of food preference has forced researchers to understand key factors that affect consumer behaviour towards a product, which is a complicated process involving many different factors. Reliable instrumental texture assessments suffer a common flaw of being incapable of mimicking varying oral conditions due to the dynamic nature of texture perception and the great variance between individuals. This discrepancy has resulted in low correlations between instrumental and sensory assessments. The best way to understand how a consumer ‘feels’ about a product is still to conduct sensory tests and complete the results with the instrumental tests. However, sensory tests are highly time consuming and costly. Furthermore, their results depend on the personal physiological and transcribing capabilities of the terminology and the scoring used (Boyar and Kilcast 1986). Even though a few perception models have been proposed, these difficulties with bridging the instrumental and sensory assessments remain.

For a long period in the development of the sensory evaluations of foods, sensory testing was only defined as tasting. However, it was later understood that limiting sensory studies to taste alone was inadequate for describing the human experience, and now, the term sensory evaluation includes aroma, texture and appearance alongside taste. To provide reliable information, a systematic approach to the sensory assessment of texture is needed, for which the following criteria might be considered.

2.3.1 Principles of Sensory Evaluation

2.3.1.1 Human Senses

It is known that humans perceive sensory properties through their senses. The five main human senses are vision, gustation, olfaction, touch and hearing, which are related to the perception of appearance, taste, odour/aroma, texture and sound, respectively (Kilcast 1999). Meilgaard et al. (2007) suggested that the sequential order of perception by the human senses are appearance, odour/aroma, consistency, texture and flavour.

It is not surprising that appearance is the first sense perceived because we generally look at a food sample before doing anything. The initial impression of the food often gives a hint for the remaining senses, and perception according to the other senses is often influenced by appearance. The visual senses evaluate not only colour but also size, shape, visual texture, etc. Visual cues give an early but strong expectation of flavour, taste and texture of foods, attributes that would normally be sensed with modalities other than vision (Spence et al. 2010).

Gustation is defined as sensations triggered by the tongue to soluble, non-volatile materials (Kilcast 1999). There are five main taste sensations that are known: salty, sweet, sour, bitter and umami. The tongue contains taste receptors (taste buds) that were believed to be organised as groups of cells located in papillae, as shown in Figure 2.6. However, recent studies have shown no such evidence for the distribution of taste buds, and they are more likely to be placed everywhere on the tongue (Chandrashekar et al. 2006, Hoon et al. 1999, Nelson et al. 2001, Nelson et al. 2002, Adler et al. 2000). It has been demonstrated that taste stimuli are strongly influenced by pH and temperature (Meilgaard et al. 1991). Additionally, chemical/trigeminal senses are also included in gustation, in which irritants that correspond through the pain response with the stimulation of the trigeminal nerve are detected (Kilcast 1999). Good examples of this sensation are the tastes of ginger or wasabi, which give off heat, and some chemicals such as menthol and sorbitol for their cooling response (Kilcast 1999). Trigeminal senses usually have high thresholds and contribute to the sensation of flavour.

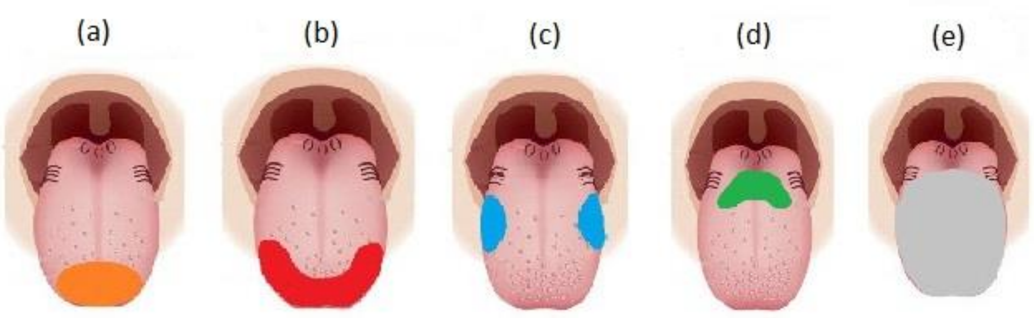


Figure 2.6 Distribution of taste buds on the tongue: (a) sweet sensation, (b) salty sensation, (c) sour sensation, (d) bitter sensation and (e) umami sensation.

Olfaction, which perceives odour/aroma sensations, is much more complex, with odours detected as volatiles by the olfactory epithelium located in the roof of the nasal cavity. Odour receptors are easily saturated. It should also be noted that flavour perception occurs though a combination of gustation and olfaction sensations (Kilcast 1999).

Texture, the main sensation system assessed in the present study, is the outcome of touch through tactile sensors and comprises two components: somaesthesis (tactile sensation and skin feel), and kinaesthesis (deep pressure). Texture sensation can arise through a tool such as cutlery. The texture sensation process is shown in Figure 2.7. A full review of texture sensation/perception dynamics will be provided in the following sections.

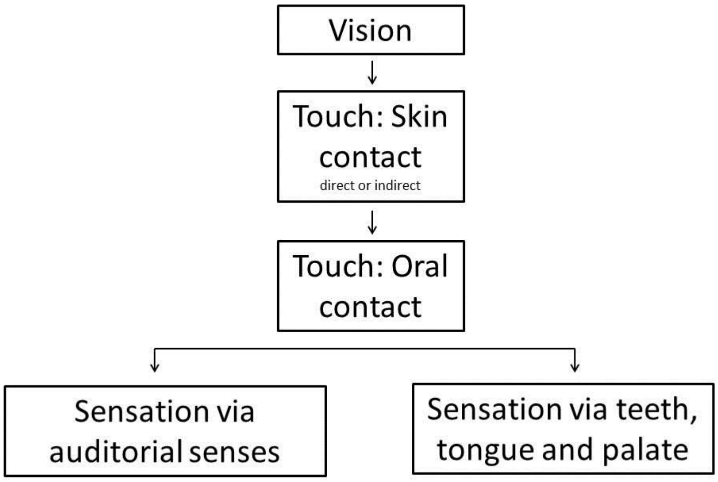


Figure 2.7 Schematic diagram of texture perception process, where vision, touch and hearing senses involve (van Vliet 1999).

Although the five main human senses were individually discussed above, in practice, each sense is affected by the other senses, making the perception system highly complicated. For instance, colour is the primary factor affecting appearance, but it can also influence the perception of flavour (Cardello 1996). Or the sensation of sound created during oral processing was found to tribute to texture perception. For example, crisps or crunchy foods create a sound during biting and chewing that has great importance for the perceived texture (Vickers 1991). An important cautionary note arises from the dynamic nature of oral processing, with catastrophic changes occurring in the structure of food during oral processing that effect the taste, odour and especially the perception of texture (van Vliet 1999). During these changes, the temperature, amount of saliva and change in pH influence perceived sensations, making these highly complex to examine throughout a sensory test.

Senses	Before 1st bite	After 1st bite	Perception
Visual	↔		Appearance
Olfactory	Nasal ↔	Oral ↔	Flavour
Gustatory		↔	
Trigeminal		↔	
Touch	Visual contact ↔	Oral contact ↔	Texture
Hearing		↔	

Figure 2.8 Different sensory modalities perception diagram, during oral processing (Kilcast 1999).

Figure 2.8 illustrates the sensory modalities during interaction with foods. It shows the different perceptions that occur before, during and after oral processing. Visual cues, nasal olfactory sensations and texture cues occur even before we start consuming the food. After the first bite, flavour sensation occurs because of the olfactory, gustatory and trigeminal senses. Oral contact with the tongue and sound waves created during the oral processing also provide an idea of the texture. Therefore, texture, the main domain examined in the present study, starts to be perceived before consuming the food and continuous throughout the oral processing. Ideally, to understand the perception of texture, test should take place under blindfolded conditions to avoid visual cues and samples should have similar taste and sound properties.

As human senses mostly work in cooperation with each other, understanding a single perception mechanism (appearance, flavour, etc.) is a highly complicated procedure. The model presented in Figure 2.9 has been adapted from Cardello (1996) and shows the five human senses and their main roles in influencing an individual's food preference and acceptance. From this it can be seen that the physicochemical structures of foods are determined by physical measurements, whereas senses can only be determined by sensory tests. Performing a sensory test is therefore the key to understanding the sensation of a particular attribute.

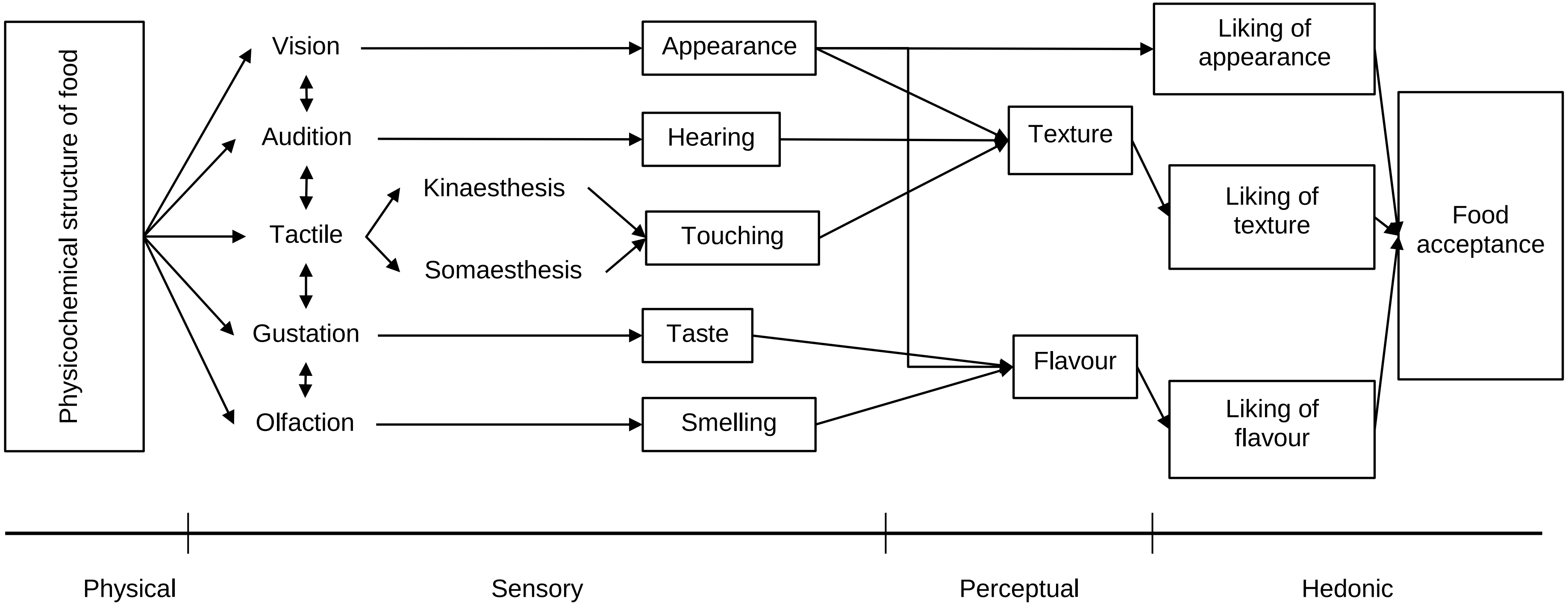


Figure 2.9 Food acceptability model (Cardello 1996).

2.3.2 Basic Requirements for Sensory Analysis

The challenges of understanding texture perception limits and dynamics discussed above have forced researchers to develop systematic approaches for sensory tests. The basic requirements for a well-designed systematic sensory test are illustrated in Figure 2.10.

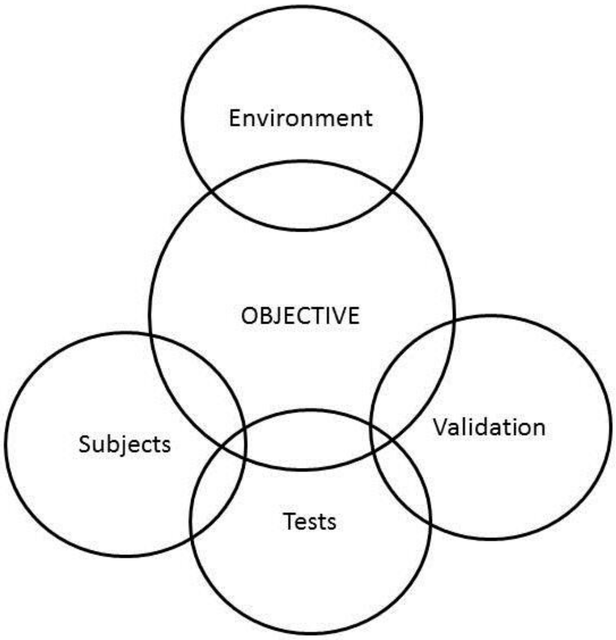


Figure 2.10 Schematic illustration of ideal sensory analysis (Kilcast 1999).

The most important factor in the design of a sensory test is defining its objective. The objective is central to the system; therefore, it should be determined using an accurate, clear, precise and cost-effective approach and should take account of the primary purpose, target group and resources of the sensory test (Kilcast 1999).

The test environment can influence the outcome of a sensory analysis. To provide high-quality data, the environment should be carefully chosen. Ideally, it should be easily accessible and close to the resources and preparation area, should have sufficient lighting and ventilation.

The subjects are the main contributors to the sensory analysis, and most of the time, they are the ‘instrument’ of the sensory test. The number of subjects, their level of expertise (trained or untrained) and any special circumstances (infant, adult, elderly, etc.) are important factors that should be considered when designing the test.

The validation of the data obtained usually requires appropriate statistical analysis, which is essential for data interpretation.

Alongside these essential elements of a well-designed approach, selecting the sensory test methodology is also critical. The success and feasibility of the objective depend to a great degree on the method chosen. There are three main classes of sensory tests:

1. Discrimination/difference tests,
2. Descriptive tests, and
3. Hedonic/affective tests (Kilcast 1999).

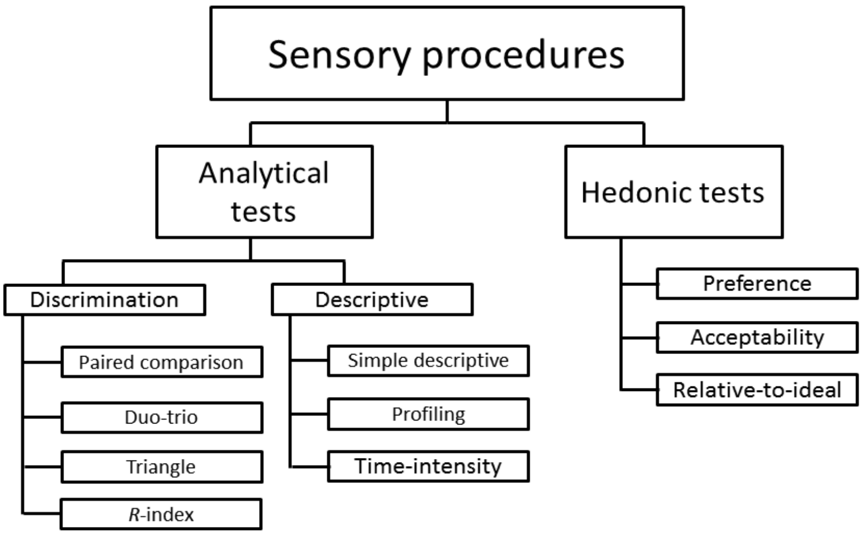


Figure 2.11 Main classification of sensory testing procedures (Kilcast 1999).

The main sensory tests are shown in Figure 2.11. Basically, analytical tests are considered as laboratory sensory analysis where hedonic sensory tests as consumer sensory analysis (Bi 2008). These two tests are differentiated according to their motivations. As described earlier in this chapter, the aim of the present study was to establish a sensitivity map of the human tongue and fingertip in relation to their capabilities for discriminating texture. For this, discrimination tests were used. The following section provides further details about such tests.

2.3.3 Discrimination Tests

Discrimination tests were one of the earliest methods used to investigate the capability of detecting certain stimuli, and they remain popular (Bi 2008, Kilcast 1999). They are usually conducted to fulfil one of two main aims: to establish whether a difference exists between samples (the recognition threshold) or to find the lowest level of detection (the absolute threshold) using comparative or ranking scales (Bi 2008). The main types of discrimination tests are paired comparison, duo–trio, triangle, two-out-of-five and ‘A’-‘not A’ tests. In addition, a method known as a shortcut signal detection test (R index) has been introduced, but its applications are still being investigated (Lee and van Hout 2009). These methods will be discussed further in the following sections.

2.3.3.1 Discrimination Test Methods

2.3.3.1.1 Paired Comparison Test

In paired comparison tests, panellists are given two different blind-coded samples and are asked to choose which one provides either a greater or lesser amount of stimulus; sometimes they are allowed the option of judging that there is ’no difference’. Sometimes, the test is adapted to a format, referred to as a ‘simple difference test’, in which panellists are asked if the samples are the same or different (Stone and Sidel 2004). In paired comparison tests, subjects are usually selected from an untrained population. If they are required to be trained in particular characteristics, then a descriptive test should be used instead of a discrimination test (Stone and Sidel 2004).

A modified version of the simple difference test is the ‘degree of difference test’ (The Institute for Perception 2003, Rousseau et al. 1999). This usually uses multiple samples with similar characteristics, and the outcome aims to clarify discrimination capability (Lee et al. 2007).

Another form of paired comparison test is the A-not A test, which does not have a standard format (Lee et al. 2007). In this method, assessors are usually given a specific sample and are asked to explore its characteristics and remember its properties throughout the test, so they can answer whether other samples are same or different (Kilcast 1999).

The present study used simple difference tests, and panellists were required to test the samples using their fingertip and orally and to respond whether the samples were the same or different. Degree of difference tests were also used, as described in Chapter 6, where surface roughness was assessed, and participants were asked to stroke their fingertip on solid surfaces and to indicate their perception score compared to that of the reference sample.

2.3.3.1.2 Duo–Trio Test

In duo–trio tests, subjects are presented with a reference sample followed by two further samples, one of which is the same as the reference. Assessors are expected to identify the sample that is identical to the control sample. This method can be applied with a single reference or using the other sample as the reference at different times to increase the reliability of the results (Kim and Lee 2012). The duo–trio test is often used for quality control procedures, and it is useful when the shape of the samples is not identical to that of the reference (Kilcast 1999).

2.3.3.1.3 Triangle Test

In this test, assessors are presented with three samples, where two are identical and the third is different. The samples should be presented in all possible permutations, and the assessors are asked to choose the odd sample among the three. A potential problem with this technique is when the samples have a strong flavour, taste or texture, which could overpower the taste or suppress the mechanoreceptors for correct sensation (Stone and Sidel 2004).

2.3.3.1.4 Two-out-of-Five Test

In the two-out-of-five test, assessors are served with five samples where three are identical and two are different. Subjects are asked to identify the two identical samples from the five that are presented in all 20 possible combinations. This test is highly sensitive, but requires the investment of more time and effort by the investigators and is also challenging for the participants due to large number of testing (Kilcast 1999).

2.3.3.1.5 Difference-from-Control Test

The difference-from-control test is an overall difference test that can be performed with more than two samples and a control. Assessors are usually presented with an identified control sample and a range of test samples, and they are asked to rate the samples on an anchored scale, which includes ‘no difference from control’ and ‘very different from control’ (Meilgaard et al. 2011).

2.3.3.1.6 R-Index Test

The R-index is a non-parametric statistical magnitude introduced by Brown (1974), which is widely used in psychophysics and recently, in consumer research studies (Lee and van Hout 2009). R-index or shortcut signal detection is a method where test samples are compared with previously experienced standards. Assessors are asked to rank these samples in four categories: ‘standard’, ‘perhaps standard’, ‘perhaps not standard’ and ‘not standard’. The resultant data are calculated as R-indices, representing the probability of correct identification. This method requires a large number of judgements, causing fatigue to the assessor and also to the investigator (Kilcast 1999).

2.3.3.2 Determining Threshold

Thresholds are not well defined in literature and moreover, in the past they were believed to not exist (Lawless and Heymann 1998, Morrison 1982, Swets 1964). More recently, threshold values have been accepted to be essential for highlighting vital conditions, such as the legal limits of air pollution, set level of added substances to drinking water, lethal dose of medicines and chemicals and many vital applications that require hundreds of panellists to map the population’s sensitivity (Meilgaard et al. 2011). The threshold concept has also been adapted to human anatomy and sensations such as temperature (hot or cold), taste (sweet, sour, etc.) or vibration. However, there remains an additional gap in threshold studies about texture sensations, which could provide information for many industries and individuals. Furthermore, establishing the textural threshold of a particular attribute provides an opportunity for the creation of a human sensitivity map, if sufficient reliable evidence can be obtained.

A threshold is the limit of sensory capability, which can have four different meanings:

1. Absolute threshold,
2. Recognition threshold,
3. Difference threshold or
4. Terminal threshold.

The absolute threshold is the lowest stimulus that can produce a sensation, such as the lowest sound, dimmest light or weakest taste (Meilgaard et al. 2011, Field et al. 2005).

The recognition threshold is the level at which a specific stimulus can be detected and recognised. For example, when a panellist starts to recognise the sensation of sucrose taste in water, this is considered to be the recognition threshold for sucrose taste (Meilgaard et al. 2011). The recognition threshold has a higher value than the absolute threshold.

The difference threshold is the level at which an increase in stimulus can be perceived, which is usually determined using a paired comparison test of the samples to the control (Craig 1972). The difference threshold level is determined by small changes from the standard and is tested until the subject just notices a difference (Meilgaard et al. 2011). For this purpose, the just noticeable difference (JND) method, which is explained below, is often used. In the present study, the main motivation was observing the difference threshold for the textural attributes. This will be discussed further in the relevant chapters.

The terminal threshold is the magnitude of stimulus at which a further increase will no longer be detected. Usually, pain will start gradually if this threshold is exceeded (Meilgaard et al. 2011).

Obtaining any kind of threshold values is not a simple task; it requires small differences from the standard for accurate measurements. Moreover, threshold values vary within the population between individuals and groups (Meilgaard et al. 2011). To minimise bias, test samples must therefore be carefully selected from those with similar attributes, and then the obtained results should be carefully analysed. In addition, selecting the subjects from general and similar populations will increase the reliability of the tests. It should also be noted that the threshold is not an exact value but rather a value on stimulus continuum.

In general, threshold values have been obtained from a whole population graph to avoid outlier extra-sensitive/dull subjects. In this plotting of the whole population graph the threshold value could be selected at different levels of perception (10, 20 or 50 %). Occasionally, for vital studies such as of pharmaceuticals or climate change, the threshold value can be obtained from 10 % or 20 % of the total responses, to minimise the risk in terms of health and safety (Davis 1997). However, in most of the food practices the stimulus level identified by half of the population (50 %, median) is accepted as the threshold value, which can be obtained from the model plot shown in Figure 2.12 (Meilgaard et al. 2011, Laing 1983, Chaplan et al. 1994, Clark and Mehl 1971).

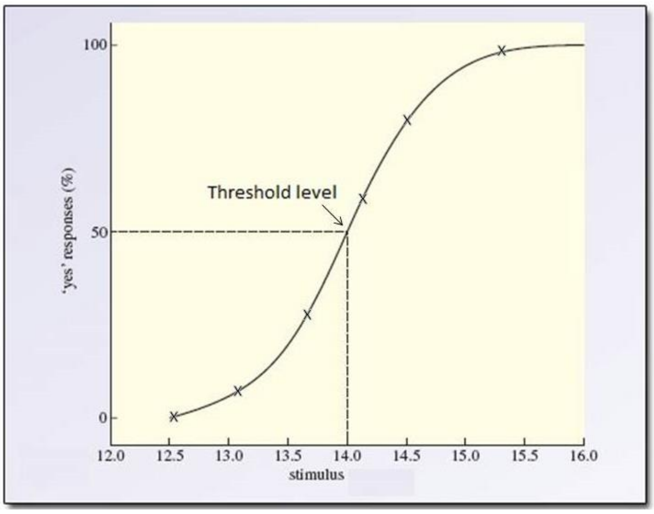


Figure 2.12 Typical threshold determination graph (Meilgaard et al. 2011).

In the present study, we used 50 % response as the threshold value. It will be assumed that any values below this level will not cause discriminable differences in texture; therefore, the threshold will indicate the minimum required change in the stimulus to create a perceivable difference.

2.3.3.2.1 Just Noticeable Difference

As mentioned above, JND is a widely used discrimination threshold assessment method. It was first mentioned by Weber while demonstrating that any change in stimulus was proportional to the magnitude of the standard stimulus and that this proportion was constant regardless of the intensity of the stimulus (this will be discussed further in section 2.4.1) (Stern and Johnson 2010). This method is a step ahead of the usual discrimination test methods (Stone and Sidel 2004). In a JND test, systematic set levels of stimulus are used as a basis for estimating how much change is necessary to detect the change in the stimulus (Stone and Sidel 2004). To perform a JND test, a constant-stimulus method is usually used with continuous sensation in each comparison (Guilford 1954, Schutz and Pilgrim 1957, Stone 1963, Perfetti and Gordin 1985, Laming 1986, Stone and Sidel 2004). Panellists are asked to report their perception as 'same/different' or 'weaker/stronger' (Stone and Sidel 2004). If test samples have proper intervals, then it is possible to obtain proportional judgements from which the best fit can be computed to find the 50 % response to represent the 'population detection threshold' (Bock and Jones 1968).

2.3.3.3 Data Analysis and Interpretation

Discrimination tests involve a high probability of guessing correctly, which reduces their reliability due to having few samples to compare with each other. For instance, when there are two samples and the subject is asked to choose the odd one, there is a 50 % chance of coincidentally finding the answer. Frijters (1988) showed the probability of guessing in discrimination tests, as presented in Table 2.6.

Table 2.6 Probability of coincidental correct response in popular discrimination tests (Frijters 1988, Kilcast 1999).

Test	Total number of samples	Probability
Paired comparison	2	50 %
Duo-trio	3	50 %
Triangle	3	33 %
Two-out-of-five	5	10 %

Another main concern in discrimination tests is the number of assessors. According to the nature of the test, there is a designated minimum number of subjects required to provide reliable results, although more participants will increase the reliability and may give an opportunity to universally generalise the results. These minimum numbers are presented in Table 2.7.

Table 2.7 Minimum number of assessors required for discrimination tests (Kilcast 1999).

Test	**Minimum number of subjects**	
	Trained	**Untrained**
Paired comparison	20	30
Duo-trio	-	20
Triangle	15	25
Two-out-of-five	10	-
‘A’, ‘not A’	20	30

The reliability of such tests also depends on errors, which are of two kinds: type 1 errors, where a panellist incorrectly reports a difference that does not exist, and type 2 errors, where the panellist is not able to identify a difference that does exist (Kilcast 1999). To increase reliability and reduce variance due to these two types of errors, it is necessary to conduct a careful investigation with as many participants as possible, preferably at least the number listed in Table 2.7.

The results of discrimination tests are usually analysed using tables of binominal expansion, even when other distributions are used. For the results, a 5 % significance level is frequently used, and the exact level of significance may also be calculated. Duo–trio, triangle and two-out-of-five tests are one-tailed, whereas a paired comparison could be one-tailed or two-tailed according to the nature of the test (Kilcast 1999).

Discrimination tests require a choice of testing method of whether to use forced choice procedures (either a two-alternative forced choice ‘2-AFC’, or a three-alternative forced choice ‘3-AFC’) or to allow the assessors to report that they perceive no difference. The inclusion of the ‘no difference’ option should be carefully considered according to the experience of the assessors, where expert and trained assessors will provide informative feedback. With inexperienced panellists, it is more appropriate to use forced choice procedures without including the ‘no difference’ option (Meilgaard et al. 1991, Stone and

Sidel 2004, Kilcast 1999). However, each sensory test has its own nature, and by considering the factors discussed above, they can be customised during application and data analysis.

2.4 Relating Instrumental and Sensory Data

Instrumental texture measurements are reliable and robust and can represent defined physical characteristics in standard units. The case for sensory perception of texture is far more complicated. A human is the ‘instrument’ of the sensory tests, and human texture perception is governed by psychophysical phenomena with their nonlinear characteristics (Rosenthal 1999). There are many differences between the instrumental and human assessments of the texture, which are listed below.

Human receptors are most sensitive when smaller forces are applied; they can also show adaptation, which may sometimes mask the real response if a stimulus is kept constant for a period of time, leading to a reduction in sensitivity (Rosenthal 1999). The human brain works by comparing signals with either a reference tested previously or a learned experience. For example, the question of hot or cold is processed in the brain by comparing different references, indicating that the brain works using relative thinking.

Another difference between the instrumental and human texture measurement results from temperature differences. It is well established that textural features and rheology are temperature-dependent properties. With instruments, the temperature can be kept constant at a set value, but in human tests, the temperature does not usually remain constant. The human body is normally at 37 °C, with the oral surface usually a few degrees lower than this (Sund-Levander et al. 2002). When food is introduced for oral processing, it undergoes a series of changes in temperature, which alter its physical behaviour (Rosenthal 1999).

The presence of saliva in the mouth is another main factor that contributes to food sensation in sensory studies, unlike in instrumental assessments. An average human has been found to secrete 1.5 litres of saliva per day (Rosenthal 1999). Saliva is a non-Newtonian fluid that contains the digestive enzyme amylase and unusual forms of proteins and polypeptides.

Most instrumental analyses do not include a system to introduce and mix saliva into the food system during the assessment of physical properties. Even if they did, it may not be possible to duplicate the correct amount of saliva, given that in humans the amount secreted depends on the type of food stimulating the salivary glands.

Another factor that exists only in human tests is the movement of the jaw and tongue during oral processing, which is important for texture perception (Rosenthal 1999). These movements depend on the type of food and would be expected to affect the sensation of texture. For instance, if the food is shear-thinning, as most foods are, as a result of the movement of the jaw and tongue, the food will become thinner, and texture sensation will constantly change. Similarly, the shear rate of the tongue is predominantly important in texture sensation. Therefore, for the best possible instrumental analysis of a sample, it is necessary to select a particular shear rate (if the sample is non-Newtonian) similar to that applied in the mouth. Shama and Sherman (1973) found that shear rates in the mouth were in the range 0.1 to 1000 s^{-1}. Later, Bourne (2002) reported that the average shear rate of the tongue is 50 s^{-1} in a healthy adult, which is the reference shear rate value used in most texture assessments. To avoid the shear rate controversy found in literature, we used Newtonian fluid sample in our sensory tests reported in Chapter 3.

With regard to all these differences, until an optimal artificial mouth is developed, we will still need the texture analyser or rheometer to provide the best possible physical measurements. However, the previously discussed absence of a bridge between the instrumental and sensory analyses should always be taken into consideration. Also it should be remembered that instrumental and sensory measurements do not have to correlate in every case, but a ‘no correlation’ decision should only be claimed after investigating all possible options. To construct that bridge between the instrumental and sensory analyses, psychophysicists have demonstrated several laws, including Weber’s law, Fechner’s law and Stevens’ law, which will be explained in the following sections.

2.4.1 Psychophysical Laws

The first seeds of psychophysical laws were independently inspired by several people. In 1760, a French mathematician, geophysicist, geodesist and astronomer named Pierre Bouguer performed an experiment with candlelight. He placed two candles at different distances from a screen, one of them throwing a shadow that was obliterated by the other one. He found that the intensities of the lights at this point had a particular ratio that he claimed was unaffected by the brightness of the lights (Hecht 1924). In the early 1800s, another French mathematician, physicist, astronomer and freemason politician, François Arago, added to Bouguer's finding that, irrespective of the magnitude of the ratio, it can be changed by keeping the shadow of the candlelight in motion. His experiments were repeated in 1845 with a new approach taken by another researcher, Masson, who reported the ratio $\Delta I/I$ (the change in stimulus divided by the initial stimulus) was constant regardless of the intensity of the stimulus (Hecht 1924). Meanwhile, in 1837, a scientist named Steinheil had independently found the just perceptible difference concept in intensity, which could be measured with the photometer he developed. Again, independently, in 1834, the German scientist Ernst Heinrich Weber found that a person can discriminate between two weights if they at least differ by 1 or 2 parts in 30 which is given by the following equation:

$$S = \frac{\Delta I}{I} \tag{2.7}$$

where S is Weber's ratio, ΔI is the change in intensity and I is the magnitude of intensity (Fechner 1860).

Technically, Weber's law is useful for producing an index of sensory discrimination, allowing a comparison across different sensory modalities regardless of reference stimulus (Gescheider 1997). Weber's ratio can be calculated for each modality, even for those using different references but will still give an idea to the researcher of the percentage change required for detection (Gescheider 1997).

In 1858, Gustav Fechner, a German philosopher, physicist and experimental psychologist who had noticed that a slight difference in the shade of a cloud could be reduced by the interposition of smoked glass, repeated Bouguer's candlelight experiments and reported similar findings. He then investigated similar cases with starlight to observe astronomical data, introducing a logarithmic relationship rather than a linear one between the magnitude of light and its intensity. This relation had already been found by Steinheil in 1837 with his photometer. Fechner's further investigations of this psychophysical law showed that Weber's law remains valid until a certain limit, beyond which the relationship becomes logarithmic rather than linear, as illustrated by the following equation, now called Fechner's law:

$$S = k \log I + C \tag{2.8}$$

where a constant of integration *C* was added to the previous law following logarithmic approach (Fechner 1860).

In 1957, Stevens proposed a new psychophysical law in place of Fechner's logarithmic law. This involved a power law relationship between sensation magnitude and stimulus intensity, as shown in equation 2.9.

$$S = k\, I^{a} \tag{2.9}$$

where S is the sensation magnitude, I is the stimulus intensity and *a is* the power exponent that depends on the sensory modality and conditions (Gescheider 1997). The value of the exponent determines the relationship between the stimulus and sensation magnitude. For instance, when it is equal to one, the sensory magnitude is then linearly proportional to the intensity; if it is greater than one, the relationship is expected to be positively accelerating, and if less than one, then the relationship is considered to be negatively accelerating. The measured exponents for some modalities are shown in Table 2.8.

Table 2.8 Power exponents for power functions between the sensory magnitude and stimulus intensity (Stevens 1975).

Sensory modality	Measured exponent value	Stimulus condition
Sucrose taste	1.30	Sucrose taste threshold
Salt taste	1.40	Salt taste threshold
Saccharine taste	0.80	Saccharine taste threshold
Tactual roughness	1.50	Rubbing emery cloths
Tactual hardness	0.80	Squeezing rubber
Viscosity	0.42	Stirring silicone fluids
Vibration (60 Hz)	0.95	Amplitude of 60 Hz on finger
Vibration (250 Hz)	0.60	Amplitude of 250 Hz on finger

These three psychophysical laws remain valid and can be used according to the nature of the data and test. However, the appropriate law should be carefully selected for correct data evaluation, which will then give an idea about the sensitivity of humans for the sensory modality of interest. In the present study, discrimination tests were applied based on Weber's ratio calculations for the selected attributes of texture. This provided an opportunity to claim that regardless of the reference stimulus, if the magnitude of the attribute was changed according to Weber's ratio, this would create a detectable change in that attribute for that sample.

2.5 Cutaneous Sensation

Sensations that are felt through the skin are crucial for survival from injuries such as burns, broken bones and bruises (Klatzky et al. 2003). People who lose their tactile senses are reported to suffer more from injuries as they cannot sense and take action to defend against threats such as sunburn or chemical hazards (Carello and Turvey 2004). Without the sense of touch, the survival of our species would not be possible; tactile sensation could therefore be considered to be at least as important as the sensation provided by vision or hearing (Klatzky et al. 2003). Tactile senses are not only important for experiencing pain but also for pleasurable sensations such as cuddling a pet.

Tactile sensation is also the only system in humans that simultaneously interacts with objects in passive perception and active manipulation (Weisenberger 2001). Tactile sensation occurs via mechanoreceptors, thermoreceptors and nociceptors in the skin. The mechanoreceptors of the tactile system are inherited from our ancestors and are specialised to sense touch, pain, pressure, vibration or temperature, while thermoreceptors and nociceptors respond to thermal stimulation and mediate pain stimuli, respectively (Weisenberger 2001). Texture perception has been reported to be related to mechanoreceptors; therefore, this section will focus on these. As the aim of the present study was to understand the contribution of tactile sensation on the texture perception, the anatomy of the cutaneous sensation will be reviewed. Cutaneous sensations are supplied by the somatosensory system, which is responsible for

1. proprioception or body sense, i.e. the sense of skin, muscle, tendons and the vestibular system that provides feedback about the perception of the body and
2. kinaesthesis, or the sense of position, which indicates the movement of limbs (Klatzky et al. 2003).

2.5.1 Anatomy and Physiology of the Somatosensory System

The skin is the largest organ in the human body, which Gibson (1962) once called the ‘monumental facade of the human body’. It is considered to be the largest sensory organ with a mean surface area of 1.7 m^2 in adults (Weisenberger 2001). The main functions of the skin are to keep body fluids and maintaining the temperature of the body and to keep bacteria, chemicals and dirt away from vulnerable inner parts (Klatzky et al. 2003). In addition to these roles, the skin contains sensors to detect touch, vibration, etc.

The skin has a complex structure; it incorporates nerve fibres and sensory receptors to sense pain, texture and temperature. It also contains specialised glands to secrete sweat and sebum (Adams et al. 2007). There are three types of skin: hairy (such as the head), glabrous (i.e. inside the palm or under the feet) and mucocutaneous (i.e. areas with borders to the interior body such as the nose or mouth). The type and density of mechanoreceptors may show differences according to the skin type (Adams et al. 2007).

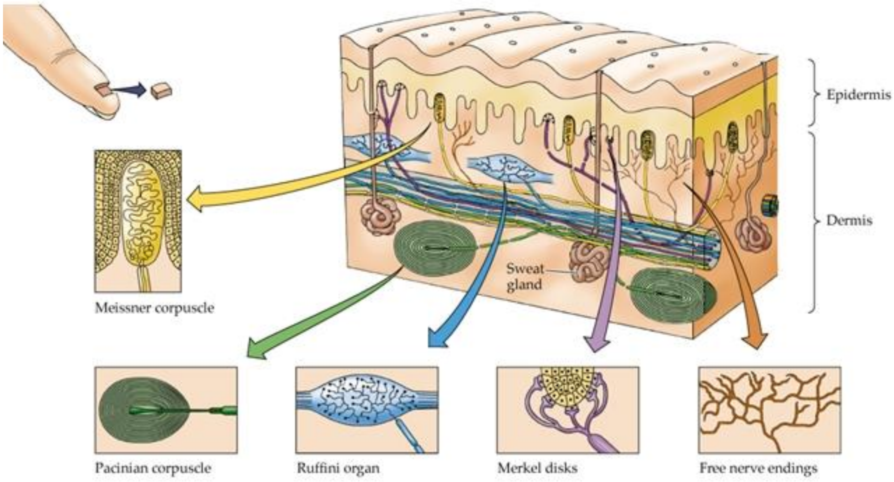


Figure 2.13 Cross-section of skin, with illustrated layers of epidermis and dermis, including four major mechanoreceptors for tactile receptors: Meissner corpuscle, Pacinian corpuscle, Ruffini organ, and Merkel disks.

The skin has three distinct parts: the outer layer of the skin or epidermis, inner layer or dermis and deeper parts known as the subcutaneous tissue (Adams et al. 2007, Klatzky et al. 2003). The epidermis is composed of tough and hard dead skin cells known as the stratum corneum (Adams et al. 2007). It has a thickness of 10 µm over most of the body, apart from the soles of the feet, where the thickness is much greater (Klatzky et al. 1985). The dermis is the deeper skin layer and is much thicker. Both layers contain mechanoreceptors that sense mechanical stimulation (Klatzky et al. 2003, Adams et al. 2007) (Figure 2.13). Beneath these two layers is the subcutaneous tissue, which is a fat tissue with a liquid phase that comprises 60–70 % of the volume of the skin (Lederman and Klatzky 1987).

2.5.1.1 Mechanoreceptors

Tactile sensation is triggered by stimulating the skin, which is tracked by mechanoreceptors located in the epidermis and dermis. Mechanoreceptors were classified in the 19th century by anatomists during their microscopic investigations (Klatzky et al. 2003). These classifications were made according to the temporal, spatial and frequency properties of the skin as discussed below.

1. *Temporal properties* or adaptation properties indicate the response to the continuous stimulation of the skin. Mechanoreceptors are divided into two

groups according to their temporal properties, namely rapidly adapting (RA) or slowly adapting (SA). Slowly adapting receptors continuously fire as long as the skin is stimulated (Tseng et al. 2009). An example of the slowly adapting sensation could be the sensation of pain, joint capsule or muscle spindle, sensations that are all perceived for as long as the stimulus occurs. In contrast, rapidly adapting receptors fire only at the onset of continuous stimulation of the skin and when it ends (Klatzky et al. 2003). Examples of the rapidly adapting sensation are putting on a wrist watch or clothes. These stimulations are sensed when we first experience them, but we do not continuously sense them, which could prove to be uncomfortable. A recent study by Bukowska et al. (2010) showed that in the skin, 67 % of the mechanoreceptors are slowly adapting; however, within the oral cavity, only 33 % of the mechanoreceptors were found to be slowly adapting. This suggests that the tongue is capable of detecting external stimuli throughout the duration of stimulation.

2. *Spatial properties* or detail resolution, which determines the capability to perceive surface-dependent details such as fine details, stretching sensations or vibration (Johnson 2001).
3. *Frequency response* specifies the ability to perceive the speed of stimuli presented to the skin, with the ability to sense someone pushing our skin approximately once in every 3 s up to extremely rapid vibrations such as those created by a drill or other machinery (Klatzky et al. 2003).

The mechanoreceptors of the oral cavity show no morphological differences to those of the skin (Capra 1995, Marlow et al. 1965, Trulsson and Johansson 2002). However, their densities might be different. There is a gap in literature regarding oral tactile sensitivity values; therefore, in the present study, tactile sensation tests (i.e. touch sensitivity or two-point discrimination) were applied to the fingertip and tongue surfaces to compare their tactile sensitivities. Mechanoreceptors are generally discussed according to their location in the oral cavity as

1. Hard and soft palates, tongue and gums
2. Periodontal membrane and

3. Muscles and tendons in the jaw (Guinard and Mazzucchelli 1996, Fujiki et al. 2001)

Mechanoreceptors found in these three parts of the oral cavity each have a specific role. Receptors on the hard and soft palates, tongue and gums are considered to be the predominant receptors for the sensation of food texture. For example, the consistency of liquids will be predominantly sensed during the shearing of the tongue to the hard and soft palates by mechanoreceptors in these areas. Additionally, semi-solid foods such as gels that are compressed rather than bitten will also indicate the use of receptors on the tongue, soft and hard palates and tongue and gums. Periodontal membrane mechanoreceptors are responsible for delivering a suitable amount of force in a particular direction and detecting the thickness of food between opposing teeth (Boyar and Kilcast 1986). In contrast, mechanoreceptors in muscles and tendons are responsible for monitoring the activity of the jaw, such as adjusting velocity and stretching movements according to the changing texture (Gordon and Ghez 1991). Depending on the food type, some other parts of the oral cavity will involve in the sensation of food. For example, mechanoreceptors in the periodontal ligaments and muscles and tendons will not be predominantly involved for soft-solid foods such as weak gels as this food type does not require chewing. Therefore, mechanoreceptors on the tongue will take charge and dominate the sensation (Kutter et al. 2011). It also worth mentioning that regardless of the food type, these receptors in different parts of the oral cavity usually work together to collect information about the texture of food.

The four main types of mechanoreceptors are listed below. They are often referred to with an indicator according to their depth in the skin as

1. located in the epidermis or
2. located in the dermis (Table 2.9).

2.5.1.1.1 Meissner Corpuscle

A Meissner corpuscle is a rapidly adapting (RA1) stack of flat cells in the epidermis of the skin, which is a relatively small mechanoreceptor with a small receptive field size (Klatzky et al. 2003, Weisenberger 2001). Meissner corpuscles are surrounded by an elastic capsule and are innervated by 2–6 afferent fibres (Weisenberger 2001). They can detect frequencies of stimuli in the range 3 to 40 Hz, and it has been established that they play a major role during hand-grip control of tools and are also involved in touch, flutter and skin stretch sensations (Shao et al. 2010, Klatzky et al. 2003, Kandel et al. 2000, Johnson et al. 2000).

2.5.1.1.2 Merkel Cell–Neurite Complex

A Merkel complex is a disk-shaped slowly adapting (SA1) receptor located at the intersection of the epidermis and dermis. It has a small receptive field size (Weisenberger 2001) and is sensitive to frequencies between 0.3 Hz and 3 Hz, which is about slow pushing ranges. Its major role is to detect fine details during skin contact (Klatzky et al. 2003, Kandel et al. 2000, Johnson 2001).

2.5.1.1.3 Pacinian Corpuscle

Pacinian corpuscles are layered capsules that surround a nerve fibre, which have a relatively larger receptive field and a structure with an onion-like appearance formed from numerous layers or lamellae (Weisenberger 2001). They are rapidly adapting (RA2) receptors located in the dermis, and they can detect frequencies in the range 10 to 500 Hz, the upper range of vibration sensed (Johnson et al. 2000, Talbot et al. 1968). Because of these receptors, we can perceive the vibration and texture of a surface by moving over it with our fingers (Macefield et al. 1996). The relationship between the afferent response and end organ has mostly been established for Pacinian corpuscles (Weisenberger 2001).

2.5.1.1.4 Ruffini Ending

Ruffini cylinders are structured as branched fibres inside a cylindrical capsule. They are slowly adapting (SA2) mechanoreceptors located in the dermis. Ruffini endings are loosely organised to reflect encapsulation, making it difficult to consider it as a mechanoreceptor. Moreover, some investigations in species of monkeys have shown no existence of Ruffini endings; therefore, it remains controversial in the field over whether or not they are mechanoreceptors (Phillips and Johnson 1981). Ruffini endings are responsible for sensing frequencies in the range 15 to 400 Hz and are shown to be necessary for the perception of stretching on the skin surface (Klatzky et al. 2003).

2.5.1.2 Thermoreceptors

Much less is known about thermoreceptors than about mechanoreceptors. It is only clear that there are various thermoreceptor structures at different levels in the skin that along with detecting skin temperature, also respond to some mechanical stimulations, making it harder to identify these receptors (Weisenberger 2001). It has been suggested that Krause's end-bulbs in the skin are responsible for thermal sensation, but some researchers disagree, considering it unlikely that a specific kind of thermoreceptor could be identified (Weisenberger 2001). Disagreement therefore remains in the field as to which receptors are responsible for temperature.

2.5.1.3 Nociceptors

Pain is sensed by the nociceptors, of which there are several that fire in the presence of excessive heat, cold, mechanical deformation, chemical irritation, electric current or a combination of these (Weisenberger 2001). Free nerve endings in the skin are most likely to be responsible for pain detection; these are widely distributed throughout the body in the epidermis and dermis. Mechano bare nerve endings and polymodal bare nerve endings have been commonly referred to as nociceptors sensitive to sharp pain and burning pain, respectively (Schmidt et al. 2000). Nociceptors have a relatively wide range of responses; therefore, they are referred to as wide-dynamic range receptors. This means that they have a low reaction to low levels of stimulation but a very high reaction to greater stimulation (Weisenberger 2001). Their primary role seems to be ensuring the survival of an individual by avoiding hazards and injuries.

All these tactile sensation sensors are illustrated in Table 2.9, according to their temporal properties (rapidly adapting or slowly adapting), spatial properties and sensations for which they are responsible, frequency responses and location in the skin layers.

Table 2.9 Characterisation of the receptors presented in the human skin, according to their temporal properties, spatial properties, frequency response and depths in the skin (RA for rapid adapting, SA for slow adapting and 1 for epidermis, 2 for dermis)

Mechanoreceptors				
	Temporal properties	**Spatial Properties and sensation**	**Frequency response (Hz)**	**Depth in the skin**
Meissner Corpuscle	RA	Hand gripping, controlling tools, touch, flutter, skin stretch	3-40	1
Merkel Cell Neurite Complex	SA	Local skin curvature, fine details, velocity, displacement	0.3-3	1
Pacinian Corpuscle	RA	Unlocalised vibration, surface texture, acceleration	10-500	2
Ruffini Ending	SA	Directional skin stretching, displacement on skin surface	15-400	2
Thermoreceptors				
	Temporal properties	**Spatial Properties and sensation**	**Frequency response (Hz)**	**Depth in the skin**
Warm, bare nerve endings	SA	High skin temperature	-	-
Cold, bare nerve endings	SA	Low skin temperature	-	-
Nociceptors				
	Temporal properties	**Spatial Properties and sensation**	**Frequency response (Hz)**	**Depth in the skin**
Mechano- bare nerve ending	Non- adapting	Sharp pain	-	-
Polymodal- bare nerve ending	Non- adapting	Burning pain	-	-

2.5.2 Pathways from Skin to Cortex

The receptors listed are responsible for sensing stimuli and transforming the feedback to afferent fibres. This signal is transported via the spinal cord and is then processed by the brain. Only after that does an individual decide to take action, if necessary. When the signals leave the spinal cord, they follow either the medial lemniscal pathway or the spinothalamic pathway. The lemniscal pathway consists of large fibres that carry signals for the sense of position of the limbs and perceived touch (Klatzky et al. 2003). The spinothalamic pathway has smaller fibres that transmit information about temperature and pain (Klatzky et al. 2003). After they leave these two alternative pathways, the signals cross over to the thalamus and are then transported to the somatosensory cortex (Klatzky et al. 2003) (see Figure 2.14 for a detailed illustration of this).

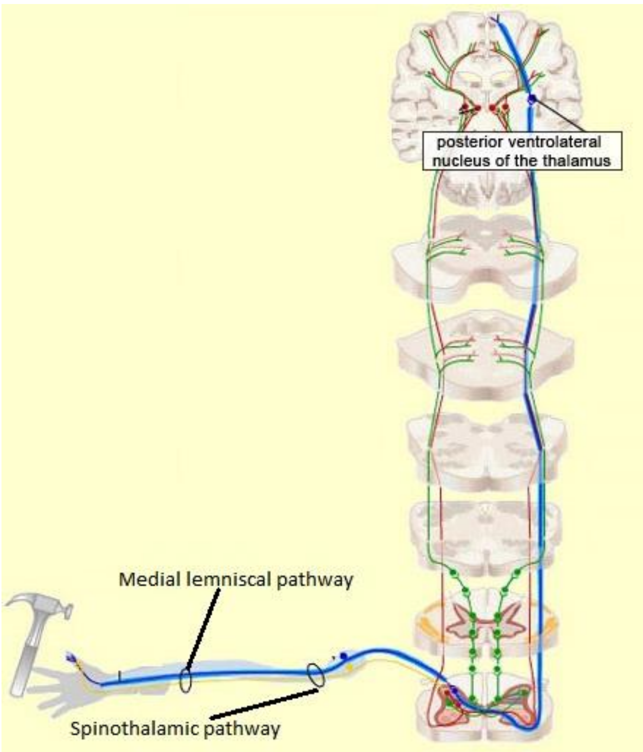


Figure 2.14 Illustration of sensory information collection through finger which is conveyed by dorsal root, spinal cord to thalamus and to somatosensory cortex (Dell 2015).

The somatosensory cortex is organised into maps that correspond to locations of the body. This was discovered by a neurosurgeon, Wilder Penfield, during brain surgery operations on conscious patients to relieve epilepsy symptoms (Penfield and Rasmussen 1950).

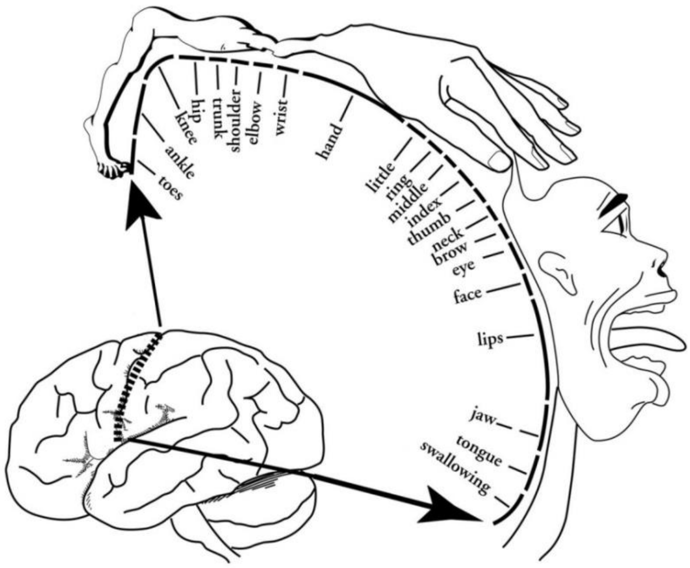


Figure 2.15 Penfield's classical diagram, which shows parts of the body with the highest tactile acuity as larger areas on the cortex (Schott 1993).

The brain map shown in Figure 2.15 is called a homunculus (which means 'little man' in Latin) (Klatzky et al. 2003). It shows some parts of the human body, such as the lips and fingers, to be disproportionally larger than the others, which represents greater tactile sensitivity. A model human statue has been developed according to the map introduced by Penfield and has been accepted as a masterpiece by the Natural History Museum of London (Figure 2.16). It was designed to show what a man's body would look like if each part grew in proportion to the area of cortex of the brain concerned with its tactile sensitivity.

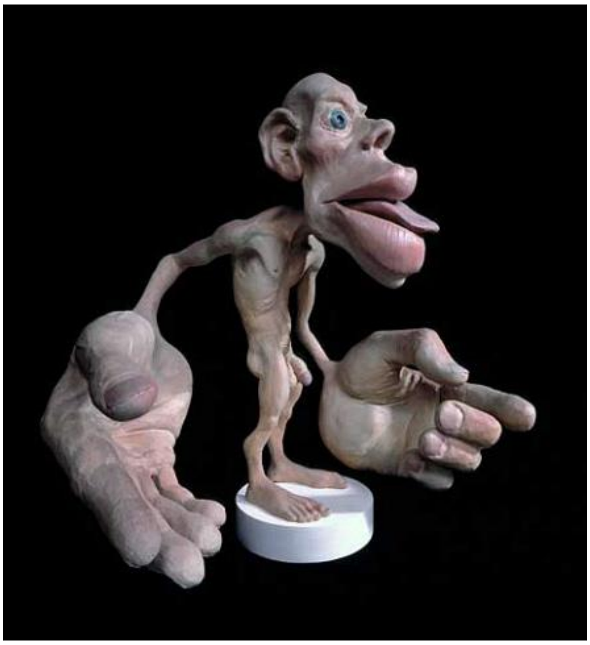


Figure 2.16 Image of the sensory Homunculus (‘Little Man’) status exhibited in London Natural History Museum (Natural History Museum 2015).

2.5.3 Perceived Senses

This section discusses cutaneous senses, including the main sensations such as perception of the distance between two different touching points and low levels of vibration or textural features of surfaces.

2.5.3.1 Acuity

Tactile acuity represents the details of detected stimuli on the surface of the skin. It is generally measured by two-point discrimination or grating acuity tests. Two-point discrimination is measured as the threshold for the narrowest distance that can be sensed as two distinctive pressure points (Aktar et al. 2015b). Grating acuity tests are mostly measured by a grooved stimulus on the skin to observe if a subject can sense the vertical or horizontal grating, which is then used as an indicator of tactile (Klatzky et al. 2003). Of the mechanoreceptors, it is believed that the Merkel receptor is predominantly responsible for acuity detection and that the density of these receptors is relatively higher in the human hand and fingers, resulting in higher acuity sensitivity (Valbo and Johansson 1978).

Tests on the tactile acuity have helped researchers create the sensitivity map shown in Figure 2.17. It is clear from this figure that fingers and lips have much greater acuity than other parts, as was shown by the homunculus map of the brain (Figure 2.15). The missing piece of the acuity sensitivity map puzzle was the sensitivity of the tongue, the only organ that senses food during oral processing. One of the aims of the present study was to understand the tongue's tactile acuity sensation. Experiments for two-point discrimination between the tongue and the fingertip will be further discussed in the relevant chapters (Aktar et al. 2015a, Aktar et al. 2015b).

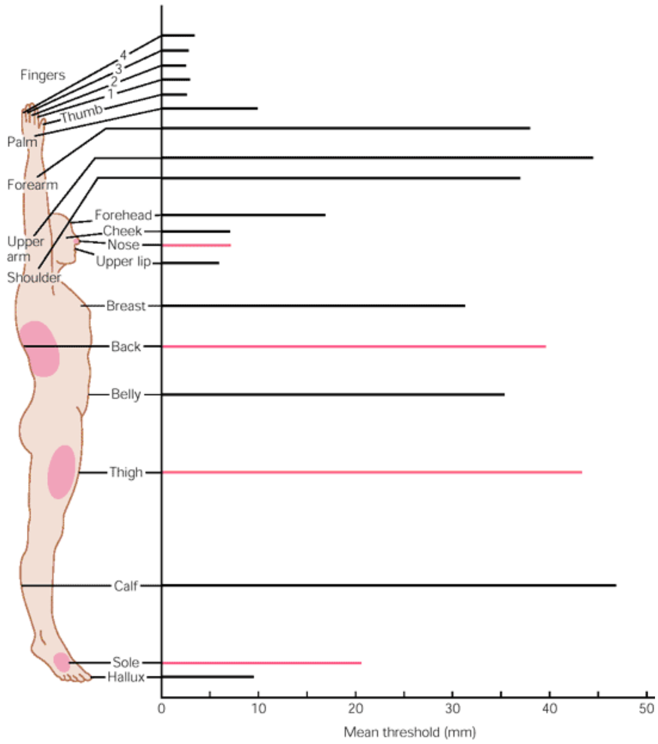


Figure 2.17 Two-point thresholds on the human body (Ormerod et al. 1997, Weinstein 1968).

2.5.3.2 Vibration

The skin is not only capable of detecting spatial details as discussed above but also capable of sensing vibration. The mechanoreceptor primarily responsible for vibration sensation is the Pacinian corpuscle, with the Ruffini cylinder also contributing to sense vibration in a minor way (Klatzky et al. 2003). Vibration applied by an electric toothbrush, mobile phone or lawnmower can be perfectly sensed by an individual through these special receptors underneath the skin. Moreover, there is an argument that textural properties are sensed through vibrotactile modalities, claiming that the sensed surface property is observed as a vibration. This theory was named the duplex theory and will be discussed further in the following section.

2.5.3.3 Texture

Current studies report that texture is sensed through mechanoreceptors (Skedung et al. 2011, Bergmann Tiest and Kappers 2006, Liu et al. 2008). Texture is usually assessed while stroking a finger on a surface such as wood or glass or even with the tongue on food to sense anything from fine grainy textures to much coarser ones. Texture sensation is critically important for food, especially because decisions on preference are made on the basis of texture along with taste. Studies in texture perception extend back to the beginning of the 20th century, with the development of psychophysics and an interest in perceptual mechanisms (Klatzky et al. 2003). In 1925, David Katz introduced the concept of texture perception as being dependent on spatial and temporal cues (Katz 1925). Spatial cues include size, shape and surface elements, such as particles, bumps and grooves, which is the texture we sense when we stroke a finger across a surface. Temporal cues denote the rate of vibrations that occur when sliding a finger on any surface such as sandpaper (Klatzky et al. 2003). The concept of perceiving texture through both spatial and temporal cues was called the duplex theory of texture perception. This theory has been supported by recent research by Mark Hollins (2000) and his team. They confirmed that the texture of fine surfaces can only be sensed when sliding a finger over it and creating a vibration. When the finger is not stroked and no vibration is created, then, only a slight difference can be sensed (of particle sizes between 10 mm and 100 mm) (Hollins and Risner 2000). This same research team also provided evidence that temporal cues are the major element of the texture perception of fine surfaces (Hollins et al. 2002). Thus, it would not be incorrect to say that temporal cues dominate the sensation of texture. This means that when we bite food or touch a food surface, we are able to sense its overall shape as well as surface properties that reflect its texture, along with structural properties such as softness or elasticity. Moreover, the duplex theory was found to be valid by Klatzky et al. (2003), even when a tool such as a knife or a chopstick was remotely used to handle the food with the tip of that tool. Texture sensation occurs through vibrations transmitted through that tool to our skin, but clearly, we sense this as the texture of the surface of the food rather than as a vibration (Carello and Turvey 2004).

Texture perception through the tactile sensation system during food consumption has similarities to that of the finger because the receptors do not show any morphological difference between a finger and the tongue. A unique attribute of oral mechanoreceptors is their ability to deliver a response under mechanical processes; in other words, they can transform information throughout the oral processing that continuously occurs during eating (Peleg 1980, Guinard and Mazzucchelli 1996). Current studies still do not focus on the oral perception properties of texture due to the challenges of systematic sensory testing. However, information about the oral tactile perception of texture is necessary to understand determinative factors for certain cases such as dysphagic patients.

2.5.3.4 Objects

We touch an object in two different ways: actively or passively. An active touch means moving a tool (such as cutlery) or touching a surface (such as with a finger or the tongue) in an active fashion. Most of our daily routine feeling of objects is considered to use an active touch (Klatzky et al. 2003). In contrast, passive touch refers to touching any surface in a static way. Studies have reported that an active touch is the more sensitive way for observing texture (Srinivasan and LaMotte 1995). Active touch has been mostly used in literature for haptic perception, i.e. the three-dimensional exploration of objects (Klatzky et al. 2003). During the sensation of objects, we use three distinct systems working in cooperation:

1. the sensory system, which involves sensation through cutaneous sensation such as touch, temperature and texture,
2. the motor system, which involves moving hands and fingers across the surface and
3. the cognitive system, which involves processing the information obtained by the sensory and motor systems (Klatzky et al. 2003).

These processes working together create a sensation with active touch, and the fact that active touch involves this process makes it possible to sense the features of an object. In a review, Gibson (1962) claimed that we relate to active touch as 'touching' and passive touch as 'skin experience'. For example, when an object is pushed onto our skin (passive touch), we feel a pricking sensation, and when we push an object with our finger (active touch), we feel the properties of the pointed object (Krueger 1970).

A study by Klatzky et al. (1985) illustrated that if an individual has a previous experience of an object, it takes only a few seconds to identify the object with haptic exploration under blindfolded conditions. Haptic exploration was observed to involve universally common distinctive hand movements by participants, which was called exploratory procedures (EPs) (Lederman and Klatzky 1987, Lederman and Klatzky 1990). These movements were also found to be related to the object's qualities that were being questioned (Klatzky et al. 2003).

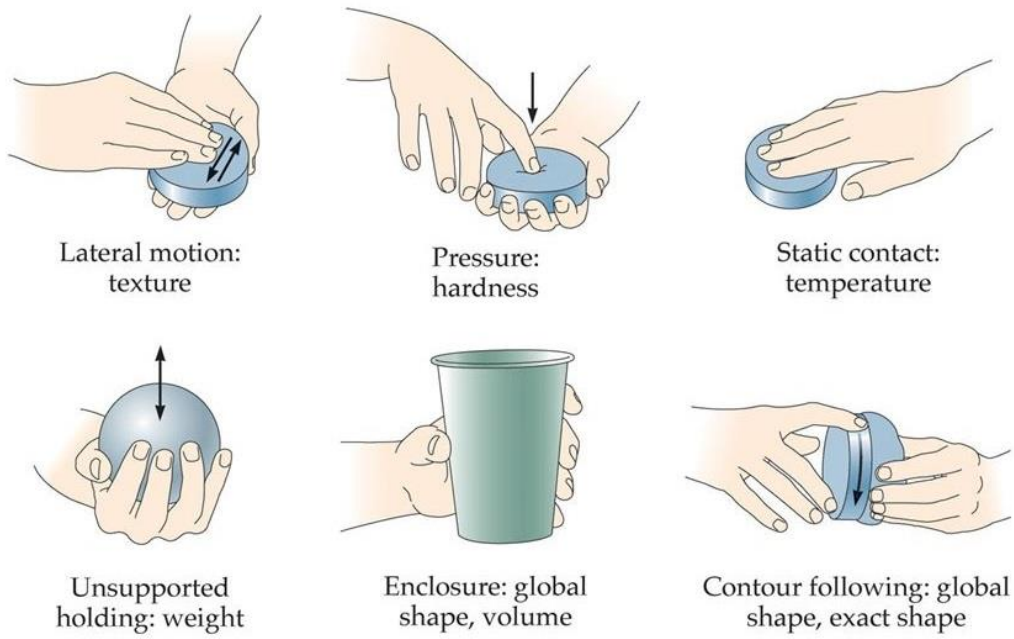


Figure 2.18 Exploratory procedures (EPs) observed from the participants (Lederman and Klatzky 1987, Lederman and Klatzky 1990).

Figure 2.18 illustrates exploratory procedures. These movements were found to be common between the participants obtaining information about texture, hardness, temperature, weight, shape and volume under blindfolded conditions.

Researchers have been trying to find out what happens physiologically in mechanoreceptors and neurons when we try to explore an object with our fingers and hands (Klatzky et al. 2003). For example, to succeed in opening a bottle of water, we need to obtain information about the size and contour of the lid and the amount of force it requires for grasping. Later, the information collected through exploratory procedures will transform into an action of twisting the cap of the bottle with sufficient force to open it because of the mechanoreceptors in the skin and neurons in the somatosensory cortex and parietal and frontal lobes (Klatzky et al. 2003).

In contrast, our experience with food is quite different because during oral processing, we use our tongue instead of a finger to sense the texture and overall shape of the food. If it is a hard food that requires biting, such as a biscuit, then, we need to establish the amount of force required for mechanical breakdown by the teeth. Once this force is determined, further mechanical breaking will occur with the involvement of the whole dental elements and jaw. During the oral process, we will continuously sense the texture of the biscuit, which will be constantly changing. The direction and magnitude of these forces of the oral elements during oral processing will be highly dependent on the food type.

2.6 Summary of the Literature and Literature Gap

In the present chapter, current status of the literature had been further reviewed. As a summary, recently texture studies have become more attractive to researchers, with especially defining the terminology, demonstrating physical and psychophysical measurements, and also understanding the relation between physical and psycho-physical measurements. In addition, the biological aspect of sensation has also been studied for the basic human senses and receptors. However, there are still untouched areas that will be studied in this study. Tactile sensation was shown as responsible sense for texture and there is consensus that this sensation system is governing the texture perception. However, there is no observed study showing that relationship between the tactile sensation and texture perception. Furthermore, in order to prove or disapprove that statement we need to answer:

- Which texture attributes must be tested?
- Which part of the human body should be used as a testing tool to understand food texture perception?
- Which methods can be used for measuring the texture physically and physiologically?
- What are the limitations of physical and physiological texture measurements?
- Which methods can be used for measuring tactile sensitivity?
- What are the limitations of tactile sensitivity assessments?
- Is there a direct relationship between the tactile sensation system and texture perception?

These listed questions will be answered in following chapters, which will be focusing on particular attributes and testing of texture perception and tactile sensation with the tongue and fingertip by using an instrumental assessment and pair-wise comparison sensory tests. The relationship between particular textural attributes and tactile sensitivity will also be investigated in order to illustrate the possible relationship.

Chapter 3
Viscosity Discrimination Capability and Touch Sensitivity

3.1 Introduction

Viscosity is the main textural property of fluids. For most people, liquid foods would usually be soup or beverages, but the situation is quite different for individuals for whom eating solid food is challenging, such as some elderly people, babies and mentally disabled people. These vulnerable people need to depend on liquid foods for their nutrition. In this regard, the oral behaviour of fluid foods is critical, especially when there is a risk of choking. Furthermore, increasing longevity has focused scientists' attention on the needs of the ageing population, with people who may be missing teeth or who have lost muscle capability and therefore need modified textured foods. Liquids and thickened liquids are frequently used to feed these people due to the reduced risk of aspiration by delaying the swallowing action (Robbins et al. 2002, Garcia et al. 2005, Logemann et al. 2008). However, the modification of liquid foods flow behaviour for safe swallowing and oral processing, it has not been supported with clear evidence (Steele et al. 2014). To establish the needs of these vulnerable individuals, we need to first clarify to what extent viscosity can be sensed, and the first step for this should be to consider healthy individuals' perception limits. These findings may then be used to predict an 'ideal' viscosity for food for the vulnerable people. Despite the medical need of understanding viscosity perception, a perception limit of viscosity is also important for the general understanding for food scientists and food manufacturers. Furthermore, texture sensation is an interesting topic for oral processing scientists, something that is not often states. Understanding the limits of texture sensation will allow the creation of a suitable model to obtain perception through calculation, avoiding the need for challenging sensory tests.

Viscosity is a poorly controlled attribute, with claims that there is a gap in the literature about viscosity control and its applications (Steele 2005). For this reason, in the present study, we approached the question minimally by assessing the perception limits of Newtonian fluid.

The viscosity of food has been found to have an effect during swallowing; therefore, we believe that it is important to understand the discrimination threshold of fluid samples. This would show how great a difference in viscosity is required to be perceptible. Such findings would be helpful for the medical food industry in producing special food for the vulnerable groups mentioned earlier. Additionally, they could ultimately be used by oral processing scientists in modelling oral perception limits.

Perception has been a popular area of research, and it is known that tactile sensation is responsible for texture perception. However, the oral perception of food has not yet been widely investigated, and to date, the oral perception of fluid properties has been investigated in only a handful of studies, with most studies reporting from a non-oral rather than an oral perspective (Steele et al. 2014). Studying the perception of textural attributes under oral and non-oral conditions is interesting and may eventually be used to replace sensory tests. In the present study, we tested the viscosity discrimination capability of the index fingertip and tongue, which represent non-oral and oral conditions, respectively. These findings will be important in establishing whether or not these two most sensitive parts of the human body have a similar tactile sensation. Following the confirmation of results by further independent studies, oral processing scientists would be able to correlate the results of sensory perception tests using the fingertip with estimated oral perception results, which may allow tests that would avoid the potential effects of other distracting properties of the sample such as taste, flavour or texture. This is also missing from literature. Reported viscosity perception studies have shown interesting results. For instance, studies by Smith et al. (1997) and Smith et al. (2006) investigated perception levels for Newtonian fluids of intermediate levels of viscosities (between 52 mPa.s and 202 mPa.s) and showed that increments of 2.6 and 3 fold were perceivable. Pangborn et al. (1978) showed that the oral perception of viscosity is related to the actual viscosity for gum-thickened fluids, which have a non-Newtonian character. Christensen (1979) used magnitude estimation techniques to evaluate the oral perception of sodium carboxymethyl cellulose-thickened fluids and obtained a power law with an exponent of 0.34–0.39 to represent the relationship between instrumental and perceived viscosities under a 100 s^{-1} shear rate, with a very high correlation. He also demonstrated that doubling the actual viscosity was perceived as a ten-fold increase. A similar approach was applied by Smith et al. (2006), who confirmed Christensen's power law exponent and also reported that perceived viscosity increases one-fifth as fast as the actual viscosity. They also reported that the viscosity discrimination capability was much lower for elderly participants. For that reason, in the present study, we excluded elderly subjects. A recent study by Steele et al. (2014), which tested the oral perceptual discrimination capability for xanthan gum-thickened non-Newtonian samples, reported discrimination of a 0.67-fold increase in apparent viscosity at 50 s^{-1}.

These studies, except those of Smith et al. (1997) and Smith et al. (2006), used non-Newtonian samples, where flow properties depend on the shear rate. When using a non-Newtonian sample, the main limitation will be the inconsistency of the oral shear rate. Even though there have been studies reporting the oral shear rate, it is still hard to generalise a specific figure for the shear rate. For instance, National Dysphagia Diet: Standardization For Optimal Care (2002), Felt (1999) and Wood (1968) claimed the tongue shear rate to be 50 s^{-1}., whereas Shama and Sherman (1973) claimed that it was 10 s^{-1}. To avoid multifactorial conditions that have already been presented in oral tests, we used Newtonian samples, where the oral shear rate would not have an effect on the sensed viscosity.

In the present study, we explored the viscosity discrimination capability of healthy individuals using Newtonian samples by progressively increasing the viscosity through increases in concentration. The decision to use golden syrup for the samples was motivated by its Newtonian character and also, as it is a well-known product throughout the world. Unlike honey, the properties of golden syrup are not dependent on the season of the year. The progressive increases of viscosity ranges were described in accordance with Weber's ratio calculation shown in Chapter 2. Our study used a simple pairwise comparison method by assessing the panellists' discrimination capability with their dominant hand index fingertip and tongue to compare oral and non-oral perceptions. The results were plotted, and the threshold value was selected as the just noticeable difference (JND) value for 50 % of the population's response (Meilgaard et al. 2011, Laing 1983, Chaplan et al. 1994, Clark and Mehl 1971).

Our objectives were as follows:

1. To establish the subjects' ability to correctly identify the change in Newtonian liquids viscosity with golden syrup by fingertip and tongue.
2. To establish the subjects' tactile sensitivity by the fingertip and tongue through a touch sensitivity test.
3. To establish whether the viscosity discrimination capability is determined by touch sensitivity.

3.2 Materials and Methods

3.2.1 Materials

Golden syrup is an amber-coloured inverted sugar solution usually processed from sugar cane or sugar beet. It is an alternative to honey and is mostly used in baking and desserts. Golden syrup was selected for this study due to its Newtonian character so as to eliminate the factor of shear rate differences between the subjects (Shama and Sherman 1973). In addition, golden syrup is a common and popular food ingredient used in the food industry and is well known by consumers around the world.

Lyle's Golden Syrup (Tate & Lyle, Nottinghamshire, UK) was purchased from a local supermarket. Throughout the experiments, it was stored in its original metal can container at ambient temperature. The syrup was diluted with distilled water at specific concentrations to obtain a range of viscosities, as shown in Table 3.1. Sample 1, with the lowest viscosity, was selected as the reference sample.

Table 3.1 Concentration range of the Newtonian golden syrup samples (* reference sample)

Sample Number	Actual Concentration (%)
1*	6.70
2	12.20
3	20.00
4	30.00
5	33.00
6	37.00
7	40.00
8	42.40
9	45.60
10	48.40

3.2.2 Methods

3.2.2.1 Rheological Properties of Golden Syrup

The flow behaviour of the golden syrup samples was examined using a shear dynamic rheometer (Malvern Instruments Ltd., Worcestershire, UK). The viscosities of the samples were obtained at 25 ^{o}C with double gap geometry (DG25 geometry). Each experiment was done in 3 replicates with the samples prepared from different batches, and the mean viscosity values were calculated.

3.2.2.2 Sensory Tests

3.2.2.2.1 Participants

For viscosity discrimination and touch sensitivity tests, 30 participants (16 females and 14 males) were recruited. The participants were non-smokers and had no medical complications, eating disorders, oral diseases or skin problems. The age range was 19 to 49 years, with a mean of 29.9 ± 9.0 years. The participants' mean body mass index (BMI) was 22.5 kg/m^2, which is classified as within the normal range according to the World Health Organization (World Health Organization 2015). Written informed consent was obtained from each participant as required by the ethical committee of the University of Leeds. During the initial introduction, the participants were informed of what would be involved in the task and were told to sign the consent form if they voluntarily agreed to participate. All tests were conducted in a designated sensory lab within the food science building at the University of Leeds.

Ethical approval of the research project was obtained from the faculty ethical committee (MEEC 12-013) (please see the Appendix A), and all test procedures followed the ethical rules and regulations set by the University of Leeds, UK.

3.2.2.2.2 Viscosity Discrimination Capability Tests

The aim of the viscosity discrimination capability tests is to establish the minimum difference in viscosity that can be detected. In the present study, the particular objective was to determine the viscosity discrimination capability of the general population using their dominant hand index fingertip and tongue. For this purpose, simple pairwise comparison tests were conducted. The actual viscosities and calculation of the viscosity ratio for the samples are presented in Table 3.2.

Table 3.2 Newtonian golden syrup samples actual viscosity values (mPa.s). Viscosity ratio (△I/I) of each sample was calculated by dividing the difference from reference (△I) to the actual viscosity of the reference sample (* reference sample)

Sample Number	Actual Viscosity (mPa.s)	Viscosity difference from the reference (mPa.s)	Viscosity ratio	Multiplication factor
	I	ΔI	$\frac{\Delta I}{I^*}$	$\frac{(\frac{\Delta I}{I})_n}{(\frac{\Delta I}{I})_{n-1}}$
*1	1.05	0.00	0.00	-
2	1.18	0.13	0.12	-
3	1.48	0.43	0.41	0.29
4	2.09	1.04	0.99	2.41
5	2.56	1.51	1.44	1.45
6	2.78	1.73	1.65	1.15
7	3.23	2.18	2.08	1.26
8	3.61	2.56	2.44	1.17
9	4.25	3.20	3.05	1.25
10	4.95	3.90	3.71	1.22

As outlined in section 3.2.1, the syrup samples were selected according to their viscosity values to obtain progressive increases within the samples. To control this increase, the multiplication factor between each sample was calculated. The mean multiplication factor was 1.42 ± 0.45, which meant that the viscosity values of the samples were increasing by a 0.42 fold (i.e. by 42 %).

The participants were informed about the definition of viscosity, using the word ‘thickness’ during the information session to avoid any potential complications from using scientific terms. For the assessment of viscosity discrimination, the samples were presented as a pair of a reference and a test sample. The same reference sample was continuously used throughout the task, and each test was performed using the fingertip (non-oral) and tongue (oral).

For the fingertip tests, the participants were blindfolded to avoid any visual cues about the samples. Approximately 0.2 ml of the syrup sample was placed with a disposable pipette on the dominant hand index fingertip, specifically at the inner pad of the finger. The participants were asked to apply shearing with the thumb without twisting their hand. Between samples, the fingertip and thumb were cleaned with an antibacterial wet wipe and dried with a paper towel. After each pair of tests, the participants were asked to answer the question of simple pairwise comparison: 'Are they the same or different in terms of thickness'?

For safety and convenience, the participants were not blindfolded during the tongue tests. Instead, the sensory booth was lit with red light to mask the colour difference between the samples. The participants were supplied with a cup of water to cleanse the mouth between the samples. Approximately 1 ml of sample was used, and the participants were asked to perform a simple pairwise comparison between the reference and test samples. The participants were instructed to deposit the whole sample on the middle of their tongue surface and to apply a shear against the hard palate to test the viscosity of the samples. It was not necessary to instruct them to apply a specific shear rate due to the Newtonian behaviour of the samples.

During the viscosity discrimination capability tests, the samples were arranged in ascending order of viscosity, although the participants were not informed of this. The tests were stopped when the third consecutive correct detection of viscosity difference was obtained, and the lowest viscosity value was taken as the participant's discrimination capability value. The cumulative responses of the participants were plotted for the calculation of the JND value, which was taken as the population's viscosity discrimination.

3.2.2.3 Touch Sensitivity Tests

Touch sensitivity is defined as the minimum amount of force that can be positively sensed by a particular skin surface. For the assessment of touch sensitivity, Semmes–Weinstein Monofilaments (SWM) Touch Sense® sensory evaluators were purchased from North Coast Medical Inc. (Gilroy, CA, USA) (Figure 3.1). The SWM kit contains 20 monofilaments with different target forces designed to provide a non-invasive evaluation of cutaneous sensation levels throughout the human body. The target force of the filaments ranges from 0.008 g to 300 g, and the intervals were designed as logarithmic intervals. According to the manufacturer (North Coast Medical Inc. 2013), the monofilaments provided a target force with 5% accuracy.

Figure 3.1 Semmes Weinstein Monofilaments (SWM) kit which consists of 20 different monofilament starting from 0.008 g force up to 300 g increasing with logarithmic increments.

Similar to the discrimination tests, touch sensitivity was assessed on the dominant hand index fingertip and tongue surface. The participants were blindfolded to avoid any visual cues. They were instructed to sit in a comfortable position. For the fingertip tests, they were asked to put their arm on the bench and keep the hand in a relaxed position with the index fingertip open and ready for the tests. For the tongue tests, they were instructed to open their mouth and stretch their tongue outside the mouth in the most comfortable position. The touch point was carefully selected at the front central position approximately 1.5 cm from the front tip for the tongue and on the tip of the index finger. The filaments were designed to apply the targeted force when compressed perpendicular to the surface until bowed for approximately 1.5 s. The test principle is illustrated in Figure 3.2. During the tests, the participants were asked to give a sign (a sound or hand movement) when a touch was detected. The tests were initiated with a monofilament applying 1 g of force and were then continued in descending order towards the lowest available force of 0.008 g. When the participant failed to detect two consecutive monofilaments, the test was stopped, and the lowest detected force level was taken as the participant's touch threshold. For reasons of hygiene, the monofilaments were cleaned with antibacterial wet wipes between the tests.

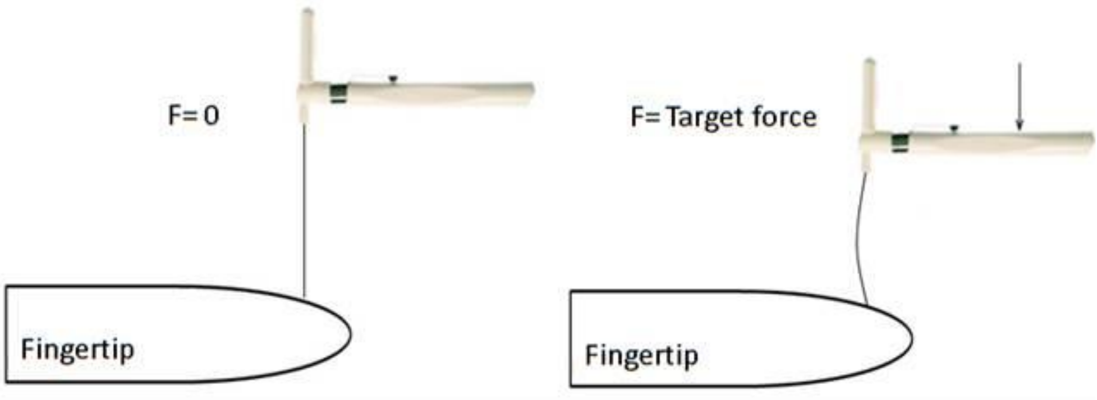


Figure 3.2 Illustration of the principle for the touch sensation tests. Force was applied in perpendicular to the test surface. Before pressing the actual force was 0. With the pressing action actual force rises up to the target force of that particular monofilament when bended.

3.2.2.4 Statistical Analysis

The data obtained from the experiments were statistically analysed using XLSTAT 2014.3.04 statistical software (Microsoft, Mountain View, CA, USA). The data that were tested for threshold values were log-normal (probit analysis) fitted within confidence intervals to obtain the JND values. The Mann–Whitney U-test was selected to be the most appropriate according to the sensory data to test the differences between the sensory experiments. A p-value of 0.05 was set as the significance level. Microsoft Excel was used to obtain the mean, median, standard deviation and coefficient of determination (R^2) values for age and BMI.

3.3 Results and Discussion

3.3.1 Viscosity Discrimination Capability

Figure 3.3 shows the data obtained from the sensory test to determine the viscosity discrimination capability with Newtonian fluid samples on the index fingertip (Figure 3.3a) and tongue (Figure 3.3b) as cumulative population distributions plotted against the logarithm of viscosity ratio to obtain the population threshold.

The general practice for finding the threshold value is to use the value at the 50th percentile in the accumulated population distribution, referred to as the population threshold (Lawless and Heymann 1998). Based on this approach, the graphs were plotted with probit data analysis, which is log-normalisation analysis that shows the best fit and calculates the median value. According to the analysis, the viscosity discrimination threshold was found to be 41.5 % for the fingertip (Figure 3.3a) and 32.0 % for the tongue (Figure 3.3b). These values show that to obtain distinctive viscosity levels, the viscosity needs to be increased by 0.42 and 0.32 fold for the fingertip and tongue, respectively, which suggests that the tongue has a higher sensitivity for detecting changes. This difference in the viscosity discrimination capability was statistically significant ($p = 0.027$).

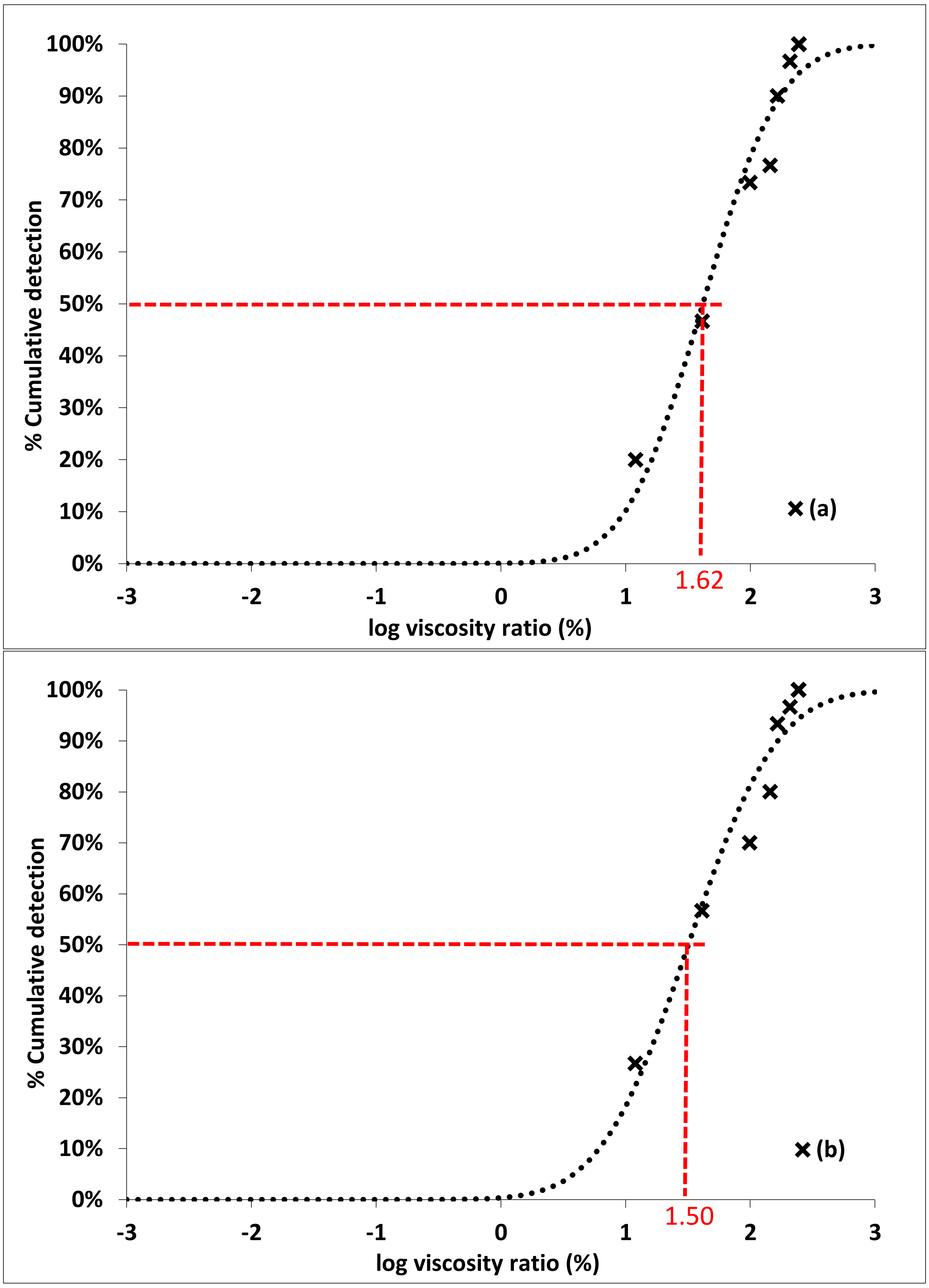


Figure 3.3 Log-normal best fitted (probit analysis) cumulative response of the individuals (n = 30) shown as population percentage against the logarithm of the viscosity ratio (%); (a) the fingertip ($10^{1.62}$ = 41.5 %), (b) the tongue ($10^{1.50}$ = 32 %)

The main reason for the tongue being more sensitive at viscosity discrimination than the fingertip may be the tongue's greater overall experience with foods throughout life. The result may therefore be due to experience and learning about food texture. This concept raises the question of whether texture sensation is an innate or experienced attribute. Texture sensation dynamics might be dependent on culture, which emphasises the possibility of it being a learnt property while based on the innate senses of tactile sensation. However, there is still an absence of solid evidence about the proportion of texture perception capability that is learnt or innate.

The differences in viscosity were only detectable above increases by 0.42 and 0.32 fold. Extrapolating these values of multiplication to viscosity ranges beyond those tested in our protocol suggests an opportunity to calculate discriminate values for healthy adults for any levels of viscosity. For instance if 5 mPa.s is used as the viscosity value for a reference food sample then it would need increments of 7.1, 10.1, 14.3 and 20.3 mPa.s with the fingertip and 6.6, 8.7, 11.5 and 15.2 mPa.s with the tongue, to create perceptible differences. These values could provide a hypothesis for future researchers, perhaps in the cosmetics or food industry, to confirm these thresholds with Newtonian samples.

Another interesting question was whether there is a difference between genders and age groups. In this study, our aim was to observe a general threshold value for healthy adults; therefore, we selected the participants from a narrow age range. Descriptive statistics (mean value and 95 % confidence intervals) of the results according to gender are shown in Table 3.3.

Table 3.3 Descriptive statistics for mean Newtonian viscosity discrimination capability tests, which shows the mean, standard deviation and 95 % confidence interval lower and upper bound values for female and male participants (n = 30, 16 females and 14 males).

Group	Viscosity discrimination (%)		Standard deviation		95 % confidence interval			
					Lower bound	Upper bound	Lower bound	Upper bound
	Fingertip	Tongue	Fingertip	Tongue	Fingertip		Tongue	
Female	26.90	24.40	2.50	2.80	21.50	32.30	18.50	30.30
Male	24.70	24.00	2.50	2.40	19.20	30.20	18.80	29.30
Overall Mean	25.90	24.20	1.80	1.80	22.20	29.50	20.50	28.00

These indicate no significant difference between genders, suggesting that texture sensation limits are not dependent on gender.

3.3.2 Touch Sensitivity

Figure 3.4 shows the data from the sensory test with SWMs on the fingertip (Figure 3.4a) and tongue (Figure 3.4b) in the form of population distributions. Threshold values were obtained according to the approach described in section 2.3.1. The participants were not able to detect the lowest available force (0.008 g) in this technique. Based on the 50th percentile approach for the threshold calculation, touch sensation was found to be 0.032 g force on the fingertip (Figure 3.4a) and 0.022 g force on the tongue (Figure 3.4b).

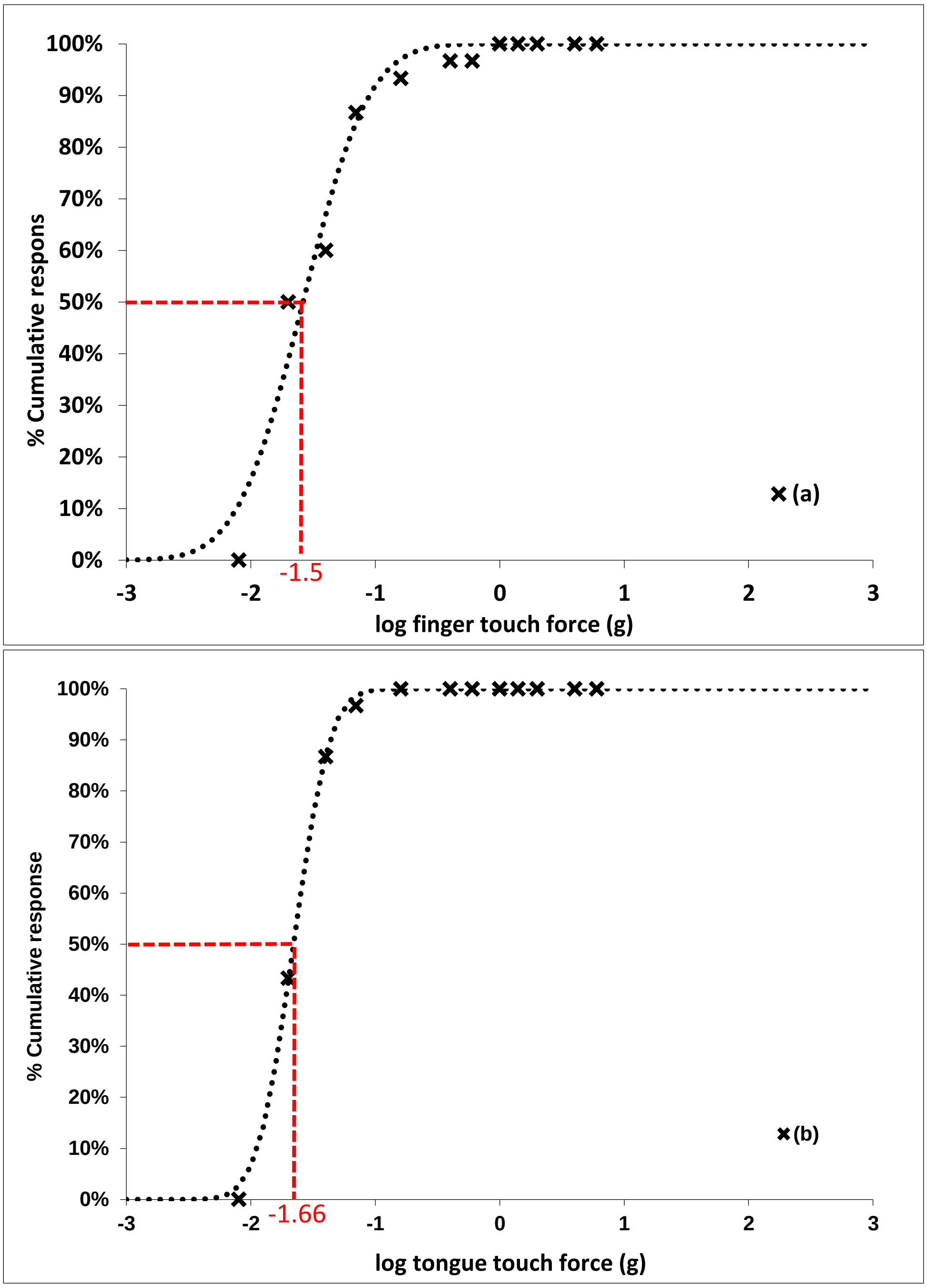


Figure 3.4 Log-normal best fitted (probit analysis) cumulative responses of the individuals (n = 30) shown as population percentage against the logarithmic touch sensitivity force (g);(a) the fingertip [median: $10^{-1.5}$ = 0.032 g, (between 0.03 to 0.09 g)], (b) the tongue [median: $10^{-1.66}$ = 0.022 g, (0.02 to 0.05)].

Touch sensitivity between the oral and non-oral surfaces was found to be similar. As described earlier, touch sensitivity was assessed with SWMs on the fingertip and tongue surface, a standard method for the determination of touch sensation capability (Jerosch-Herold 2005, Bell-Krotoski and Tomancik 1987).

However, this technique has been reported to be unreliable for neurological assessments. The use of SWMs was chosen for the present study as it provides a reliable, non-invasive, quick and easy method for establishing touch sensation for general purposes (Lundborg 2000, Schreuders et al. 2008). The technique has been applied to most parts of the body to provide a sensitivity map of the human body. However, there is a gap in literature about the touch sensitivity of the human tongue. The present study aimed to fill this gap by finding the tongue's touch sensitivity and comparing it with that of the fingertip. The reason for selecting the fingertip for comparison was due to its characterisation as the most sensitive tactile part of the human body (Schmidt 1986). Furthermore, the fingertips and the tongue are the only parts of the body used for the tactile detection of food materials; while the tongue is undeniably the organ most used in the textural sensation of food, the fingertip is the part of the body most used for tactile sensation in general.

The statistical analysis showed no significant difference of touch sensitivity between the tongue and fingertip (p = 0.598). However, the distribution of the data for the fingertip and tongue showed some dissimilarity between them. The distribution of the collected thresholds was between 0.2 and 0.4 g force for the fingertip, whereas the tests on the tongue showed a distribution only between 0.2 and 0.16 g force. This visually observed difference between the fingertip and tongue suggests that within a population of healthy adults, the touch sensitivity of the fingertip covered a wide range, while that of the tongue was over a much narrower range. One possible explanation could be that touch sensitivity varies across parts of the body. Alternatively, this visual difference could be due to individual differences and lifestyle. Individual physiological factors such as the density of mechanoreceptors in a particular area are believed to affect sensation. Individual differences in physiology or lifestyle could affect skin condition and cause gradual wear of or damage to the skin surface

Another investigation was the potential for touch sensitivity difference between genders. Descriptive statistics (mean and 95% confidence intervals) for the participants are shown in Table 3.4. These suggest that gender does not affect touch sensitivity.

Table 3.4 Descriptive statistics for mean touch sensitivity including the mean, standard deviation and 95 % confidence interval lower and upper bound values for female and male participants (n = 30, 16 females and 14 males).

Group	Touch sensitivity (g)		Standard deviation		95 % confidence interval			
					Lower bound	Upper bound	Lower bound	Upper bound
	Fingertip	Tongue	Fingertip	Tongue	Fingertip		Tongue	
Female	0.06	0.03	0.01	0.01	0.03	0.08	0.02	0.04
Male	0.06	0.05	0.03	0.01	0.01	0.12	0.02	0.07
Overall Mean	0.06	0.04	0.01	0.005	0.03	0.09	0.02	0.05

The threshold values obtained in these experiments show considerable similarity to those available in literature. The touch sensitivity threshold of the index fingertip reported by Joris Hage et al. (1995) was given as a range from 0.008 g to 0.6 g force. Similarly, Gillenson et al. (1998) reported the threshold as the range from 0.008 g to 0.07 g force. This correspondence between literature and the findings of the present study supports the reliability of the approach used for touch sensitivity. Unfortunately, there are no confirmed reports about the touch sensitivity of the tongue, but the results of the present study show that the tongue has at least the same touch sensitivity as the fingertip.

3.3.3 Viscosity Discrimination and Touch Sensitivity

This study was triggered by the objective of establishing the determinative factor for viscosity discrimination. As reported by previous studies, tactile sensation was found to be responsible. With this in mind, it was hypothesised that an individual with greater touch sensitivity has a better textural discrimination capability, but to date, no evidence for this has been reported. For this reason, we tested tactile sensation (touch sensitivity) and the viscosity discrimination capability on the two most sensitive parts of the human body, the fingertip and tongue. The results for viscosity discrimination and touch sensitivity were analysed for possible correlations.

As can be seen from Figure 3.5, the relationship between the capability for viscosity discrimination and touch sensitivity of the fingertip (Figure 3.5a) and tongue (Figure 3.5b) substantially varies between individuals, resulting in low correlation coefficient values (finger touch sensitivity and viscosity discrimination capability R^2 = 0.01 and tongue touch sensitivity and viscosity discrimination capability R^2 = 0.03). This disproves the hypothesis of possible correlations between the two tests. According to these findings, it can be concluded that touch sensitivity does not have a significant relationship to the viscosity discrimination capability for Newtonian fluids.

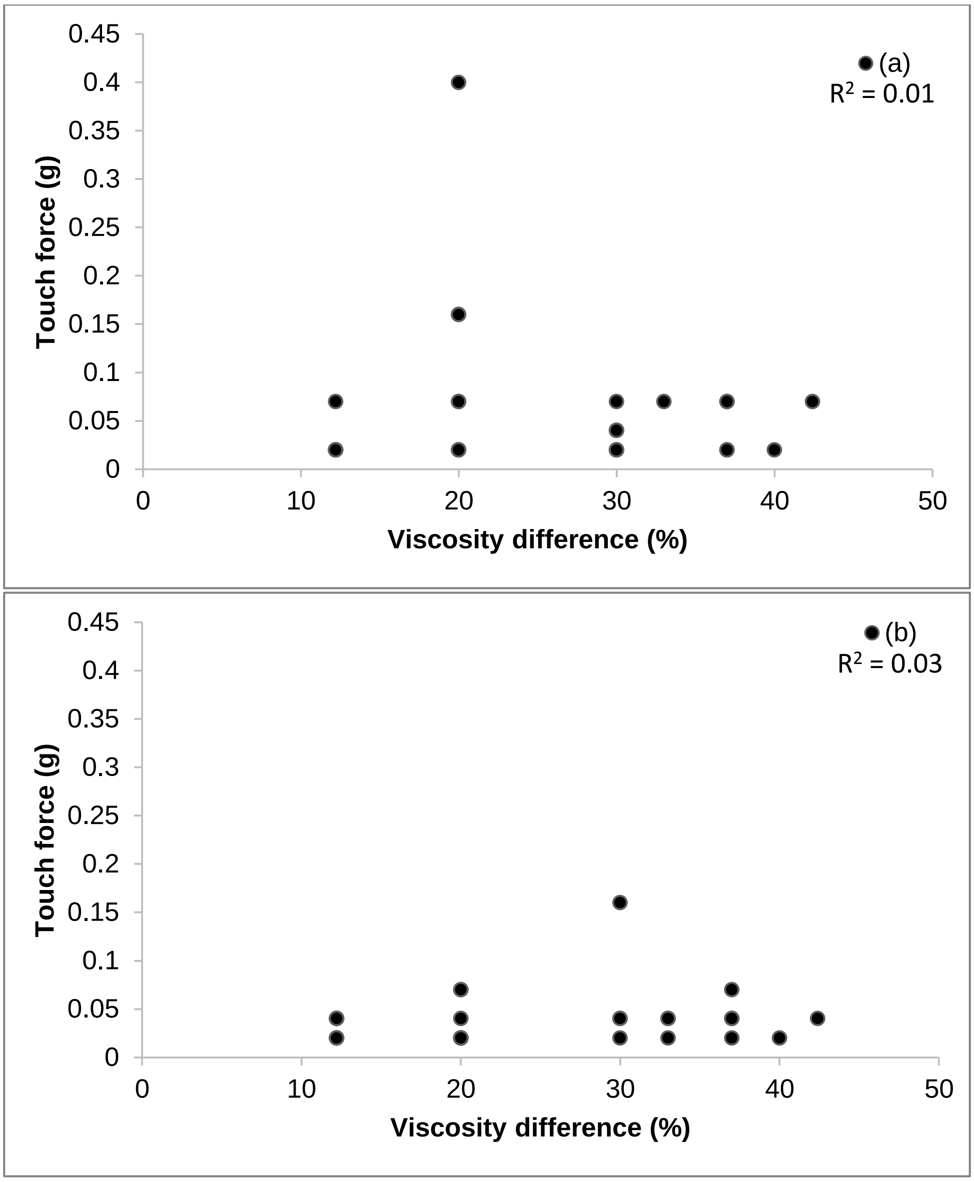


Figure 3.5 Individual's (n = 30) capability of viscosity discrimination capability against the touch sensation; for fingertip (a) and for the tongue (b).

The high variation in viscosity discrimination between the participants could be due to the complicated process of sensation and perception. Moreover, the main corresponding sensation has not yet been established: 'Is viscosity sensation a physiological or a psychophysical driven attribute?' (Guinard and Mazzucchelli 1996). This question can be interpreted as, 'Is viscosity perception innate or learnt'? as asked earlier. We believe that the answer to this question should be both: we have received the tactile receptors genetically from our ancestors, but we experience and learn different textures throughout our life. Inborn receptors responsible for tactile sensation are still not specified for texture as for taste and aroma due to their greater complexity. In another words, apart from knowing that texture sensation is driven by mechanoreceptors, the mechanisms behind the operating receptor or receptors remain unknown. Furthermore, there is no direct correspondence of instrumental textural properties and human sensation that could simplify the process for understanding the mechanism responsible for texture sensation

3.4 Limitations

The results should be interpreted in the context of acknowledged limitations. First, the findings represent the perception of viscosity difference achieved through changing the concentration of Newtonian syrup fluids. Therefore, the findings may not be generalizable to the viscosity discrimination capability for other fluids, even Newtonian, because their sensory properties may differ. Noteworthy Newtonian fluids are not common as food products. Shear rates in the mouth may vary, which will affect the apparent viscosity for non-Newtonian samples.

More importantly, regardless of the flow property, viscosity is dependent on temperature. This study was conducted at room temperature. However, during sensory testing, the temperature on the skin surface and tongue, generally accepted to be 37 °C and 32 °C, respectively, was not controlled (Engelen 2012). Viscosity may show variation within the instrumental analysis and sensory findings of viscosity discrimination.

A purpose of this study was to determine the viscosity discrimination capability and to investigate whether it correlates with touch sensitivity. Although care was taken to minimise the influence of distracting factors, it was not entirely possible to eliminate all cues other than viscosity. The samples selected for this study were syrup solutions with varying concentrations used to control the viscosity because we aimed to test Newtonian samples. However, using greater concentrations of syrup to increase viscosity resulted in increased sweetness, which may have been a potential distraction in judging relative viscosity. Ideally, future studies should use taste-matched sample systems involving small increments, preferably under temperature control.

In addition analysed results were obtained from a group of participants (N = 30) who recruited in these tasks, therefore the reported values were limited with these individuals.

Another limitation was due to the instrument (SWM) used for touch sensitivity measurements. SWM assesses touch sensation based on force detection rather than pressure (stress), which could cause bias during touch sensitivity assessments. The pressure applied by the monofilaments varies due to the range of different diameters each monofilament has. To minimise this bias, the diameters of the monofilaments were measured. The smallest monofilament (0.008 g) had a diameter of 0.02 mm, whereas the largest detected threshold monofilament (0.6 g) had a diameter of 0.2 mm. According to literature, both extremes were lower than the threshold of human capability for space discrimination using the fingertip, which is 2 mm (Schmidt 1986).

Our findings reveal some interesting implications. Firstly, viscosity can be controlled to create detectable/undetectable food rheology with Newtonian samples. For instance, in the food industry where there is a need to control the texture of a particular product, the ingredients have to be adjusted to control the rheology. By changing the amounts of those ingredients (i.e. thickeners) below the detection threshold, this should not lead to rejection of the product. Additionally, the findings may be useful for food manufacturers producing specific foods for vulnerable individuals (dysphagic patients, elderly individuals, etc.). They can design the ingredients of their texture-controlled foods according to the threshold values to result in sensible or insensible thickness. The cosmetic industry also uses viscosity as their determinative attribute for the acceptability of many products. Because the present study showed the threshold for fingertip discrimination capability for Newtonian fluids, the cosmetic industry could potentially use that value to change the perceived rheology. Methodologies used in this experiment could also provide useful information for oral processing scientists to design further studies on texture perception phenomena.

3.5 Conclusion

Table 3.5 summarises the results of this work.

Table 3.5 Experimental findings observed from the participants (n = 30) for the viscosity discrimination threshold values (%), touch sensitivity (g) and the calculated correlation coefficient between these two experiments (R^2).

	Viscosity discrimination threshold (required perceptible change)	**Touch sensitivity threshold (g)**	**Correlation between the viscosity discrimination threshold and touch sensitivity**
Fingertip	41.50 %	0.032 g	No correlation
Tongue	31.95 %	0.022 g	No correlation

Although there has been a common assumption that there is a correlation between touch sensitivity and texture discrimination, our results do not prove such a relationship. Assuming this lack of correlation is confirmed by future independent research, possible reasons for the finding are listed according to a logical approach. Initially, viscosity is an attribute sensed by the application of shearing between parallel surfaces (e.g. thumb to index fingertip). Touch sensation testing requires perpendicular static compression of the applied forces. Therefore, dynamic and static actions may not have a clear relationship between them due to the different nature of the stimuli. Mechanoreceptors in the human body are of different types, with each responsible for a different kind of stimulus. The touch and viscosity discrimination tests may also have different receptors responsible for them.

Therefore, those new findings still requires to be approved or disproved by independent researchers for viscosity. In addition, it is still essential to carry out similar systematic approaches with other textural attributes with different kind of food systems.

Chapter 4
Firmness Discrimination Capability and Tactile Sensitivity and Correlations with Muscle Capability

4.1 Introduction

Previous findings have shown that the viscosity of simple fluids is not directly perceived by tactile senses. To take that concept a step further, other textural attributes can be investigated; in the present study, firmness was selected for this. The reason for selecting firmness was our ambition to use more popular food samples of food gels instead of uncommon Newtonian fluids. Firmness can be defined as the resistance to yield during the compression of a sample (Brown et al. 2003). Firmness is often used for describing a quality attribute of foods, where it can be defined as resistance to yielding (crushing or breaking) when food is compressed by the application of deformation, as observed by machinery (Szczesniak and Bourne 1969). The firmness properties of soft food samples are determinative factors for preference. For example, fudge is usually purchased due to its taste and also for its texture (firmness).

Firmness has been instrumentally measured using a few different techniques based on deformation, puncture, a penetrometer or the shearing principle (Szczesniak and Bourne 1969). Deformative firmness is a technique where a food sample is compressed under a standard force, and the distance compressed is used as an index of firmness. Deformative firmness measurements have been performed by a number of investigators on various foods including cheese by Blair and Coppen (1941); snap beans, peas, sweet corn and apples by (Bourne 1982); tomatoes by Hall (1964) and Oliveira et al. (2015); bread by Cornford (1963) and Ponte et al. (1962); strawberries by Haller et al. (1932) and Rose and Nelson (1954); raspberries by Nybom (1962); fresh potatoes by Bourne and Mondy (1967) and apples by Paoletti et al. (1993). Another approach to firmness is to use puncture tests, which cause irreversible crushing of samples and measure the force required for the puncturing process as an index of firmness (Szczesniak and Bourne 1969). Puncture tests that have been applied to various food samples including processed apples by Esselen et al. (1967); strawberries by Haut (1935), Døving et al. (2005) and Døving and Måge (2002); tomatoes by Jackman et al. (1990); berries by Khazaei and Mann (2004) and sour cherriesby LaBelle and Woodams (1964). A third approach has used penetrometer tests where a probe is sunk a certain distance into the sample with a certain force, and the time value obtained is used as a measure of firmness. Penetrometer firmness assessments have been made by the following: Wearmouth (1952) for Cheddar cheese; Delwiche and Sarig (1991) for peaches, pears and apples and Valente et al. (2009) for mangos. Another type of firmness assessment uses the shearing principle used for various products including cheese curd by Emmons and Price (1959) and Voisey and Emmons (1966) and cooked spaghetti by Voisey (1975). In addition, the resonant sonic technique for firmness measurements is commonly used due to its non-invasive nature. Sonic measurements have included investigations by De Belie et al. (2000) for pears, Valente et al. (2009) for mangos and Abbott et al. (1995) for apples.

As well as the instrumental measurements of firmness, a sensory correlation of physical values has been assessed for numerous samples. The most common practice for sensory firmness assessment has used few samples and has investigated perceived values by comparison. In literature, firmness has been tested under both non-oral and oral conditions. Some studies in this domain include those on milk proteins by Modler et al. (1983), fish by Hurling et al. (1996), apples by Finney (1971) and peaches by Thai and Shewfelt (1990).

The perception of the sensed texture can be defined as the feedback obtained through the basic senses, both inherent and arising from expectations based on preconceived experience learnt by testing different foods (Foegeding et al. 2011). However, throughout the development of machinery and sensory techniques to measure firmness, the aforementioned principles have not been proved to correlate with the perceived firmness (Szczesniak and Bourne 1969). Instrumental techniques for texture assessments are well developed in terms of physical measurements; however, due to the lack of correlations, it remains unclear how these physical values are sensed (Foegeding et al. 2011, Guinard and Mazzucchelli 1996, Lawless and Heymann 1998, Meilgaard et al. 2011). However, a correlation between food structure and perception limits would provide knowledge to food scientists and also to the food industry, which is needed to confirm quality across different batches.

To understand the physical attributes of perception mechanisms, we need to understand which senses are involved. Physiological studies are already in agreement that texture must be an attribute that is sensed by mechanoreceptor(s) in the tactile system. However, the various receptors that are the most dominant have still not been established by experimental results (Kilcast and Eves 1991). To investigate the texture perception mechanism, it is necessary to understand the particular roles of mechanoreceptors. Once obtained, this understanding can be transformed into a mathematical model that can then estimate a physical value, a method more economical in terms of investment and time.

This work was conducted as a complementary task to the previous study on viscosity sensation to understand whether firmness perception is determined by tactile senses. Additionally, certain muscles' capabilities were investigated, and their correlation with firmness discrimination capability and tactile sensitivity was analysed. Similar to the work discussed in the previous chapter, this study was not hypothesis-driven but more exploratory. Instead of a defined hypothesis, tests on food firmness were designed with the aim of answering the following questions:

1. What is the perception threshold of relative firmness for non-oral (fingertip) and oral (tongue) surfaces?
2. What are the non-oral and oral tactile sensation [touch sensitivity and two-point discrimination (2PD)] limits?
3. What is the role of tactile sensation on firmness discrimination capability?
4. Does muscle capability influence texture sensation and touch sensitivity?

4.2 Materials and Methods

4.2.1 Materials

As described above, the firmness discrimination capabilities were assessed with semi-solid food samples that were prepared with an instant gel powder consisting of carrageenan and locust bean gum (Vege-gel, Dr.Oetker Ltd. Bielefeld, Germany). Gels were selected as a semi-solid food sample for this study due to their popularity and easily controllable preparation method, which allowed the control of textural properties. Moreover, their use gave the option of avoiding substances with taste, aroma or colour that might affect the sensory assessment of firmness.

Prior to each sensory session, fresh samples were reconstituted in a range of concentrations (Table 4.1) to achieve different firmness (breaking hardness) levels. The gels were prepared by adding distilled water to a specified amount of gel powder and were brought to boiling point to induce gelling behaviour. The hot mixture was then transferred into a cubic mould with the dimensions $1.8 \times 1.5 \times 1.5$ cm, as shown in Figure 4.1. To cool the samples to room temperature, they were stored for 2 h at ambient temperature and were then moved into a refrigerator (4 °C) for 12 h. After that time, they were moved back to room temperature and stored for another 2 h to bring them to thermal equilibrium for the test. This helped avoid temperature differences.

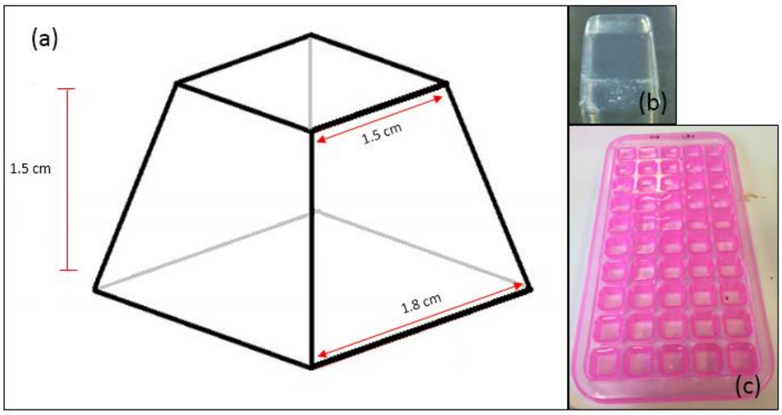


Figure 4.1 Semi-solid food sample illustration with the dimensions and real images. (a) Illustration of the dimensions in 3D image, (b) real image of single gel sample, (c) real image of the gel mould used for sample preparation.

Table 4.1 Concentration range of the semi-solid (vege-gel) samples (*reference sample).

Sample Number	Actual concentration (%)
1*	1.70
2	1.80
3	1.87
4	1.92
5	1.99
6	2.05
7	2.11
8	2.16
9	2.22
10	2.40

4.2.2 Methods

4.2.2.1 Texture Analysis of the Gel Firmness

Gel samples were assessed for their firmness (braking hardness) using a TA-XT Plus texture analyser (Stable Micro Systems Ltd., Surrey, UK). For this purpose, compression tests were conducted at room temperature (25 °C) using a flat-ended, 40-mm diameter cylindrical aluminium probe. Compression tests were conducted at a speed of 2 mm/s, and the peak force required for breaking the sample was taken as the firmness (Alsanei et al. 2015). Each sample was tested five times, and the mean value was calculated as the firmness.

4.2.2.2 Sensory Tests

4.2.2.2.1 Participants

Thirty-two participants (15 females and 17 males) were recruited. All were non-smokers with no reported medical problems, eating disorders, special diets, oral diseases or skin diseases to avoid bias from these. The age range was 21 to 62 years (mean 34 ± 9 years) and the mean body mass index (BMI) was 23 ± 3 kg/m^2.

Prior to the session, each individual was informed about the concept of the tests but not the specific purpose of the investigation and was asked to give written consent. The tests were conducted in the sensory lab in the school of food science and nutrition building. Ethical approval was obtained from the ethical committee of the University of Leeds, UK (MEEC 12-013), and all tests followed the ethical rules and regulations of the university.

4.2.2.2.2 Semi-Solid Firmness Discrimination Capability Tests

Semi-solid gel firmness was defined as the resistance perceived during compressing a sample to its breaking point (Brown et al. 2003). The procedure of the sensory tests was simple pairwise comparison using the just noticeable difference (JND) method to obtain the threshold value of firmness discrimination.

Figure 4.2 Sample presentation to the assessors. 9 paired samples (reference sample and test sample) in increasing range of firmness.

Semi-solid firmness discrimination experiments were conducted for the tongue and fingertip. Samples were assigned a random three-digit code and were presented in ascending order of firmness values, although the participants were not informed about this order (Figure 4.2). Each participant was personally assisted throughout the whole session and was given general information about the terminology of firmness/breaking. Each sample was paired with a control sample that was used throughout the task. The participants were asked to compress and break the pair of gels either with their dominant index fingertip or in their mouth using their tongue. The participants were required to state whether each pair of samples was the 'same' or ‘different’. The task was stopped when three consecutive ‘different’ answers were reported, and the first detected different sample of these three was noted as an individual’s threshold. During the fingertip discrimination tests, the fingertip was wiped between each sample with wet tissue and then dried with a paper towel. Similarly, during the tongue discrimination tests, the participants were asked to rinse their mouth with water between tests.

4.2.2.3 Tactile Sensitivity Tests

In addition to the texture discrimination task, the tactile sensitivity of the participants was examined by two different measurements: touch sensitivity and two-point discrimination (2PD). Similar to the previous procedures, tactile assessments were performed on the fingertip and tongue. Prior to the tests, the participants were blindfolded and were asked to sit in a comfortable position. For the fingertip tests, the participants were asked to place their dominant hand on the bench in a way such that their index fingertip was available, and the test was applied to the middle of the top finger pad. For the tongue tests, the participants were asked to open their mouth and extend their tongue out in a relaxed position; the test was applied to a front central position, approximately 1.5 cm from the front tip of the tongue.

4.2.2.3.1 Touch Sensitivity

Touch sensitivity was assessed in this study as a part of the tactile sensitivity tests. It was measured using Semmes–Weinstein Monofilaments (SWMs) purchased from North Coast Medical Inc. (Gilroy, CA, USA), a common technique for touch sensitivity assessment, to determine the minimum force that could be detected by the participant (the touch sensitivity threshold) (Wiggermann et al. 2012). The test protocol was similar to that used in the previous study, but in the present study, forces were applied in ascending order rather than descending. The main reason for this methodology change was feedback from the previous study’s participants about fatigue caused by greater forces. Therefore, in this and the following studies, we used forces in an ascending order starting from 0.008 g and stopping when the participant experienced sensible forces for three consecutive monofilaments. During the touch sensitivity tests, a monofilament was pressed perpendicular against the test surface (fingertip or tongue) until the filament bowed and was kept still for

1.5 s. The lowest force sensed was taken as the touch sensitivity threshold for the participant. Between the tests, the monofilaments were wiped with antibacterial wet wipes.

4.2.2.3.2 Two-Point Discrimination Tests

2PD was examined using a disc-shaped instrument (shown in Figure 4.3), which is used for testing spatial acuity by measuring the narrowest distance between two pressure points that can be distinctively sensed (Cholewaik and Collins 2003, Craig and Lyle 2001). For this purpose, a Touch-Test® two-point discriminator sensory evaluator (Figure 4.3) was used, which was purchased from North Coast Medical Inc. (Gilroy, CA, USA), with a range of distance between the pressure points from 0.25 mm to 15 mm.

Figure 4.3 Two-point discriminator, used to assess the threshold distance for the sensation of two different points touching.

The test protocol is illustrated in Figure 4.4. The discriminator was perpendicularly pressed onto the skin for at least 1.5 s in a static manner with various gaps between the two pressure points.

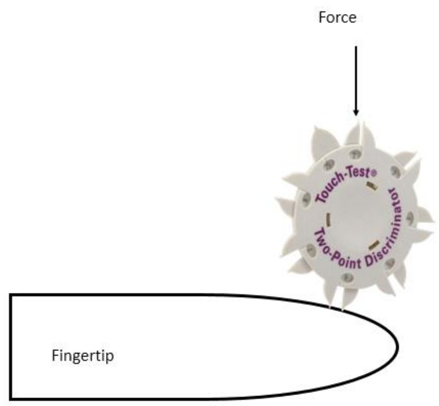


Figure 4.4 Illustration of two-point discrimination testing protocol on the fingertip surface.

During the tests, the participants were blindfolded to avoid any visual cues, and they were asked to report how many touching points they sensed. The tests were initiated at a distance between the points of 8 mm, and this was reduced towards 0.25 mm, until the participant could no longer detect two distinct touches. When the participant reported sensing a single point three consecutive times, the test ceased, and the smallest reported distance was noted as the participant's threshold value. However, some of the participants reported that they could sense the narrowest gap (0.25 mm) as two individual touches, which should be highlighted as a main limitation of the technique. Between each application, the two-point discriminator was cleaned with an antimicrobial wipe.

4.2.2.4 Muscle Capability Tests

As well as the assessment of tactile sensitivities, selected muscles' capabilities were tested to obtain its possible relationship with the texture discrimination tests. In particular, muscle capability tests were divided into two main parts: oral tests (on the tongue) and non-oral tests (of the hand/finger). The oral test used the measurement of the maximum isometric tongue pressure (MITP), which is believed to indicate the triggering force for chewing, compressing and swallowing (Alsanei and Chen 2014). For the non-oral tests, we measured the finger grip and hand grip capabilities, which have been found to be important during eating especially while opening a food package, using cutlery or transferring food from the plate to the mouth (Laguna et al. 2015).

The purpose of these tests was that a possible correlation between the muscle capability and texture perception could provide useful information, especially for converting muscle capability to the predicted perception magnitude for the textural attribute.

4.2.2.4.1 Maximum Isometric Tongue Pressure Tests

MITP is defined as the maximum pressure that can be applied by the tongue. It was measured using an Iowa Oral Performance Instrument (IOPI Model 2.2, Medical LLC, IOPI Medical, Carnation, WA, USA) (Figure 4.5a). IOPI is a medical instrument developed for the assessment of patients going for rehabilitation. It requires a disposable tongue bulb (Figure 4.5b), which is connected with a thin tube to a simple pressure transducer to record the change in the air pressure during the compression of the tongue against the hard palate (Ono et al. 2009). During the tests, the participants were asked to place the bulb in the middle of the oral cavity between their tongue and hard palate and apply as much pressure as they could. The tests were repeated five times for each participant, and between the tests, a few minutes were given for the relaxation of the tongue.

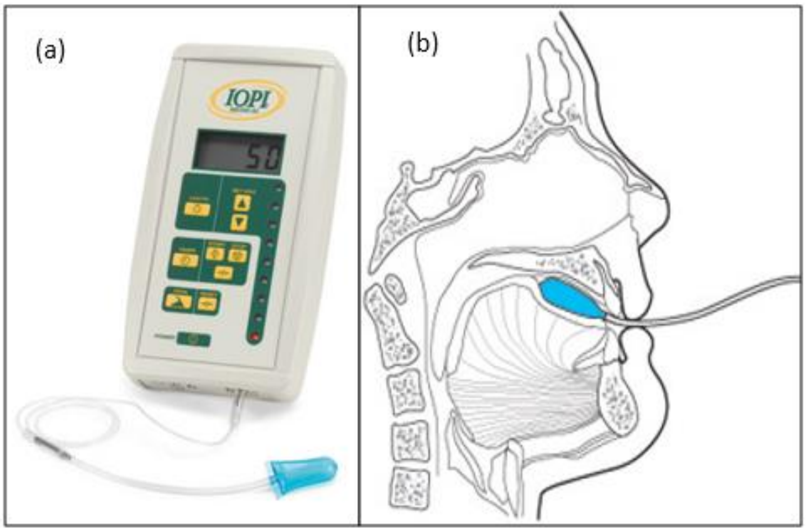


Figure 4.5 Maximum isometric tongue pressure assessment instrument and application protocol. (a) The pressure transducer and a single use tongue bulb, (b) illustration of the tongue bulb position inside the mouth (Alsanei and Chen 2014).

4.2.2.4.2 Maximum Hand Grip Capability Tests

Hand grip capability was assessed using an adjustable JAMAR handheld dynamometer (Patterson Medical Ltd., Nottinghamshire, UK) (Figure 4.6), which measures the maximum force applied. The device is mostly used for clinical purposes during the rehabilitation process for neuromuscular patients (Butler et al. 2011). This dynamometer has adjustable levels, which should be adjusted according to the age of the participant and size of the hand. In the present study, the second level of adjustment was selected as we recruited a general healthy population of adults reported to be most comfortable at this level (Trampisch et al. 2012).

Figure 4.6 Maximum hand grip force measurement device, JAMAR handheld dynamometer with adjustable levels for the panellist/patients convenience. There is a digital screen on the dynamometer which shows the maximum force applied.

The test protocol followed the one that was described by Trampisch et al. (2012). The participant was asked to squeeze the JAMAR dynamometer as hard as they could for approximately 3 s, preferably with the elbow flexed to a 90° angle and with the forearm and wrist in a neutral position. The test was repeated three times for each individual, and the mean value noted. Between the measurements, the participants were asked to rest to avoid the fatigue of the muscles.

4.2.2.4.3 Maximum Finger Grip Capability Tests

Finger grip capability was assessed using a modified device designed by Dennis Flanagan et al. (2012). The device, purchased from Tekscan (South Boston, MA, USA), consists of a flexible transducer sensor that can measure the force between two compressed surfaces. A multimeter purchased from a local warehouse was connected to the sensor (Figure 4.7). For the comfort of the participants, the sensor was covered with neoprene self-adhesive discs of 1-cm diameter on both sides to create some volume for gripping

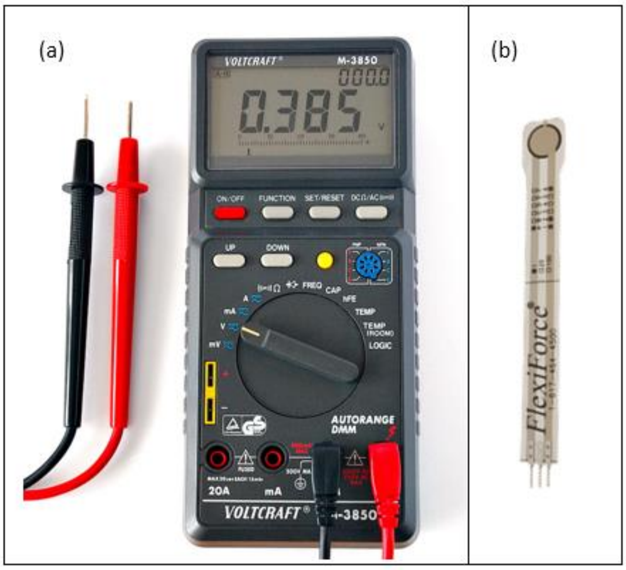


Figure 4.7 Modified finger grip measurement device which consists of a multimeter (a), and a flexi-force sensor (b).

The multimeter was only able to measure the resistance (in Ω), which was converted to the compression force prior to the study using the texture analyser (Stable Micro Systems, Godalming, UK). During this process, a range of different compression forces were applied to the sensor and the resistance value obtained was noted from the multimeter screen to produce a calibration curve (Figure 4.8).

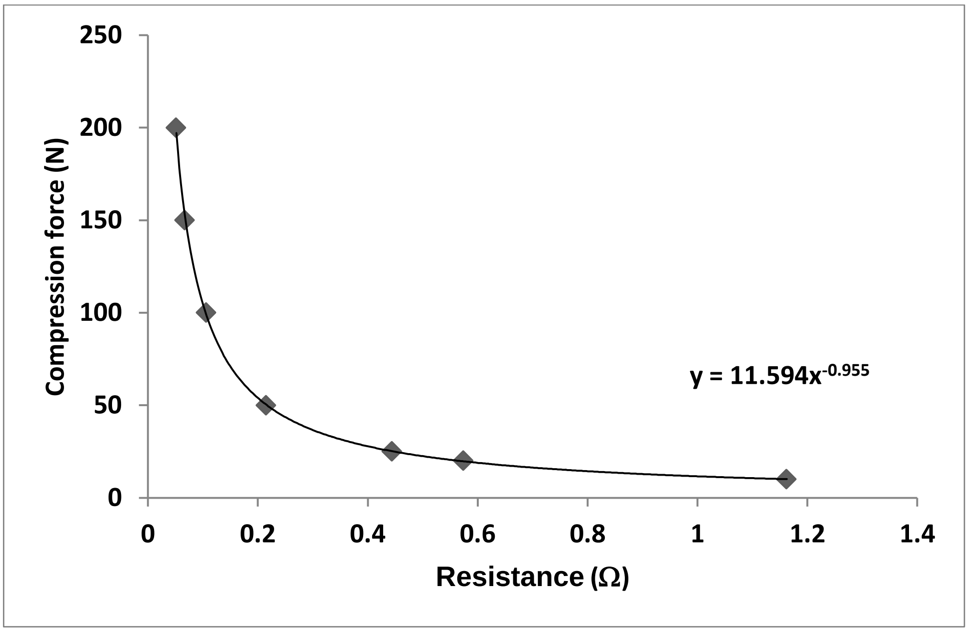


Figure 4.8 Calibration curve for the measured resistance values (Ω) by the multimeter into the compression force (N) using the texture analyser. Data was fitted with power law and the formula is shown in the graph.

During the experiments, the participants were asked to squeeze the padded sensor between the index finger and thumb of their dominant hand. The minimum resistance (which represented the greatest force applied) was noted as their capability. The test was repeated three times for each participant with a break between each to avoid muscle fatigue.

4.2.2.5 Statistical Analysis

The data from the experiments were analysed with XLSTAT (Microsoft, Mountain View, CA, USA) to obtain Pearson correlation coefficients. General descriptive statistical analysis, such as mean, median and standard deviation values, were calculated using Microsoft Office Excel 2010 (v14.0). Data for the threshold analysis (firmness discrimination tests, touch sensitivity and 2PD) were presented in log-normal (probit analysis) best fitting to find the JND values.

4.3 Results and Discussion

4.3.1 Firmness Measurement for the Gels

Textural properties, the firmness (breaking hardness) values, were assessed with the texture analyser. These values and more detailed calculations can be seen in Table 4.2.

Table 4.2 Semi-solid samples actual firmness values (N), firmness ratio (△I/I) of each sample calculated by dividing the difference from reference (△I) to the actual firmness of the reference sample (* reference sample).

Sample Number	Actual Firmness (I) (N)	Firmness difference from the reference (△I) (N)	Firmness Ratio $\frac{\Delta I}{I^*}$	Multiplication factor $\frac{(\frac{\Delta I}{I})_n}{(\frac{\Delta I}{I})_{n-1}}$
1*	2.58	0.00	0.00	-
2	2.81	0.23	0.09	-
3	2.99	0.41	0.16	1.78
4	3.12	0.54	0.21	1.31
5	3.31	0.73	0.28	1.33
6	3.48	0.90	0.35	1.25
7	3.65	1.07	0.41	1.17
8	3.81	1.23	0.48	1.17
9	4.00	1.42	0.55	1.15
10	4.61	2.03	0.79	1.44

Ten gel samples were selected according to their firmness values. The multiplication factor was the determining factor for sample selection, defined as the difference between stimuli expressed as the firmness of the harder sample divided by the firmness of the softer sample. This value helped us create minimal increments between the samples (Steele et al. 2014). For our samples, the average multiplication factor was 1.32 ± 0.19, which meant that the firmness value of the samples was increasing by a factor of 0.32-fold or 32 %.

4.3.2 Sensory Tests

4.3.2.1 Firmness Discrimination Capability

The participants' firmness discrimination capabilities were tested by asking them to compare nine pairs of samples (one reference and one test sample each) and report if they could detect any difference in firmness with the fingertip and tongue. An individual's threshold value was noted after three consecutive 'different' answers, and the thresholds obtained were plotted using probit analysis as described in the previous chapter. From this plot of cumulative population versus the logarithm of firmness ratio, the median was obtained and taken to be the population threshold.

Figure 4.9 illustrates the firmness discrimination capabilities of the index fingertip (a) and tongue (b).

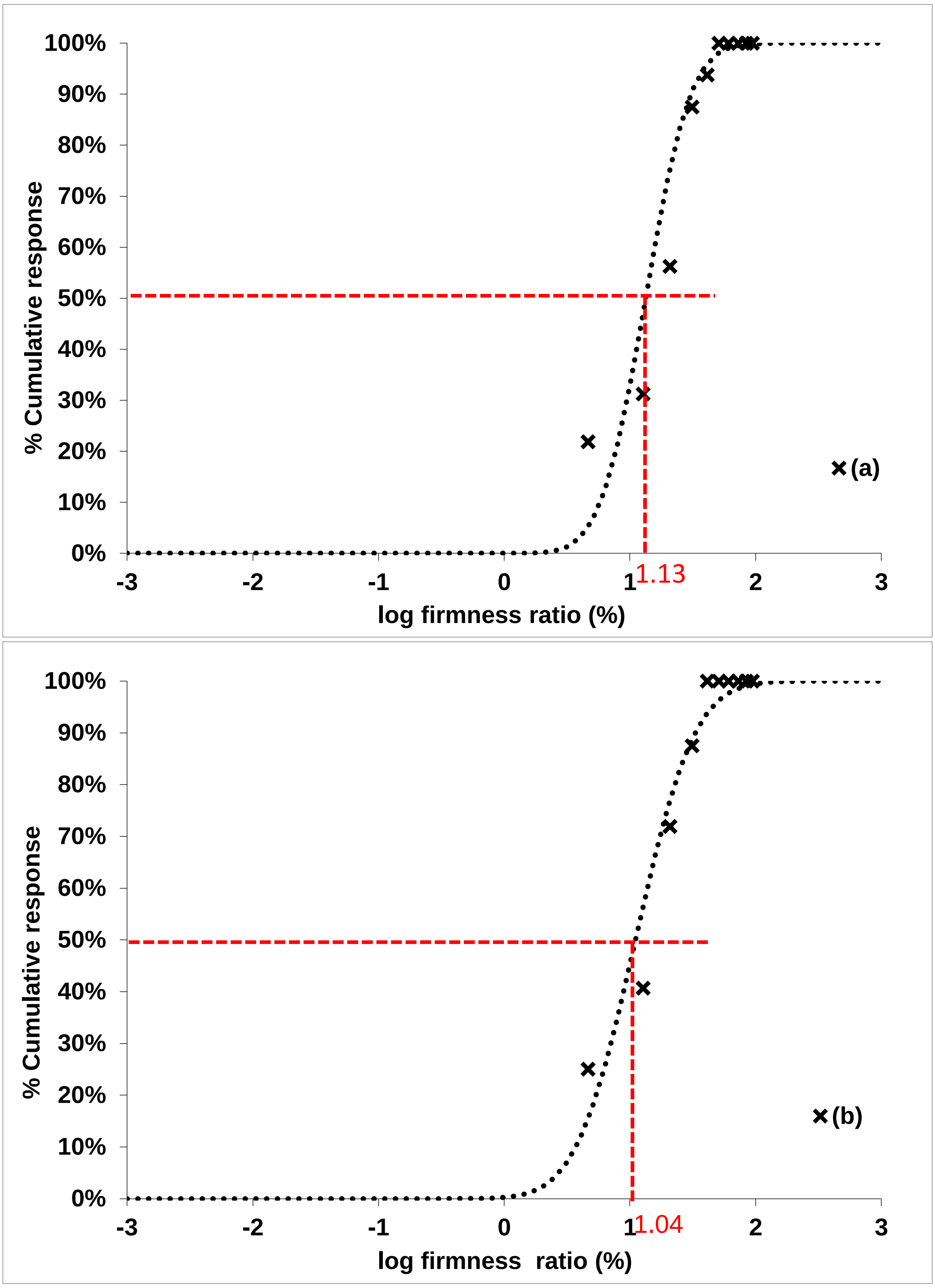


Figure 4.9 Log-normal best fitted (probit analysis) cumulative responses of participants (n = 32) shown as population percentage against the logarithmic firmness difference (%); (a) the fingertip (Median: $10^{1.13}$ = 13.3 %), (b) the tongue (Median: $10^{1.04}$ = 11.1 %)

Figure 4.9 illustrates the firmness discrimination capabilities of the index fingertip (a) and tongue (b). From this, the firmness discrimination threshold value for the tested population was found to be 13.3 % for the fingertip and 11.1 % for the tongue, i.e. for the fingertip, a change of at least 13.3 % in the firmness value is needed to create sensible difference, whereas the change would need to be at least 11.1 % for the tongue. These results show that the tongue has similar sensitivity to the fingertip in detecting a change in firmness. Further analysis showed that there was no statistically significant difference between the discrimination capabilities of the fingertip and tongue ($p > 0.05$).

In addition to observing the JND threshold, another interesting approach to firmness perception was to consider the possible effects of gender and age. Due to involving only a general population of adults, it was not possible to divide the participants into age groups. The descriptive statistics (mean and 95 % confidence intervals) for firmness discrimination of the female and male participants are shown in Table 4.3.

Table 4.3 Descriptive statistics for mean firmness discrimination capability tests, which shows the mean, standard deviation and 95 % confidence interval lower and upper bound values for female and male participants (n = 32, 15 females and 17 males).

Group	Firmness discrimination capability (%)		Standard deviation		95 % confidence interval			
					Lower bound	Upper bound	Lower bound	Upper bound
	Fingertip	Tongue	Fingertip	Tongue	Fingertip		Tongue	
Female	25.70	30.30	2.50	3.40	20.30	31.20	23.00	37.50
Male	15.60	15.70	2.50	3.00	10.20	21.00	9.40	22.00
Overall Mean	20.30	22.50	2.00	2.60	16.30	24.40	17.30	27.70

These values show that the male participants had a higher sensitivity to discriminating similar firmness textures ($p < 0.05$), although there have been no previous reports that could support this finding.

Unlike in the study described in the previous chapter, the fingertip and tongue showed a similar sensitivity to firmness discrimination. As the aim is to use fingertip perception for predicting the oral perception of texture, having similar sensitivities gives useful information.

To our knowledge, these concepts have not been observed in literature, and confirmation from independent researchers would be required for findings on firmness or any other attributes.

4.3.2.2 Tactile Sensitivity

4.3.2.2.1 Touch Sensitivity

SWMs were used to determine touch sensitivity. This technique has been reported as a standard touch sensation assessment method (Jerosch-Herold 2005, Bell-Krotoski and Tomancik 1987). Figure 4.10 illustrates the log-normal (probit analysis) best fit curves for the cumulative population against the touch sensitivity for the fingertip (a) and tongue (b).

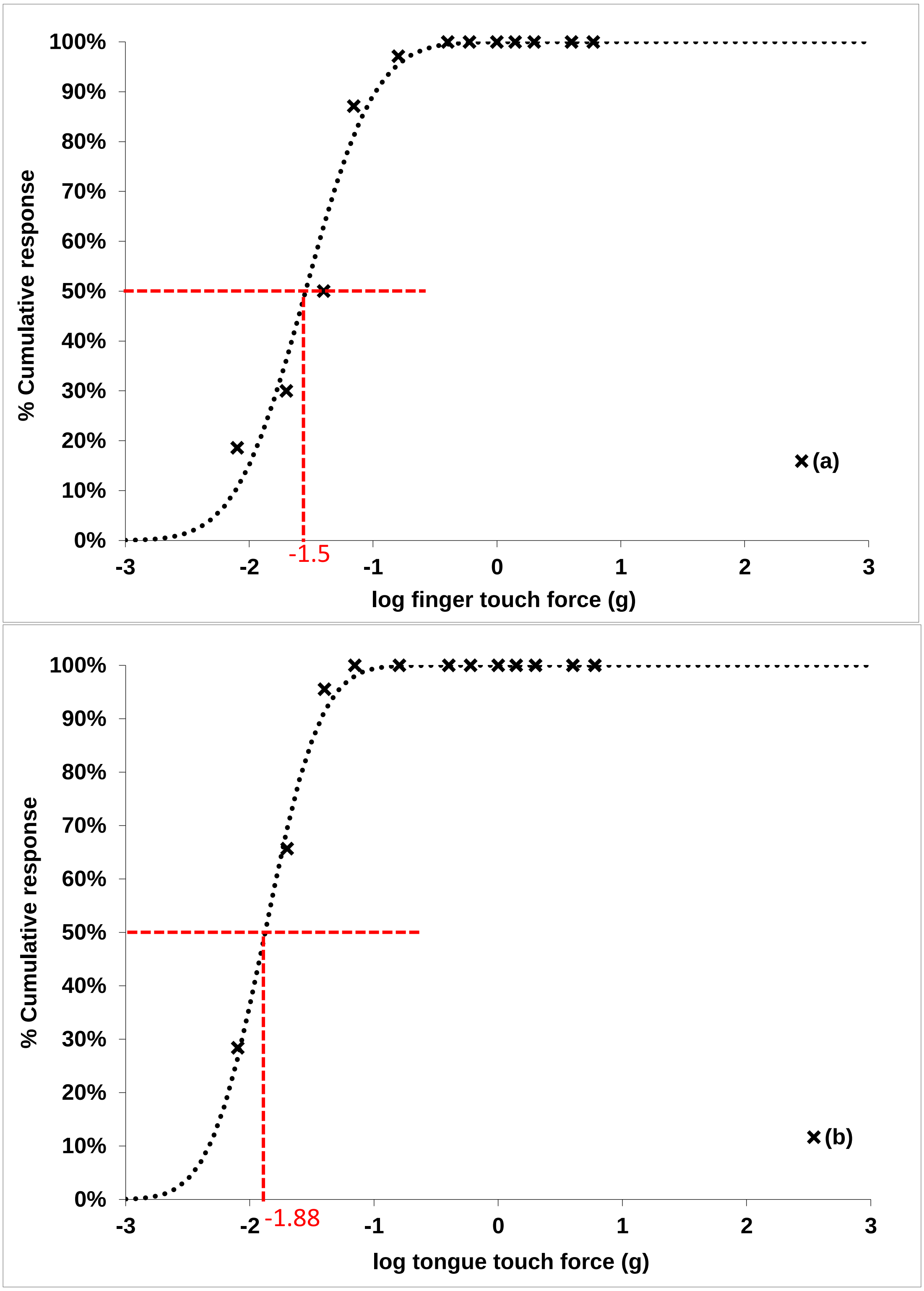


Figure 4.10 Log-normal fited (probit analysis) cumulative response of the particpants (n = 32) shown as population percentage against the touch sensitivity (g): (a) the index fingertip ($10^{-1.55}$ = 0.028 g); (b) the tongue ($10^{-1.88}$ = 0.013 g).

According to these, the fingertip touch sensitivity as a population threshold (cumulative median value) was 0.028 g force, whereas for the tongue, it was 0.013 g. These touch sensitivity threshold values represent the minimum forces required for the detection of touch; in other words, lower values would not be expected to be sensed by the fingertip or tongue. Actual touch sensitivity, the tongue showed a slightly higher sensitivity than the fingertip ($p < 0.05$).

In addition, in the previous chapter, the touch sensitivity graphs for the fingertip and tongue showed a substantial difference in their data distribution range, supporting the suggestion that the tongue has a higher touch sensitivity. Similarly, in the present study, the data were distributed within the range 0.05 to 0.1 g for the fingertip and 0.02 to 0.03 g for the tongue. As discussed previously, this finding suggests that the tongue has a higher touch sensitivity. These findings, which confirm our previous study, also emphasise that touch sensitivity does not depend on the test protocol followed, which involved a descending order of stimuli in the previous study but an ascending order in the current one.

Touch sensation results have also been calculated with descriptive statistics for the mean values, standard deviation and 95 % confidence intervals for the female and male participants, with the results shown in Table 4.4. The mean touch sensitivity values for the female and male participants did not show a statistically significant difference ($p > 0.05$). It therefore cannot be suggested that either gender is more sensitive in terms of touch sensitivity thresholds.

Table 4.4 Descriptive statistics for mean touch sensitivity, which shows the mean, standard deviation and 95 % confidence interval lower and upper bound values for female and male participants (n = 32, 15 females and 17 males).

Group	Touch sensitivity (g)		Standard deviation		95 % confidence interval			
					Lower bound	Upper bound	Lower bound	Upper bound
	Fingertip	Tongue	Fingertip	Tongue	Fingertip		Tongue	
Female	0.07	0.03	0.01	0.003	0.05	0.08	0.02	0.04
Male	0.09	0.03	0.02	0.002	0.04	0.14	0.02	0.03
Overall Mean	0.08	0.03	0.01	0.002	0.05	0.10	0.02	0.03

Previous studies have reported the touch sensitivity of the fingertip, as seen in Table 4.5. Our findings fit well with these as well as our previous study on viscosity discrimination, which provides support for our experimental procedure.

Table 4.5 Touch sensitivity (g) thresholds found by previous researchers by the Semmes-Weinstein Monofilaments (SWM) on the fingertip.

Previously obtained results	Fingertip touch sensitivity (g)	Tongue touch sensitivity (g)
Gillenson et al. (1998)	0.008 to 0.07 g	
Joris Hage et al. (1995)	0.008 to 0.6 g	
Chapter 3	0.023	0.021
Current study	0.028	0.013

4.3.2.2.2 Two-Point Discrimination

2PD was assessed to find the tactile acuity of touch (Goldstein 2010). 2PD measures the closest two points that can be discriminated by touch and is considered to reflect the level of sensitivity, or conversely, it may be used to demonstrate a loss in sensitivity (Periyasamy et al. 2008). In the present study, a static approach was followed for the 2PD tests, which is considered to be the standard application, with higher feasibility and reliability for nerve integrity assessments (Ferreira et al. 2004, Periyasamy et al. 2008).

Figure 4.11 shows the results of the 2PD test plotted as a cumulative population against the measured distance. Unfortunately, the data did not have a wide enough spread to obtain a 50 % value as the population threshold. In other words, more than half the participants were capable of detecting the lowest possible distance available in the current technique. In literature, 2PD has been presented as a mean value rather than as a cumulative median. The reason for this could be the limitation of the technique as was the case in the present study. In this study, therefore, the 2PD values for the fingertip and tongue were presented as the mean threshold values. The figure shows the cumulative population against the two-point distance that cannot be sensed as two individual touches.

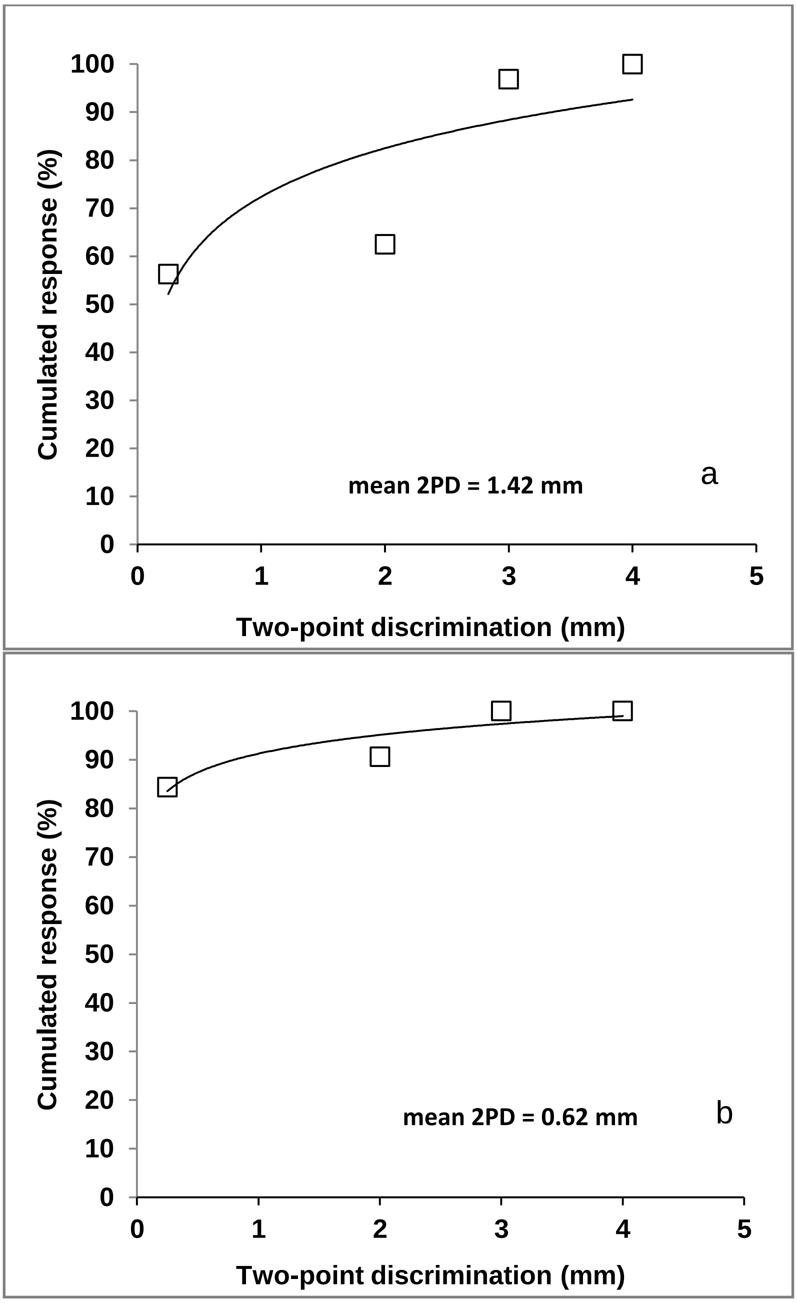


Figure 4.11 Cumulative responses of participants (n = 32) shown as population percentage against the distance (mm) between the two points: (a) the index fingertip (mean two-point discrimination = 1.42 mm); (b) the tongue (mean two-point discrimination = 0.62 mm) (with guide to eye lines).

Figure 4.11a shows the 2PD threshold for the fingertip with a mean minimum distance of 1.42 ± 0.62 mm. Similarly, Figure 4.11b shows the distribution for the cumulative population against 2PD for the tongue and gives a mean value for the minimum distance of 0.62 ± 0.16 mm. At smaller distances than these two threshold values for these test surfaces, two points would not be detected as distinct. These mean values of the 2PD threshold show that the tongue has a higher tactile acuity than the fingertip ($p < 0.05$). This has already been shown by our findings for touch sensitivity, the other type of test showing tactile sensation.

Another interesting consideration was comparing the 2PD thresholds between the female and male participants. The descriptive statistical analysis for this is shown in Table 4.6.

Table 4.6 Descriptive statistics for 2PD, which shows the mean, standard deviation and 95 % confidence interval lower and upper bound values for female and male participants (n = 32, 15 females and 17 males)..

Group	2PD (mm)		Standard deviation		95 % confidence interval			
					Lower bound	Upper bound	Lower bound	Upper bound
	Fingertip	Tongue	Fingertip	Tongue	Fingertip		Tongue	
Female	1.42	0.43	0.39	0.18	0.60	2.25	0.04	0.80
Male	1.43	0.78	0.32	0.25	0.75	2.10	0.26	1.30
Overall Mean	1.42	0.62	0.20	0.16	0.92	1.92	0.30	0.94

According to the descriptive statistics (95 % confidence intervals), there were no statistically significant differences between the female and male participants ($p > 0.05$), suggesting, as confirmed by previous tactile practices of touch sensitivity, that there is no evidence of gender difference.

2PD is a popular technique due to its easily applied, non-invasive nature. Previously obtained 2PD threshold values for the fingertip and tongue are shown in Table 4.7.

Table 4.7 Reported 2PD values for the fingertip and tongue.

Researcher	Fingertip 2PD threshold (mm)	Tongue 2PD threshold (mm)
Chandhok and Bagust (2002)	1.66 ± 0.09	
Menier et al. (1996).	2.2	
Johnson and Phillips (1981)	0.87	
van Boven and Johnson (1994)	0.94	
Minato et al. (2009)		1.09 ± 0.35
Okada et al. (1999)		1.7 ± 0.1
van Boven and Johnson (1994)		0.58
Maeyama and Plattig (1989)		1.65 ± 0.433
Ruth (1951)		1.5 ± 0.5
Current study	1.42 ± 0.62	0.62 ± 0.16

The fingertip 2PD threshold value obtained in the present study is similar to that reported in literature; similarly, the tongue 2PD threshold also showed a good fit with the reported threshold values. This confirmation may provide further support for the reliability and reproducibility of the technique.

The 2PD test is mostly used for determining the recovery level for patients undergoing treatment. It is generally accepted as a measure of tactile spatial resolution. However, Craig and Johnson (2000) rejected it as a measure of spatial resolution due to the crudeness and inadequacy of its measurement. Despite this review, we believe that 2PD indicates tactile acuity with reliable and reproducible results, except for clinical applications that may require more sensitive measurements.

The initial reason for developing this test was to investigate unhealthy individuals' tactile sensitivity during nerve recovery. Therefore, researchers should not withstand this reality and present the results claiming the limitations of big increments between the sensation levels. In the present study, most participants were capable of detecting the narrowest distance available, and due to this, the data distribution shown in Figure 4.11 was not wide enough to cover the whole distribution of the population. This disadvantage prevented the probit analysis of the data as in the JND method of finding the cumulative median of the logarithmic 2PD distances. Hence, the mean threshold value was presented.

4.3.2.3 Muscle Capability Tests

The results of the muscle capability tests were analysed for texture discrimination correlations as well as age and gender effects, where a limitation of the narrow range of ages of the participants should be noted. It should be emphasised that the main aim of this particular task was to find out whether the muscle capability was a determinative factor for texture discrimination.

4.3.2.3.1 Effect of Age and Gender on Muscle Capabilities

1. Maximum Isometric Tongue Pressure Tests

The MITP capability of the participants was assessed in accordance with general practice in literature, and the mean MITP value was calculated to be 54.1 ± 12.8 kPa. MITP plotted against age and gender can be seen in Figure 4.12.

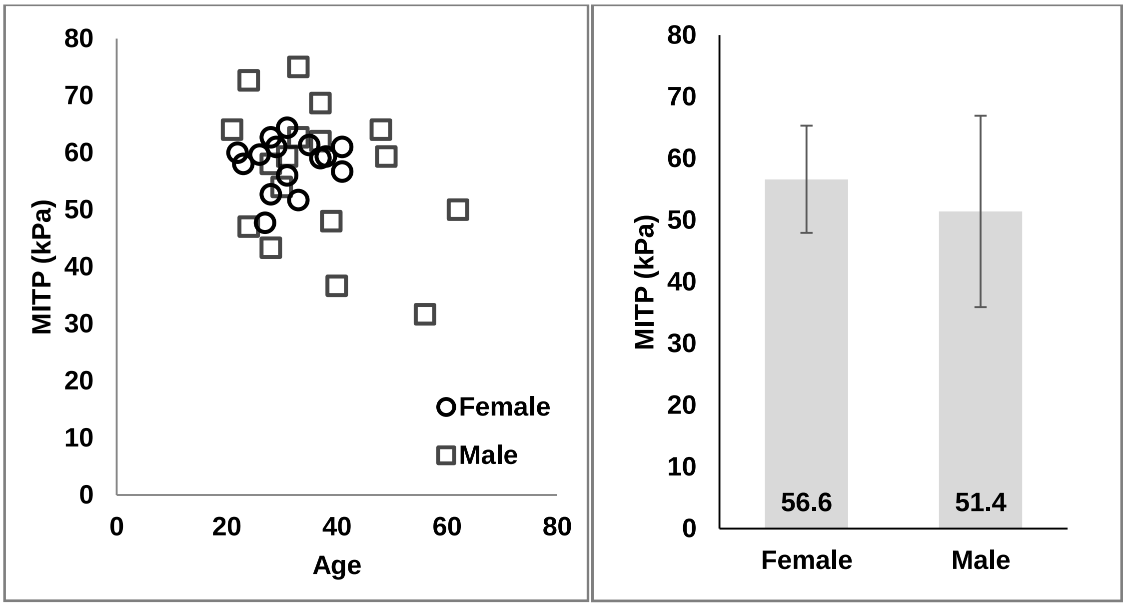


Figure 4.12 Measured maximum isometric tongue pressure (MITP) of the participants (n = 32, 15 females and 17 males) according to the age (a) and gender (b) of the panellists with standard deviation error bars.

Unsurprisingly, no significant effect of age on the muscle capability was found ($p > 0.05$), probably due to the similar ages of the participants. The effect of age on MITP was investigated by Deurenberg and Deurenberg-Yap (2009), who reported that the muscle capability is relatively stable until the age of 40 years but that ageing reduces MITP after that. A recent study by Alsanei and Chen (2014) showed that age does not change MITP until the age of 65 years, but thereafter, it starts to dramatically decrease.

In the present study, gender did not show a statistically significant effect on MITP ($p > 0.05$). The study by Alsanei and Chen (2014) also reported that gender does not have a significant effect on tongue pressure capability, suggesting that our finding about gender is valid and reliable.

2. Maximum Hand Grip Capability Tests

Hand grip capability was tested, with mean values calculated for each hand. Right hand grip capability was 29.7 ± 10.9 kg, whereas that for the left hand was 27.9 ± 11.3 kg. Figure 4.13 shows the mean values for the right and left hand grip forces according to age (a) and gender (b) of the participants.

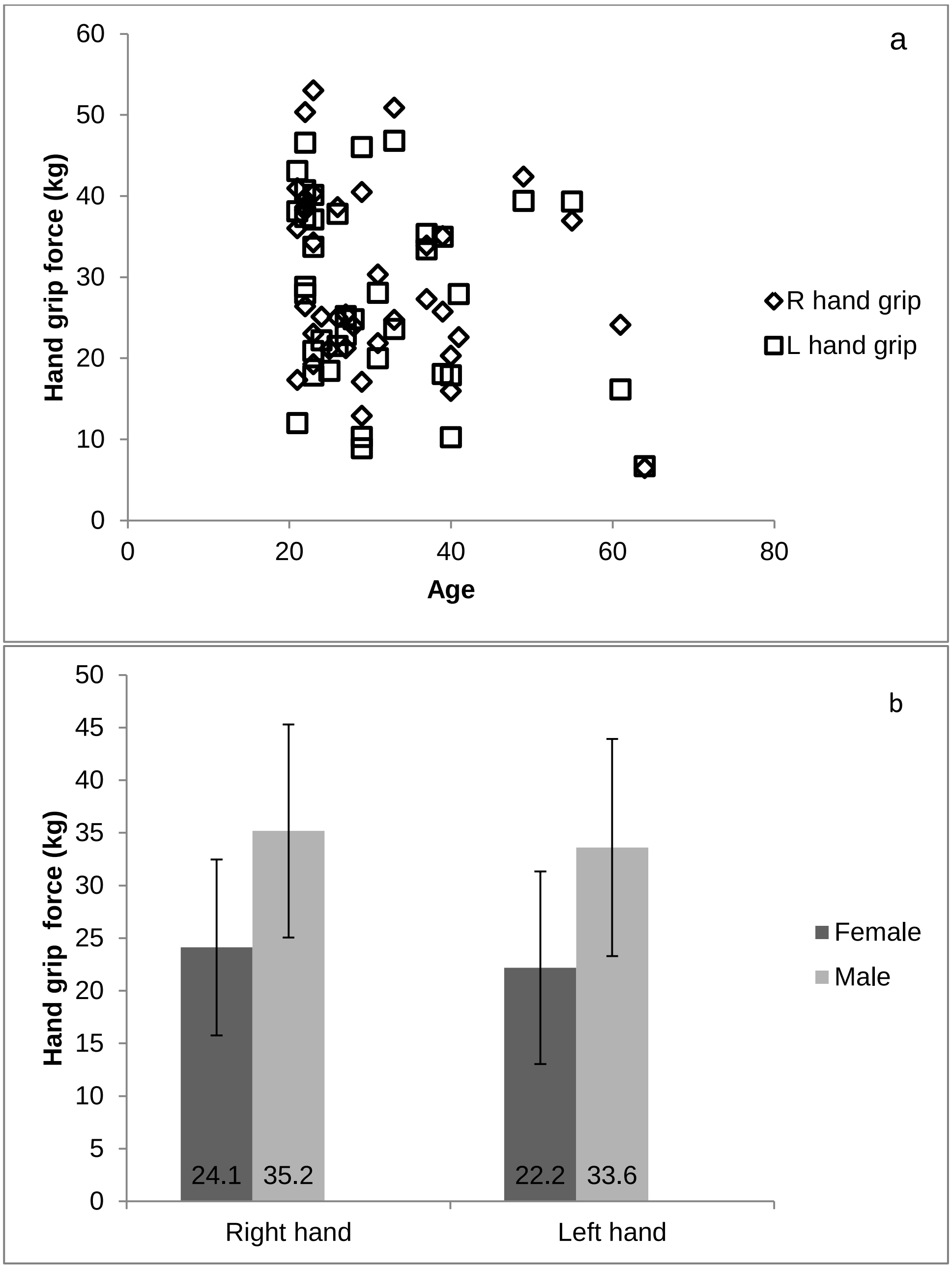


Figure 4.13 Right and left hand grip force capabilities of the participants (n = 32, 15 females and 17 males); compared with age (a) and gender (b) with standard deviation error bars.

No statistically significant effect of age on the hand grip capability was found ($p > 0.05$). If the test population had been much bigger, an effect on the muscle capability may have been seen, and the lack of an effect may have been due to the narrow age range of the participants within the present study. As expected, previous studies have suggested that the hand grip capability strongly decreases with age (Alsanei and Chen 2014, Frederiksen et al. 2006).

Figure 4.13b shows the differences between genders for both the right and left hand. These analyses showed that the female participants had a weaker hand grip capability than that of the male participants ($p < 0.05$). This was in agreement with previous studies where it was reported that in the adult female population, the hand grip force was 24.12 ± 9.59 kg, while for men it was 37.56 ± 7.75 kg and that females had a lower muscle capability (Gentil and Tournier 1998).

3. Maximum Finger Grip Capability Tests

Finger grip capability was assessed. The mean finger grip force was 3.9 ± 1.6 kg force. As can be seen from Figure 4.14a, the capability significantly decreased with age ($p < 0.05$), an effect that may have been even stronger if the tests were performed with a larger population. Gender difference was also investigated (Figure 4.14b), and similar to the results for the hand grip capability, the female participants showed lower mean finger grip force (3.2 ± 0.9 kg) than the male participants (4.7 ± 1.9 kg) ($p < 0.05$).

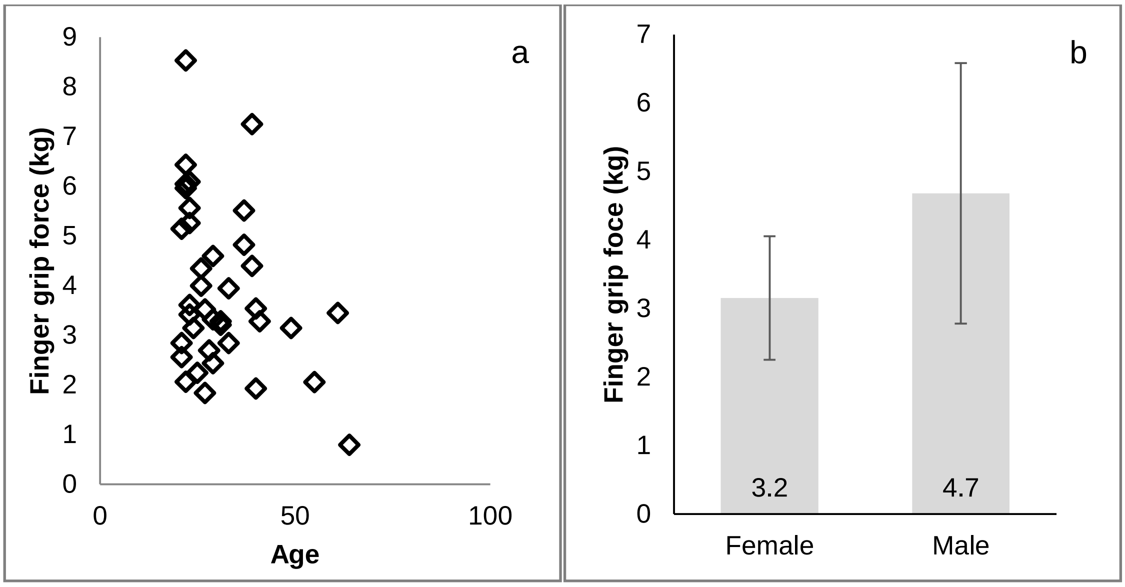


Figure 4.14 Finger grip force of the participants (n = 32, 15 females and 17 males) against the; age (a) and gender (b) with standard deviation error bars.

From the analysis of age and gender effects for the muscle capabilities tested, it was obvious that, apart from the tongue, gender has an impact on the muscle capability. This is not surprising as anatomically, females have been found to be weaker in muscle capability. This could be due to training of the muscles; if that is the case, it could explain why no gender effect on tongue capability was observed. It is possible that the capabilities of muscles that are not obviously trained differently between genders will be determined by the evolution progress, which would explain why the tongue has similar muscle strength between genders. The impact of age on the muscle capabilities was also assessed, but the narrow age range of the participants meant that any variation that might be caused by age was not observable. However, it should be noted that the primary reason for testing the muscle capabilities in the present study was to determine their relationship with texture rather than age and gender which is the target of the following topic.

4.3.2.4 Cross-Correlations of the Experiments

The aim of this chapter was to investigate the relationship between the textural (semi-solid) firmness discrimination capability and tactile sensation (touch sensitivity and 2PD ability) for the fingertip and tongue. While designing the tests, it was assumed that texture is perceived through the tactile sensation system; therefore, the magnitude of texture sensation through the tactile detectors could be understood by finding tactile sensitivity correlation. Additionally, the muscle capabilities were also examined, including the MITP, finger grip and hand grip capabilities. The hypothesis behind these experiments was that there is correlation between muscle capability and texture sensation.

4.3.2.4.1 Firmness Discrimination Capability versus Tactile Sensitivity

The relationship between the firmness discrimination capability and tactile sensitivity (touch sensitivity and 2PD) was analysed, and Figure 4.15 shows the participants' texture discrimination capabilities plotted against their tactile sensitivity (touch sensation and 2PD) for the fingertip (a) and tongue (b).

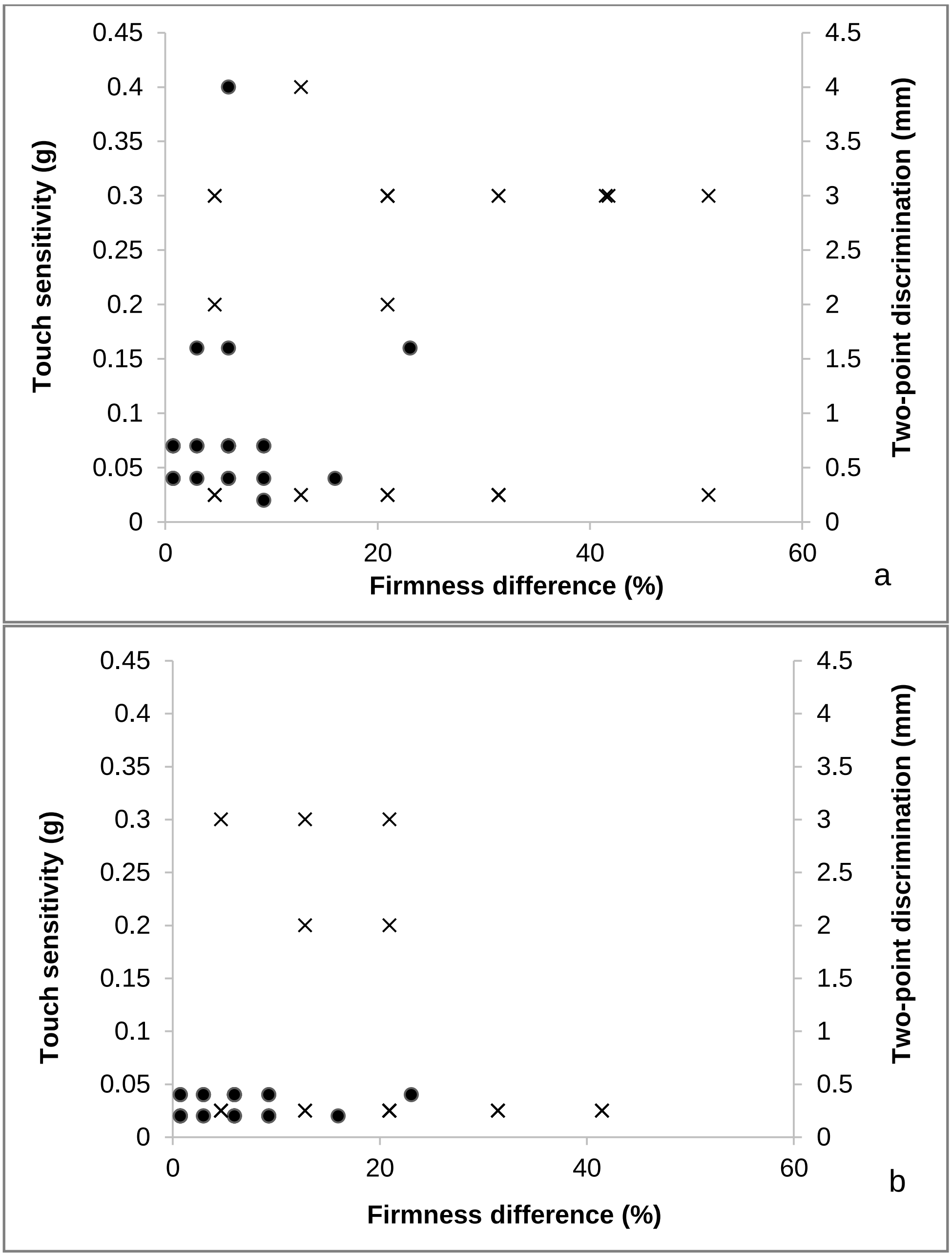


Figure 4.15 Individual's (n = 32) capability of firmness discrimination and touching sensitivity (●) and two-point discrimination ability (×): (a) index fingertip; (b) tongue.

Those plots are highly scattered and show very low correlations between the capabilities for the fingertip and tongue. These graphs and statistical analysis showed that there is no significant correlation between the semi-solid firmness discrimination capability and tactile sensation (touch sensitivity and 2PD) (p > 0.05).

These results seem to disprove the initial hypothesis that tactile sensation determines firmness perception. There could be numerous reasons for not observing such a relationship, but the main cause may be the complexity of texture sensation. It is common knowledge that tactile sensitivity has a role in the perception of texture. However, texture is a multiparameter property, with many factors affecting the texture observation process, such as temperature, water holding capacity and synergy between mechanoreceptors. As well as the complexity of perception, texture could also be a learnt and trained attribute of sensation arising from culture and daily habits, as was discussed in the previous chapter. Moreover, a lack of correlation between an individual's capability for tactile sensitivity and texture discrimination could be due to tactile sensitivity being assessed in a static manner, while texture sensation was a dynamic process, which has been found to affect the sensitivity (Pont et al. 1999). This would be an interesting topic for future studies.

Therefore, it still cannot be claimed that texture perception is not determined by the tactile senses. There may still be some correlation between tactile sensation and texture perception, perhaps not with gel firmness, but with other attributes. To establish whether or not there is a correlation, it is necessary to examine different attributes perhaps still with the gel samples. For firmness perception, there is no direct correlation between texture discrimination and the tactile sensation capability, which would need to be confirmed.

4.3.2.4.2 Pearson's Correlation Coefficients of Firmness Discrimination Capability, Touch sensitivity and Muscle Capabilities

Texture perception was also tested against the muscle capability as well as tactile sensation by calculating Pearson correlation coefficients, as presented in Table 4.8.

Table 4.8 Pearson's correlation coefficients matrix with measured capabilities and sensitivities (Values in bold are different from 0, which claims a correlation with a significance level alpha=0.05).

Variables	Gender	Age	BMI	Finger touch sensitivity (g)	Tongue touch sensitivity (g)	Finger 2PD (mm)	Tongue 2PD (mm)	Finger firmness discrimination (%)	Tongue firmness discrimination (%)	MITP (kPa)	Right hand grip (kg)	Left hand grip (kg)	Finger grip (kg)
Gender	**1**	0.230	0.128	0.027	0.100	0.027	0.179	0.062	-0.059	-0.200	**0.512**	**0.506**	**0.467**
Age	0.230	**1**	**0.450**	0.246	**0.422**	-0.022	-0.066	**-0.335**	-0.311	-0.303	-0.270	-0.241	**-0.350**
BMI	0.128	**0.450**	**1**	0.028	0.175	-0.214	-0.100	-0.247	-0.151	-0.169	-0.224	-0.287	-0.155
Finger touch sensitivity (g)	0.027	0.246	0.028	**1**	-0.042	0.150	-0.123	**-0.371**	**-0.389**	0.149	0.072	0.020	-0.172
Tongue touch sensitivity (g)	0.100	**0.422**	0.175	-0.042	**1**	0.034	0.025	-0.037	0.037	-0.137	-0.112	-0.125	-0.159
Finger 2PD (mm)	0.027	-0.022	-0.214	0.150	0.034	**1**	0.234	0.045	-0.196	0.054	0.038	0.011	0.063
Tongue 2PD (mm)	0.179	-0.066	-0.100	-0.123	0.025	0.234	**1**	0.009	-0.202	-0.023	0.244	0.197	**0.350**
Finger firmness discrimination (%)	0.062	**-0.335**	-0.247	**-0.371**	-0.037	0.045	0.009	**1**	**0.561**	-0.005	0.168	0.274	0.118
Tongue firmness discrimination (%)	-0.059	-0.311	-0.151	**-0.389**	0.037	-0.196	-0.202	**0.561**	**1**	0.102	0.080	0.170	0.231
MITP (kPa)	-0.200	-0.303	-0.169	0.149	-0.137	0.054	-0.023	-0.005	0.102	**1**	0.128	0.030	-0.013
Right hand grip (kg)	**0.512**	-0.270	-0.224	0.072	-0.112	0.038	0.244	0.168	0.080	0.128	**1**	**0.933**	**0.603**
Left hand grip (kg)	**0.506**	-0.241	-0.287	0.020	-0.125	0.011	0.197	0.274	0.170	0.030	**0.933**	**1**	**0.568**
Finger grip (kg)	**0.467**	**-0.350**	-0.155	-0.172	-0.159	0.063	**0.350**	0.118	0.231	-0.013	**0.603**	**0.568**	**1**

A correlation matrix of Pearson's correlation coefficients was constructed from the data to establish whether a relationship existed between the muscle and firmness discrimination capabilities with the tactile sensitivities. As can be seen from Table 4.8, the muscle capability is correlated with the gender. As discussed earlier female participant were found to have weaker muscle capability. Moreover, the grip capability with right and left hand and with the finger grip shows corelations, where it could be highlighted in the relevant and symmetric muscles there is a correlation. Age correlations were not considered, due to the reason of recruiting similar age groups in the sensory tests. As the main target of this topic there was no evidence to support there being a relationship between the muscle and texture discrimination capabilities. The possible correlations seem to be random rather than showing genuine interactions of the factors. Therefore, the muscle capability, including MITP, does not affect the perception of texture.

4.4 Limitations

Despite clear conclusions from the above discussion, the limitations of the experiments presented in the present study should be acknowledged. Firstly, the firmness discrimination tests were performed with gel samples whose firmness is sensitive to temperature changes. During the texture perception assessments, the participants used their index fingertip and tongue, which have mean temperatures of 37 °C and 32 °C, respectively (add). This variation in temperature between the gel and individual contact area may have caused bias within the results. Also, it was stated that texture perception could develop with experience, which suggests that cultural background (e.g. eating with the hands, chopsticks or cutlery) further causes individual variation. Moreover, if an individual has a prior history involving tactile experience (such as playing an instrument or working with their hands), their sensitivity could be affected. Another limitation about textural perception is the dynamic nature of the oral process, which is complicated (Guinard and Mazzucchelli 1996).. This complication was minimised using tasteless and aroma-free gel samples, and we aimed to reduce the interactions due to chewing by soft-solid samples, which we believe reduced the dynamic nature of the food (Engelen and de Wijk 2012, Kutter et al. 2011).

Secondly, even though tactile assessment methods for touch sensitivity and 2PD were considered to be sensitive enough for the detection of tactile acuity for general practice, the use of these instruments resulted in some limitations. The main disadvantage with both tactile measurement instruments was the size of the increments, which could be reduced to obtain more sensitive measures. In addition, these two methods are still under debate in literature regarding their reliability in clinical assessments, although they are suitable for basic tactile examinations. This highlights that an alternative and more precise technique is required for healthy adult individuals to assess touch sensitivity and 2PD threshold.

4.5 Conclusion

The first aim of the present study was to investigate whether there was a correlation between the firmness discrimination capability and tactile sensation. Our results demonstrated that the firmness discrimination capability showed similar sensitivities for the tongue and fingertip. The JND thresholds for the firmness of the semi-solid samples were found to be 13.3 % and 11.1 % for the fingertip and tongue, respectively. In the tactile sensation tests, the tongue showed a higher sensitivity than the fingertip. Touch sensitivity was found to be 0.028 g for the fingertip and 0.013 g for the tongue, with the mean threshold for 2PD found to be 1.42 mm and 0.62 mm for the fingertip and tongue, respectively. Contradicting our initial expectation of possible correlations between tactile sensitivity and texture discrimination, the results did not show a statistically significant relationship.

The second aim of the experiments was to investigate whether the muscle capability determines texture perception and tactile sensation. The findings from the correlation analysis suggested that they are unrelated. Further analysis of the muscle capability showed that the female participants generally had a weaker capability, whereas an age correlation was not observable due to the limited age range of the participants.

These statements requires approval or disproval of the independent researchers for gel firmness and also it will be useful to illustrate the relationship between the tactile sensitivities with the other textural attributes perhaps still on the gel samples.

Chapter 5
Elasticity Discrimination Capability and Tactile Sensitivity

5.1 Introduction

The concept of texture perception has yet to be clearly defined or quantified with regard to various attributes. Addressing this fundamental concern requires an understanding of the main determinative factors, and investigating those factors will lead to a clearer concept of perception. The main question underlying this concept is whether texture perception is an inherent or a learnt ability (Guinard and Mazzucchelli 1996). The experiments on fluid viscosity and gel firmness perception described in the earlier chapters suggested that it is mostly a result of experience, initially delivered by inherent mechanoreceptors responsible for the sensation and perception of texture. These mechanoreceptors are inherited from our ancestors, but experience can improve sensitivity to texture. In addition, previous experiences of texture for a particular type of food construct a reference and expectation, and appreciating this is a main factor for business success in the food industry (Foegeding et al. 2011, Szczesniak and Khan 1971, Lillford 1991). As mentioned earlier, the texture of food is a major attribute for consumer acceptance and preference; importantly, it is also the main indicator for swallowing initiation, which means that texture is important for the safety of the consumer, especially for vulnerable people (Foegeding et al. 2003, Kutter et al. 2011, Guinard and Mazzucchelli 1996).

When investigating the inherent factors of texture perception, it is important to examine the sensation of different parts of the body (oral and non-oral, e.g. the fingertip and tongue) to highlight any differences in sensitivity and to observe the effects of learnt factors. Mechanoreceptors have been shown to have a similar mechanical structure in the cutaneous tissues of various parts of the body (Capra 1995, Marlow et al. 1965, Trulsson and Johansson 2002), although their density could vary (Guinard and Mazzucchelli 1996). It is therefore important to test the perception of texture for different parts of the body, such as the fingertip and the tongue.

In the previous experiments, viscosity and firmness perception did not show substantial differences between the fingertip and tongue. More importantly no effects of the tactile sensitivity on the texture discrimination capabilities were observed. As the link between the tactile senses and texture perception could not be explored with those two attributes alone, we decided to investigate further attributes to confirm the absence of any link. For this reason in this chapter, elasticity perception limits were assessed along with tactile sensation.

Elasticity perception can be defined as the feedback observed during the gentle compression of a sample without any damage to the structure and also observing the process of the restoration of the sample to its original shape (Brown et al. 2003). Elasticity is one of the main attribute for soft-solid foods and indicates a specific essential quality for foods such as jellies, confectionary products, jams and marmalades (Garrido et al. 2015). Most gel foods are deliberately passed through a gelation process to preserve the food by reducing water activity (Baker et al. 1996). As well as its effects on consumer preference, gel strength is also important for industrial food processing where machinery is used. Soft-solid foods are preferred mostly because of their texture, but they may also be advantageous for vulnerable populations (such as babies and some elderly people) who may have limited oral processing capability due to their dental state. These individuals tend to compress the food to prepare its consistency such that it is ready for swallowing. Therefore, the elasticity of soft-foods is sometimes a matter of preference and at other times, a matter of necessity. To understand both these reasons requires information about the limits of perception, which can provide flexibility in changing the elastic behaviour of food without the consumer being aware of this.

As with the previous experiments, the present study was not hypothesis-driven but was designed to find answers to the following questions:

1. What is the perception limit of elasticity difference using the oral (tongue) and non-oral (fingertip) parts of the body?
2. What is the tactile sensitivity of those body parts, and do tactile sensitivity tests show any difference between static and dynamic approaches?

3. Is there a correlation between elasticity perception and tactile sensitivity?

To design a systematic approach, similar methodologies to our previous experiments were used. Instrumentally, the elasticity of soft-solid samples is determined by viscoelastic properties, which provide Young's modulus (the modulus of elasticity) (Boland et al. 2004). Conversely, the perceived elasticity of soft-solid samples has to be determined using sensory tests. To establish the relationship between tactile sensation and texture perception, tactile sensitivity was investigated with touch sensitivity and two-point discrimination (2PD) tests. However, different from the previous experiments, the difference between the static and dynamic approaches for those tests was also investigated. The test locations were the tongue and dominant hand index fingertip.

The findings of the present study would be expected to enhance our understanding of elasticity texture sensation and also provide an insight into texture perception. The basics of texture discrimination are critically important for the food industry and its research and development units in meeting the expectations of general and also vulnerable users with physical limitations for oral processing, such as some elderly people and babies, and those with a swallowing disorder (dysphagia), who do not have the ability to control swallowing.

5.2 Materials and Methods

5.2.1 Materials

In this chapter, the same semi-solid food samples were used as in Chapter 4. These samples were prepared from an instant gel powder that consisted of carrageenan and locust bean gum (Vege-gel, Dr. Oetker Ltd., Bielefeld, Germany). The powder was stored in its original box at room temperature, and the samples were prepared before each sensory assessment. Sample concentrations were selected for elasticity discrimination assessment based on the Young's modulus value (Table 5.1). The gel mixture was reconstituted by mixing with cold water and was brought to boiling point. After boiling, the solution was poured into the gel mould used in the previous chapter (Figure 4.1). The gel mould was kept at ambient temperature for 2 h to cool and was then transferred to the refrigerator (at 4 °C) for 12 h. The samples were then moved to room temperature and were kept for 2 h under this condition to be in thermal equilibrium to avoid temperature differences. As in Chapter 4, the samples all had the same taste, aroma and colour properties to avoid distractions during the experiments.

Table 5.1 Concentration range of the semi-solid (vege-gel) samples (*reference sample).

Sample Number	Actual concentration (%)
1*	1.70
2	1.80
3	1.87
4	1.92
5	1.99
6	2.05
7	2.11
8	2.16
9	2.22
10	2.40

5.2.2 Methods

5.2.2.1 Texture Analysis of Gel Elasticity

The elasticity properties of the samples were assessed using the TA-XT Plus texture analyser (Stable Micro Systems Ltd., Surrey, UK). In particular, Young's moduli were calculated based on the initial linear part of the force–displacement curve (Figure 5.1).

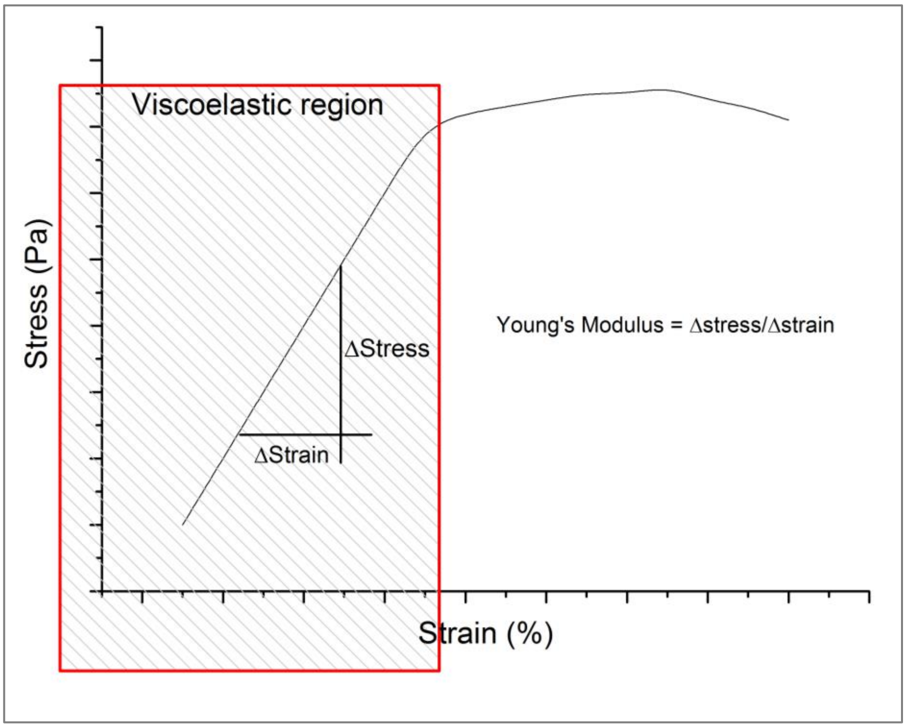


Figure 5.1 Calculation of Young's modulus, from force displacement curve.

The textural testing of the gels was conducted with compression tests at ambient temperature using a flat-ended 40-mm diameter cylindrical aluminium probe with a 2 mm/s test speed (Alsanei et al. 2015). The initial slope in the viscoelastic region was calculated as the Young’s modulus of the samples as the force per area. As the shape of the gel samples were a flat-topped pyramid, the effective cross-sectional area was calculated as geometric mean of the top and bottom surfaces from the dimensions presented in Figure 4.1. Compression tests for each concentration were repeated five times, and the mean Young’s modulus was obtained.

5.2.2.2 Sensory Tests

5.2.2.2.1 Participants

The same participants as in Chapter 4 were recruited for this sensory study. The 32 participants (15 females and 17 males) were non-smokers with no reported medical problems, eating disorders, special diets, oral diseases, skin diseases or other health problems to avoid bias due to any of these. The age range was 21 to 62 years (mean 34 ± 9 years), and the mean body mass index (BMI) was 23 ± 3 kg/m^2. During the session on informing the participants about the study, the test procedure was explained, and the participants were asked to sign the consent form if they agree to take part. Permission for the sensory tests was obtained from the faculty ethical committee (MEEC 12-013), and all test procedures followed the ethical rules and regulations as set by the University of Leeds, UK. All sensory tests were conducted in a purpose-designed sensory laboratory within the food science building at the University of Leeds.

5.2.2.2.2 Semi-Solid Elasticity Discrimination Capability Tests

As described earlier, elasticity perception is defined as the sensation obtained by gently compressing the sample without breaking it and assessing how it recovers to its original form (Brown et al. 2003). In the present study, the discrimination threshold for the elasticity of the gel samples was investigated using the Just Noticeable Difference (JND) method. The samples were arranged in ascending order of elasticity, although the participants were not made aware of this. The test method was a simple pairwise comparison, and the samples were presented pairs of a reference sample and a test sample. The participants were asked to apply a little compression with their tongue against the hard palate or dominant hand index fingertip against the presentation surface to observe the elasticity features of the samples. After each pairwise comparison, they were asked whether or not the two samples had the same elasticity. The test ceased after three consecutive positive responses, and the lowest of these three positive responses was used for the detection threshold of elasticity. Between the tests, the participant's fingertip was cleaned with wet wipes and dried with a paper towel. Similarly, during the oral assessment of the gels, the participants were asked to rinse their mouths with water between each sample tested.

5.2.2.3 Tactile Sensitivity Tests

The tactile sensitivity of the dominant index fingertip and tongue surface was assessed by two different methods: touch sensitivity and 2PD. The static and dynamic approaches for the tactile tests were also investigated. During the tests, the participants were blindfolded and were asked to sit in their most comfortable position. For the fingertip tactile sensitivity tests, they were asked to place their hand on the bench and to rest the fingertip so that it was available for the test. Similarly, for the tongue tactile sensitivity tests, they were asked to open their mouth and extend their tongue out in the most comfortable position. The testing surface was the front central position, approximately 1.5 cm from the front tip of the tongue.

5.2.2.3.1 Touch Sensitivity

The touch sensitivity threshold was assessed with Semmes–Weinstein Monofilament (SWM) Touch-Test® sensory evaluators purchased from North Coast Medical Inc. (Gilroy, CA 95020 USA). The set consists of 20 monofilaments designed to provide the non-invasive evaluation of cutaneous sensation levels throughout the body. The lowest force available was 0.008 g and the highest was 300 g, with intervals between them logarithmically increasing. The same protocol as described in previous chapters was applied.

During the assessment of static touch sensitivity, the monofilament was pressed perpendicular against the test surface until the filament bowed and was kept stable in that position for 1.5 s. During the dynamic touch sensitivity assessments, instead of holding the bent monofilament stable, the investigator moved it horizontally. Both approaches started with the smallest force and increased in ascending order until the participant sensed the touch for three consecutive monofilaments. The lowest sensed monofilament force was then taken as their touch sensitivity threshold. Between the tests, monofilaments were wiped with antibacterial wet wipes.

5.2.2.3.2 Two-Point Discrimination Tests

The 2PD threshold was examined using two different approaches: static and dynamic. The test applicator, purchased from North Coast Medical Inc. (Gilroy, CA, USA), was designed to measure the narrowest gap between two pressure points that could be separately sensed, with the distance between the points adjustable between 0.25 mm and 15 mm.

For the static tests, the discriminator was pressed perpendicular to the test surface for 1.5 s in a static manner. During the dynamic procedure, the discriminator was horizontally moved on the test surface. Both tests started with 8 mm between the points and continued with the gap narrowing towards the smallest distance of 0.25 mm. The participants were asked to report how many points they could sense, and the tests were ceased when they sensed only a single touch point for two consecutive gaps. The narrowest distance correctly sensed as two separate points was taken as their 2PD threshold. Between each test, the discriminator was cleaned with an antibacterial wipe.

5.2.2.4 Statistical Analysis

Data obtained from these experiments were analysed with XLSTAT (Microsoft, Mountain View, CA), with additional descriptive statistical analysis such as means, medians, standard deviations and confidence intervals calculated in Microsoft Office Excel 2010 (v14.0). Data for the threshold values for texture discrimination and touch sensitivity were presented using log-normal (probit analysis) best fitting to find the participants' JND values.

5.3 Results and Discussion

5.3.1 Elasticity Measurement of Gels

Elasticity or Young's modulus values were assessed with the texture analyser, and the results are presented in Table 5.2

Table 5.2 Semi-solid samples actual Young's modulus values (N), Young's modulus ratio (△I/I) of each sample calculated by dividing the difference from reference (△I) to the actual Young's modulus of the reference sample (* reference sample).

Sample Number	Actual Young's Modulus (10^4 x Pa)	Young's Modulus difference from the reference (Pa)	Young's Modulus ratio	Multiplication factor
	I	△I	△I/I*	$\frac{(\frac{\Delta I}{I})_n}{(\frac{\Delta I}{I})_{n-1}}$
1*	2.69	0.00	0.00	-
2	2.74	0.05	0.02	-
3	2.80	0.11	0.04	2.00
4	2.85	0.16	0.06	1.50
5	2.91	0.22	0.08	1.33
6	2.97	0.28	0.10	1.25
7	3.03	0.34	0.13	1.30
8	3.09	0.40	0.15	1.15
9	3.15	0.46	0.17	1.13
10	3.36	0.67	0.25	1.47

As described earlier, the samples were selected according to their Young's modulus value so as to have minimal increments. These increments were obtained using the multiplication factor as shown in the table. The mean multiplication factor, taken as the elasticity of the more elastic sample divided by the elasticity of the less elastic sample, was calculated to be 1.39 ± 0.26, which shows the magnitude of the difference between stimuli. This value can be also expressed as elasticity being incremented by a factor of 0.39-fold or 39 % between the samples.

5.3.2 Sensory Tests

5.3.2.1 Elasticity Discrimination Capability

The gel samples were tested for their elasticity discrimination threshold with sensory tests. The results of these threshold tests were presented as log-normal plots for the cumulative response of the population of participants against the logarithmic elasticity difference (%) values, where the median value was selected as the representative threshold for all the participants.

Figure 5.2 shows the elasticity discrimination capabilities of the index fingertip (a) and tongue (b) for the participants as a cumulative response against the logarithm of elasticity ratio.

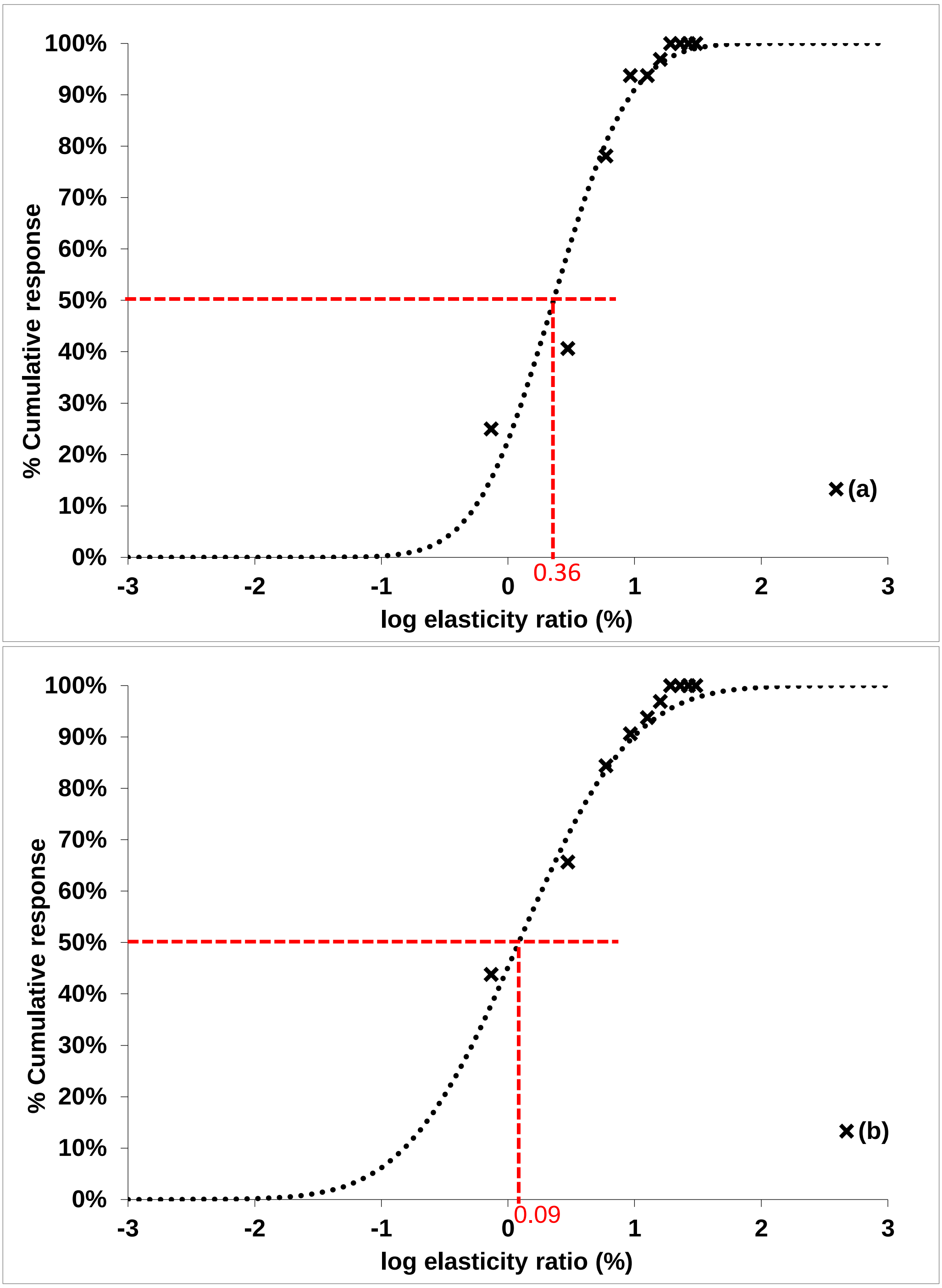


Figure 5.2 Log-normal best fitted (probit analysis) cumulative responses of participants (n = 32) shown as population percentage against the logarithmic elasticity ratio (%); (a) the fingertip (Median: $10^{0.36}$ = 2.7 %); (b) the tongue (Median: $10^{0.09}$ = 1.2 %).

From this, the elasticity discrimination threshold was observed to be 2.7 % for the fingertip and 1.2 % for the tongue. These findings highlight that to change the elasticity of food sufficiently to be perceived by the consumer, the Young's modulus of the food needs to be changed by 2.7 % for fingertip detection and by 1.2 % for tongue detection. Statistical analysis showed no significant difference between the sensitivity of the tongue and fingertips (p > 0.05).

As well as the threshold investigation, another important part of this study has been shown by descriptive analysis (95 % confidence intervals) for the female and male participants, as can be seen in Table 5.3. These calculations did not show a statistically significant difference between genders for the firmness discrimination capability (p > 0.05).

Table 5.3 Descriptive statistics for mean elasticity discrimination capability tests, which shows the mean, standard deviation and 95 % confidence interval lower and upper bound values for female and male participants (n = 32, 15 females and 17 males).

Group	Elasticity discrimination capability (%)		Standard deviation		95 % confidence interval			
					Lower bound	Upper bound	Lower bound	Upper bound
	Fingertip	Tongue	Fingertip	Tongue	Fingertip		Tongue	
Female	6.60	5.60	1.60	1.50	3.20	10.00	2.40	8.90
Male	4.60	2.90	0.70	0.70	3.10	6.20	1.40	4.40
Overall Mean	5.60	4.20	0.80	0.80	3.80	7.27	2.50	5.90

No significant difference was found for the sensitivity of elasticity discrimination capability between the fingertip and tongue (p > 0.05), as confirmed by the plots in Figure 5.2. The experiment in Chapter 4 also did not show a sensitivity difference for firmness discrimination, suggesting that the tongue has a similar texture perception magnitude to the fingertip. However, it should be noted that this was not the case for viscosity discrimination (Chapter 3), where the tongue was found to be slightly more sensitive to texture.

To our knowledge, no evidence has been reported for firmness discrimination by non-oral and oral parts of the body previously; therefore, to support and further confirm these findings, it is necessary to obtain thresholds for the gel firmness discrimination capability by other independent researchers.

5.3.2.2 Tactile Sensitivity

5.3.2.2.1 Touch Sensitivity

The SWM tool was used for the assessment of touch detection thresholds of the fingertip and tongue. This is a popular technique for touch sensation determination, although its reliability in clinical assessments is still a matter of controversy (Jerosch-Herold 2005, Bell-Krotoski and Tomancik 1987, Lundborg 2000, Schreuders et al. 2008).

Figure 5.3 illustrates the log-normal (probit analysis) best-fitted curves for the cumulative population response plotted against the static touch sensitivity of the fingertip (a) and tongue (b).

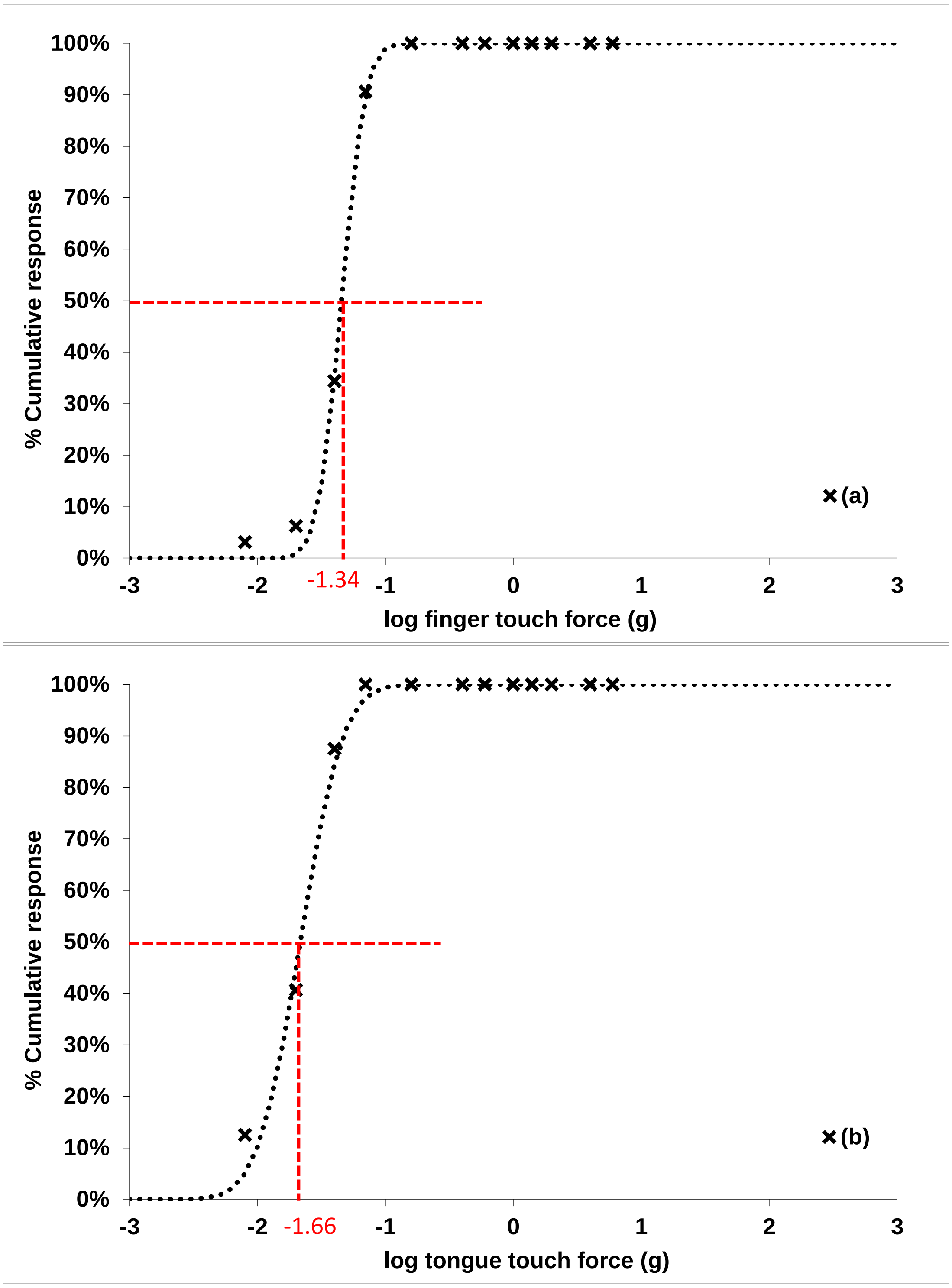


Figure 5.3 Log-normal fited (probit analysis) cumulative response of the participants (n = 32) shown as the population percentage against the static touch sensitivity (g): (a) the index fingertip ($10^{-1.34}$ = 0.046 g); (b) the tongue ($10^{-1.66}$ = 0.021 g).

This shows that the fingertip is only sensitive to a force more than 0.046 g, while the tongue shows a threshold of 0.021 g (the response of 50 % of the participants, i.e. the population threshold). Similar to the previous touch sensitivity findings, the tongue shows a slightly higher sensitivity than the fingertip (p < 0.05).

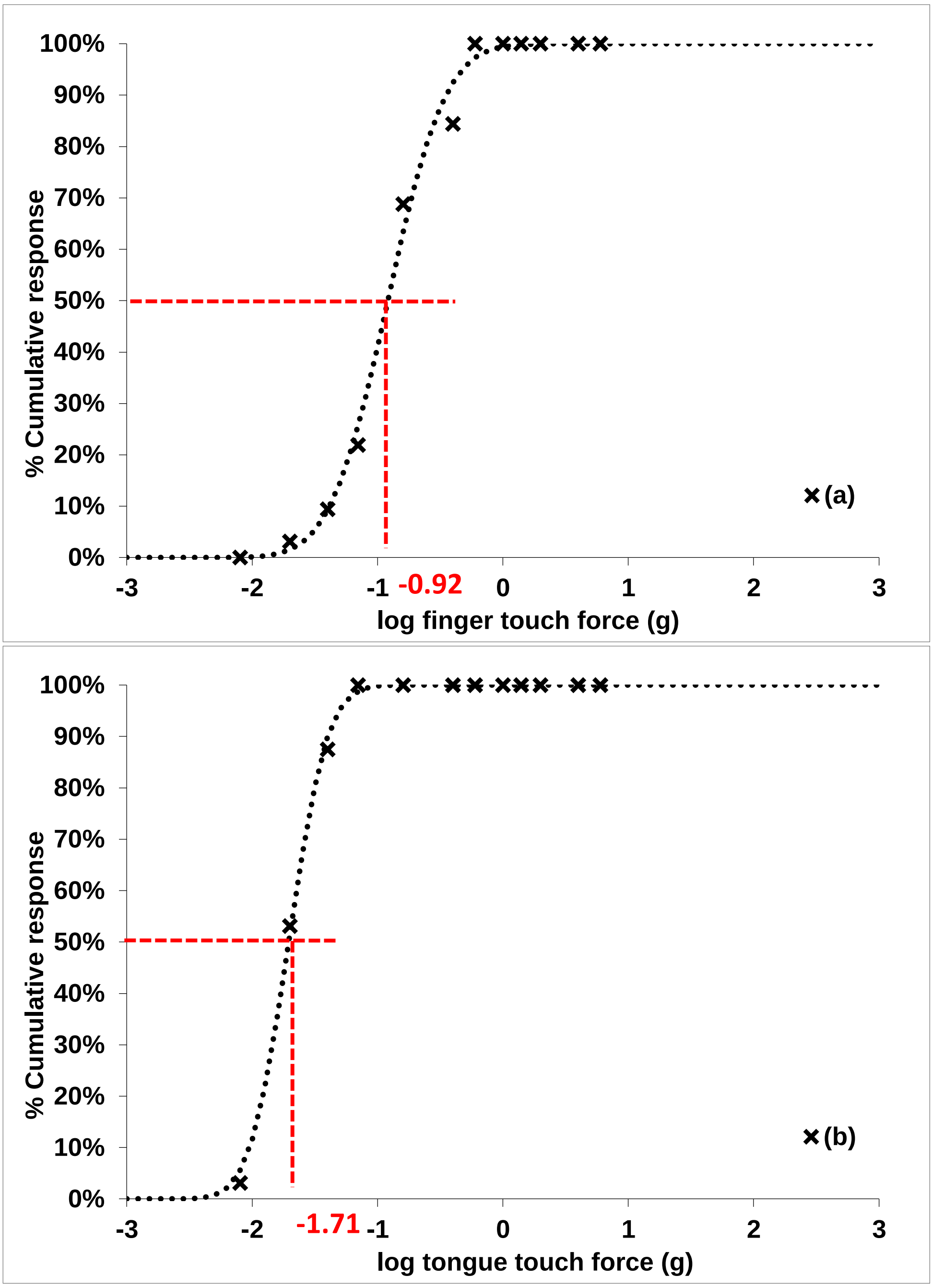


Figure 5.4 Log-normal fitted (probit analysis) of the participants (n = 32) shown as the cumulative population percentage against the dynamic touch sensitivity (g): (a) the index fingertip ($10^{-0.92}$= 0.12 g); (b) the tongue ($10^{-1.71}$= 0.02 g).

As shown in Figure 5.4a, the fingertip is only sensitive to a dynamic stimulus greater than a force of 0.12 g. Similarly, the dynamic sensitivity population threshold for the tongue was 0.020 g force (Figure 5.4b). Again, the tongue shows a higher sensitivity for dynamic touch sensation than the fingertip ($p < 0.05$).

The dynamic and static touch sensitivity values were compared. For the fingertip, touch sensitivity was significantly higher in the static test than that in the dynamic test ($p < 0.05$); however, for the tongue, there was no significant difference in touch sensitivity between the static and dynamic tests ($p > 0.05$), with almost equal threshold values. These findings show that the static approach may be a better option, giving better sensitivity at least for the fingertip. A possible reason for the greater sensitivity of the static tests is inconsistency in the force load while horizontally moving the monofilament across the test surface, which could have caused variation in the results during dynamic tests.

As with the previous experiments, the touch sensitivity data were analysed in conjunction with descriptive statistics for gender and the total group, as shown in Table 5.4. There were no statistically significant differences between genders for either static or dynamic sensitivity ($p > 0.05$).

Table 5.4 Descriptive statistics for mean touch sensitivity (static and dynamic), which shows the mean, standard deviation and 95 % confidence interval lower and upper bound values for female and male participants (n = 32, 15 females and 17 males).

Group	**Static touch sensitivity (g)**		**Standard deviation**		**95 % confidence interval**			
					Lower bound	**Upper bound**	**Lower bound**	**Upper bound**
	Fingertip	**Tongue**	**Fingertip**	**Tongue**	**Fingertip**		**Tongue**	
Female	0.07	0.03	0.008	0.003	0.05	0.08	0.02	0.04
Male	0.09	0.03	0.02	0.002	0.04	0.14	0.02	0.03
Overall Mean	0.08	0.03	0.01	0.002	0.05	0.10	0.26	0.03
Group	**Dynamic touch sensitivity (g)**		**Standard deviation**		**95 % confidence interval**			
					Lower bound	**Upper bound**	**Lower bound**	**Upper bound**
	Fingertip	**Tongue**	**Fingertip**	**Tongue**	**Fingertip**		**Tongue**	
Female	0.21	0.03	0.06	0.005	0.07	0.34	0.02	0.04
Male	0.23	0.03	0.06	0.004	0.11	0.35	0.02	0.04
Overall Mean	0.22	0.03	0.04	0.003	0.13	0.30	0.03	0.04

Previous study by (Pont et al. 1999) have found the static and dynamic approaches for touch sensitivity measurement to be similar. However, there is limited comparative evidence regarding these approaches.

5.3.2.2.2 Two-Point Discrimination

Tactile spatial acuity was assessed with 2PD using both static and dynamic approaches. As described earlier, 2PD evaluates tactile sensitivity by establishing the narrowest distance between two pressure points that are distinctly perceptible (Cholewaik and Collins 2003, Craig and Lyle 2001).

Figure 5.5 shows the results for the measurements of static and dynamic 2PD capability for the fingertip and tongue. Taking the 50 % cumulative response as the threshold, as used as the standard in the other analyses, was not appropriate here as the range of values that could be measured was not wide enough to cover the lower population ranges. Therefore, as in Chapters 4, the results of the 2PD tests were presented as mean values. For static 2PD, 1.42 mm and 0.62 mm were found to be the mean thresholds for the fingertip and tongue, respectively. For the dynamic 2PD tests, the mean thresholds for the fingertip and tongue were 1.16 mm and 0.93 mm, respectively. Overall, there was no statistically significant difference between the two different test approaches ($p > 0.05$), but the tongue was significantly more sensitive than the fingertip ($p < 0.05$), with this difference being greater with the static approach.

Previous reports suggest that static 2PD testing has a higher reliability and control over the procedure (Ferreira et al. 2004). The static testing procedure was easier to control with a constant force load.

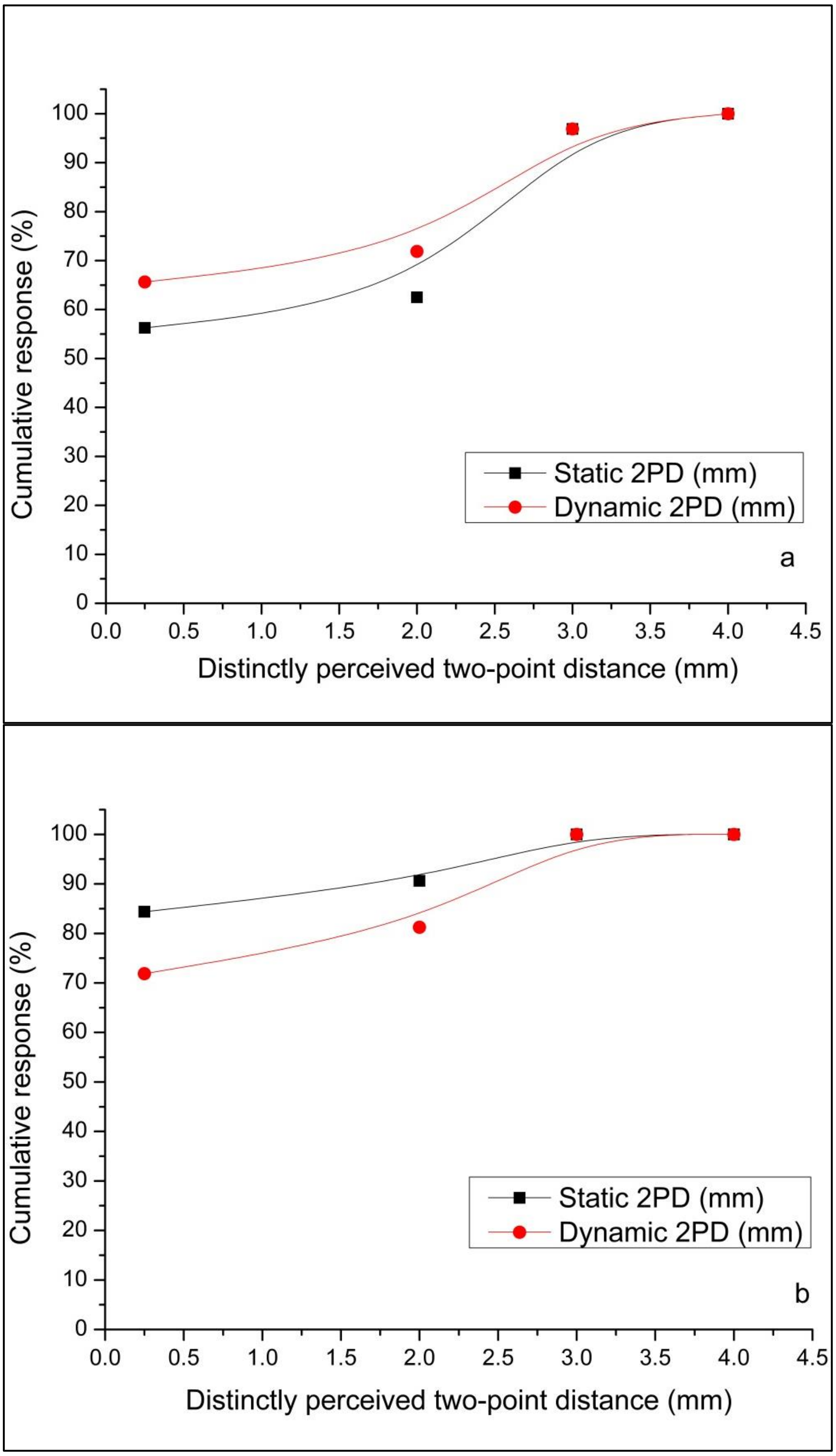


Figure 5.5 Cumulative responses of participants (n = 32) shown as population percentage against the distinctly perceived two-point distance (mm); (a) index fingertip static (mean = 1.42 mm) and dynamic (mean = 1.16 mm); (b) tongue static (mean = 0.62 mm) and dynamic (mean = 0.93 mm).

The data from the static and dynamic 2PD tests were analysed in conjunction with the descriptive statistics to investigate potential differences between genders and also to find the mean and standard deviation values with 95 % confidence intervals. These are presented in Table 5.5. There was no significant difference between genders for static and dynamic 2PD for the fingertip and tongue ($p > 0.05$). However, the tongue was more sensitive than the fingertip for either gender ($p < 0.05$).

Table 5.5 Descriptive statistics for 2PD (static and dynamic), which shows the mean, standard deviation and 95 % confidence interval lower and upper bound values for female and male participants (n = 32, 15 females and 17 males).

Group	Static2PD (mm)		Standard deviation		95 % confidence interval			
					Lower bound	Upper bound	Lower bound	Upper bound
	Fingertip	Tongue	Fingertip	Tongue	Fingertip		Tongue	
Female	1.42	0.43	0.40	0.20	0.60	2.25	0.04	0.83
Male	1.43	0.78	0.32	0.25	0.75	2.11	0.26	1.30
Overall Mean	1.42	0.62	0.24	0.16	0.92	1.92	0.29	0.94
Group	**Dynamic 2PD (mm)**		**Standard deviation**		**95 % confidence interval**			
					Lower bound	**Upper bound**	**Lower bound**	**Upper bound**
	Fingertip	**Tongue**	**Fingertip**	**Tongue**	**Fingertip**		**Tongue**	
Female	1.16	0.93	0.36	0.27	0.40	1.94	0.30	1.44
Male	1.16	1.00	0.31	0.30	0.50	1.83	0.40	1.63
Overall Mean	1.16	0.93	0.23	0.20	0.69	1.64	0.50	1.30

The findings in literature about 2PD thresholds are presented in Table 5.6, showing similar results to those observed in the present study.

Table 5.6 Reported static 2PD values for the fingertip and tongue.

Researcher	Fingertip 2PD threshold (mm)
Chandhok and Bagust (2002)	1.66 ± 0.09
Menier et al. (1996)	2.2
van Boven and Johnson (1994)	0.94
Researcher	**Tongue 2PD threshold (mm)**
Minato et al. (2009)	1.09 ± 0.35
Okada et al. (1999)	1.7 ± 0.1
Brill et al. (1974)	1.08 ± 0.23
van Boven and Johnson (1994)	0.58

5.3.2.3 Correlations between Elasticity Discrimination Capability and Tactile Sensation

The aim of the experiment described in this chapter was to investigate the correlation between elasticity discrimination capability and tactile sensitivity (with its two different measurements: touch detection and 2PD). As the static tests showed higher sensitivity, only the static data were used for the correlations.

Correlations between the elasticity discrimination capability and tactile sensation can be seen in Figure 5.6. As can be observed from these two graphs neither the fingertip (Figure 5.6a) nor the tongue (Figure 5.6b) showed statistically significant correlations between the elasticity discrimination capability and touch detection sensitivities ($p > 0.05$).

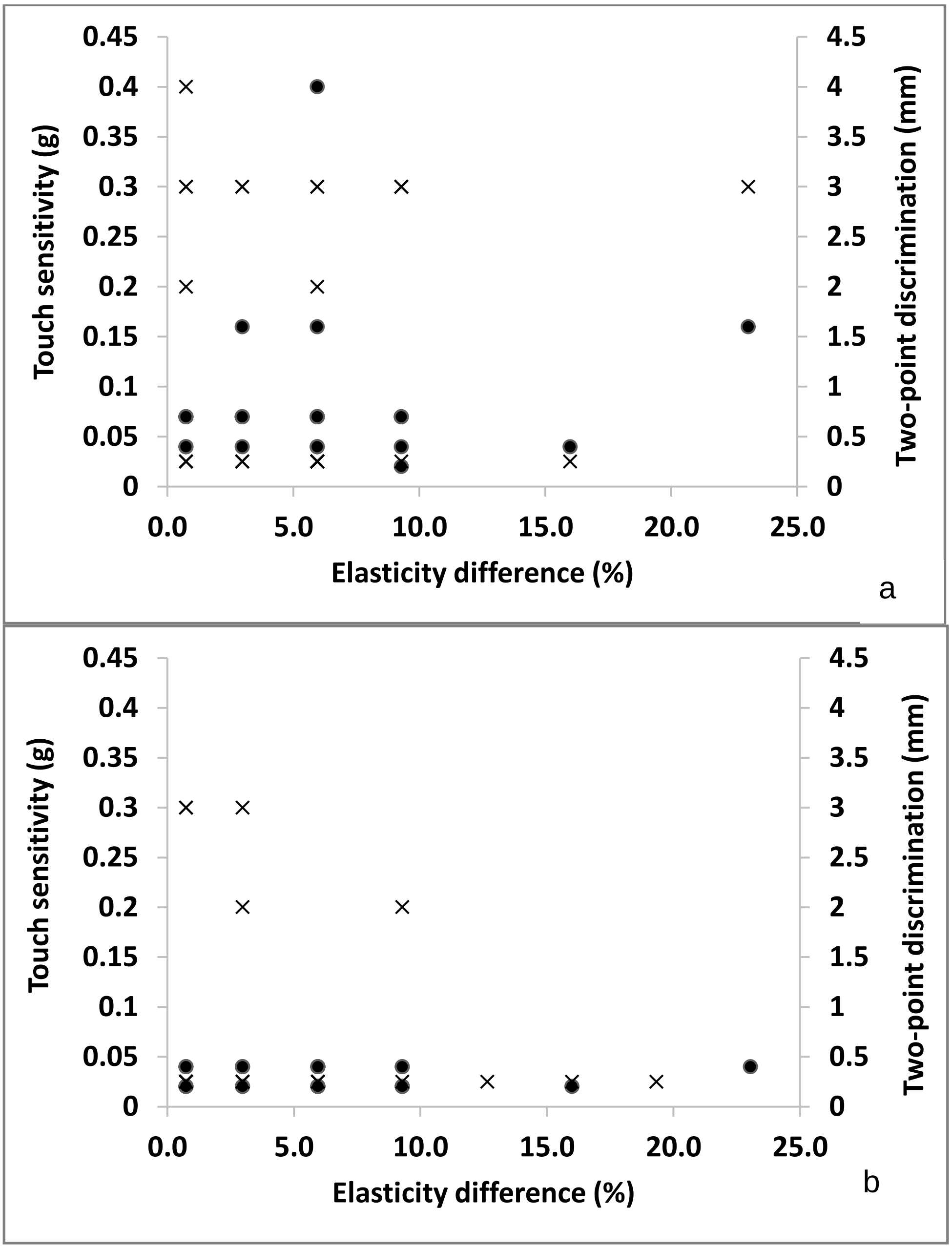


Figure 5.6 Individual's (n = 32) capability of elasticity discrimination and touching sensitivity (●) and two-point discrimination ability (×): (a) index fingertip; (b) tongue.

Finding no correlations goes against our initial expectation that there would be a correlation between elasticity discrimination and tactile sensation. There are numerous possible reasons for this result. Due to the complex nature of the elasticity sensation mechanism, the participants may not have been able to sense elasticity alone, but perhaps with dynamic changes occurring with the sample. It is still not certain that mechanoreceptors do not indicate the sensitivity of texture, but they might be contributing to rather than dominating the sensation mechanism. It is also still a possibility that texture perception is a learned rather than an innate ability, which could be developed through daily experience and cultural customs about food, as described in detail in the previous two chapters. It is also possible that the lack of correlation could be due to the nature of limitations in the tactile sensitivity test instruments as described in the previous chapters.

Bringing together the results from Chapters 3 and 4 and the current chapter, it appears that the tongue has similar texture perception limits to the fingertip. These findings open the door to the possibility of testing texture perception limits with the fingertip alone, and then, using the data to ‘predict’ oral perception.

5.4 Limitations

The findings from the present study are important, but its limitations should also be highlighted. As discussed above, the complex and dynamic nature of texture perception could have caused some bias in the elasticity observed. With the aim of minimising distraction from different textural attributes by only assessing the elasticity, the participants were asked to apply only gentle compression to the sample. Additionally, the samples used in this study were gels, which have a highly temperature-dependent structure. Although care was taken to minimise the influence of temperature change during the sensory tests, the possibility of this could not entirely be eliminated. Heat exchange between the fingertip or mouth and the gel would be expected to cause some variation.

Another limitation arose from the instruments used to assess the tactile sensitivity levels. In particular, the 2PD instrument was not sensitive enough for the healthy individuals tested, resulting in much narrower graphs that prevented the 50 % value being used as the threshold, requiring mean 2PD threshold values to be used for the non-oral and oral conditions. To obtain results with better resolution, there is a need for an alternative 2PD technique that has smaller increments.

5.5 Conclusion

In this study, the elasticity discrimination and touch detection thresholds and 2PD capabilities were measured for 32 participants on their dominant hand index fingertip and tongue surface to find out whether there was a significant correlation between the tests. The elasticity discrimination threshold was found to be 2.7 % for the fingertip and 1.1 % for the tongue, indicating the change in Young's modulus needed for a sample's elasticity to be perceived by these two parts of the body as being different. These two parts of the body did not show significant difference in terms of texture discrimination ($p > 0.05$). The touch detection threshold tests were performed both statically and dynamically. The static touch sensitivity was observed to be 0.046 g and 0.021 g for the fingertip and tongue, respectively, whereas the dynamic touch sensitivity was 0.12 g and 0.02 for the tongue. Similarly the 2PD experiments were performed both statically and dynamically. The static 2PD for the fingertip and tongue were found to be 1.42 mm and 0.62 mm, respectively, whereas the dynamic 2PD threshold was 1.16 mm for the fingertip and 0.93 mm for the tongue.

These experimental results do not support the hypothesis that there is a relationship between the elasticity discrimination threshold and tactile sensitivity measurements which ideally should be approved or disproved by independent researchers. Also further attributes of texture could be tested to contribute to the literature. The findings of Chapter 4 and current study, illustrated that tongue and finger has similar texture discriminating capability, therefore future studies could in principle only involve tests with fingertips to predict the oral discrimination.

Chapter 6
Roughness Discrimination Capability under Different Syrup Solutions, Temperatures and Force Loads

6.1 Introduction

Surface texture, i.e. surface topography, is a physical property of solid materials (Quevedo and Aguilera 2004). Surface topography is scale-dependent, which means a surface might look smooth, but when investigated under higher magnifications, it can be seen that the surface is rough. Surface properties can often be visually detected, but more often, they are detected through tactile sensation. In engineering surface texture is predominantly characterised by the coefficient of friction and roughness attributes (Shao et al. 2010). These attributes are critically important for consumer preference and also manufacturing processes, especially for solid surfaces such as wood, glass, fabrics, etc. Similarly, during oral processing, perceived roughness is a determinative factor for liking or disliking a product. For instance, for some individuals, the impurity they sense in some foods is not acceptable, considering it to be somehow rougher. Additionally, the roughness of a material has an impact on engineering operations (Quevedo and Aguilera 2004).

Surface texture is explored simply by stroking the fingertip with a particular loading force across the surface of the material (Adams et al. 2013). During these explorations, mechanoreceptors detect textural features. Bensmaia and Hollins (2003) suggested that sliding the fingertip causes vibrations that are then measured by mechanoreceptors. Sliding the finger pad on surfaces with different wavelengths may trigger different mechanoreceptors with different selective frequencies (Shao et al. 2010).

Tactile perception can be differentiated as physical or affective (Childs and Henson 2007). Physical tactile perception refers to the physical assessments on the basis of experimental data, such as evaluations of surface roughness, softness or warmth (Childs and Henson 2007, Treutwein 1995). Affective tactile perception is the relationship between a product and an individual’s judgement (Jordan 2000). It includes subjective emotions, feelings, sentiments or moods that may influence the decision to purchase the product (Akay et al. 2012, Henson et al. 2006, Russell 2003). In this regard, it can also be said that topographical features can be assessed by two different methods: instrumental assessments (physical) or sensory tests (affective). Instrumental roughness assessment techniques can be classified as contact and non-contact methods. The former includes the profilometer measurements that operate through direct contact with the surface and scan across it. The latter methods are considered to be non-invasive and are preferred when the surface is delicate (e.g. for some food surfaces). Non-contact methods include optical techniques such as optical interferometry, confocal laser microscopy and light microscopy (Bennett 1992, Thomas 1999, Cao et al. 1991, Pedreschi et al. 2000, Russ 1986, Hershko et al. 1998). Irrespective of the method used for an assessment, there will still be the major limitation of relating these assessments to real sensations. An ideal future plan for this scientific field would be to find a relationship between the affective responses of consumers and the topographical properties of surfaces, which would allow consumer behaviour to be estimated without sensory testing but with a mathematical model.

Consumer perception is important for industry as it plays an important role in preference (Barnes et al. 2004, Grohmann et al. 2007). Product design is a key factor in the business environment, and the design of surface texture for car interiors, furniture or packaging materials is critical for business success (Trueman and Jobber 1998, Karkkainen et al. 2001). It is well known that positive feedback towards products positively influences the purchasing decision (Khalid and Helander 2006, Holbrook and Hirschman 1982). Importantly, in the market, there are alternatives for every kind of product; therefore, to move forward, it is essential to understand what customers expect and need and how to control this. Thus, the dynamics of tactile sensation and the findings related to this will be valuable for many disciplines including product design, psychophysics, neuroscience and computational modelling (Elkharraz et al. 2014). Investigating tactile sensation is a difficult task; however, if the attribute can be specified in detail, it is likely that a good fit between the findings and actual sensation can be developed.

With regard to the instrumental observations of surface topography, studies have revealed important findings. For instance, Chen et al. (2009) highlighted that smooth–rough perception was related to the coefficient of friction and roughness values. Hollins et al. (1993) reported that roughness–smoothness was found to be a robust dimension of touch perception and that the ‘feel’ of an object depends on a combination of perceptual properties. On this basis, roughness can be used as a measure of touch perception under certain conditions. Friction coefficient and roughness have also been claimed to have an effect on slippery–sticky, bumpy–flat and wet–dry perceptions (Hollins and Bensmaïa 2007). These relationships illustrate that touch perception has complicated interactions with textural features and that perception is dependent on more than one physical property. Phillips and Johnson (1981) emphasised that there is some correlation between roughness and the coefficient of friction and that the oscillation amplitude applied by an individual making the assessment was found to depend on fingerprint ridges and friction coefficient (Penfield and Rasmussen 1950, Valbo and Johansson 1978). Based on these findings, it was planned that roughness and the coefficient of friction would be used in the present study as physical measures to understand the limits of human touch perception under different force loads, syrup solutions and temperatures.

The first topographical physical assessment was selected to be the measurements of surface roughness (R_a). Roughness can be defined as a measure of height differences combined with the spatial properties of the surface (Eck et al. 2013, Bergmann Tiest and Kappers 2006). Roughness is mainly mediated through vibratory information as well as spatial variance (Katz and Krueger 1989). Further studies on roughness have highlighted that it is dependent on vibrotactile cues for particle sizes below 100 µm (Bensmaia and Hollins 2005). However, for larger particle sizes, spatial cues were found to be responsible (Blake et al. 1997). This concept, as mentioned in previous chapters, is called the duplex theory which states roughness perception as a psychophysical and context-dependent attribute (Bergmann Tiest 2010). Many roughness perception studies have been reported. A review by Bergmann Tiest (2010) suggested that roughness perception has a correlation with physical surface properties such as friction, height difference and spatial pattern. The relationship between tactile perception and roughness has been tested for: cosmetic packages (Bergmann Tiest and Kappers 2006), car crash pads (Bahn et al. 2007), touch screen-printed surfaces (Childs and Henson 2007), car interior components (Liu et al. 2008), wood, sandpaper and velvet (Hollins et al. 1993), linear gratings (Cascio and Sathian 2001) and dot pattern stimuli (Eck et al. 2013, Dépeault et al. 2009, Kahrimanovic et al. 2009).

The second physical surface texture assessment in the present study was the measurement of the dynamic coefficient of friction (μ) of the surface. The coefficient of friction is a dimensionless scalar value that depends on the material's surface properties. Often, it is defined as an empirical measurement (Dowson 1998). It is the major source of sensory information when surfaces are relatively smooth (Adams et al. 2013). Friction tests between a material and human skin are complicated because skin hydration, lipid films and surface structures vary between individuals. Skin conditions are also likely to be influenced by age and anatomical site (Shao et al. 2010). Friction is in texture sensation, and an increase in the coefficient of friction has been found to decrease the level of comfort (Gerhardt et al. 2008). Additionally, (Gerhardt et al. 2008) reported that an increased surface coefficient of friction for fabrics increase epidermal moisture which is important for gripping an object as well as sensory feeling. Conversely, Klatzky and Lederman (1999) and Yoshioka et al. (2011) suggested that friction does not play a primary role in assessing surface roughness, yet it is still reasonable to claim that friction properties of the surface correlate with roughness and also with tactile sensation. Samur et al. (2009) illustrated that subjects are capable of accurately ranking friction coefficients, and Smith and Scott (1996) stated that friction is a factor in discriminative touch. Extensive studies have been conducted on the surface friction properties of materials including packaging materials (Lewis et al. 2007); fabrics (Darden and Schwartz 2009, Gee et al. 2005); touch screen-printed surfaces (Childs and Henson 2007); paper, sand paper and cardboard (Skedung et al. 2011, Ekman et al. 1965); the skin (Gitis and Sivamani 2004); rocks (Gee et al. 2005) and glass (Samur et al. 2009). However, food samples remain relatively unstudied.

In the present study factors, affecting the sensation of the surface topography has been investigated with the fingertip by using solid plaques that has textured surfaces. This study was exploratory rather than hypothesis-based and aimed to establish answers to the following questions:

1. What is the roughness discrimination threshold and what are the effects of lubricants with various viscosities and temperatures?
2. What is the effect of force load on the sensitivity of roughness discrimination?

6.2 Materials and Methods

6.2.1 Materials

Acrylonitrile Butadiene Styrene (ABS) plastics were used in this study (Standex International Ltd., Cheshire, UK). These are low-cost engineering plastics that are easily processed for fabrication and were found to be ideal materials for structural applications due to their strength, stiffness and resistance to impact, chemicals and heat. Different surface textures were available, and eight surfaces were selected for this study. Using ABS plastics gave the opportunity to use same samples with each participant.

6.2.2 Methods

6.2.2.1 Physical Assessment of the Surface Texture

6.2.2.1.1 Ra measurements

This study measured arithmetical mean roughness R_a (µm), the integral of the deviations from the mean height of the peaks and valleys of the surface. Roughness was measured using an NPflex 3D surface metrology system (Bruker Ltd., Tuscan, USA). From this measurement a three-dimensional texture profile was generated, and post-processing software was used to obtain R_a roughness values.

6.2.2.1.2 Coefficient of Friction Measurements

The coefficient of friction was determined using a tactile measurement system consisting of a two-axis load cell (MiniDyn multicomponent dynamometer type9256C2, Kistler), an X–Y motion table (series 1000 cross roller, motion link), an artificial fingertip as described by Shao et al. (2009), a controller, and a personal computer (PC) (Figure 6.1). The artificial fingertip comprises a soft visco-elastic core mounted on a hard, polyurethane back, and a soft polyurethane surface layer that has friction properties similar to human skin. The artificial finger is used as a tribology slider because of the large variation in friction properties of individuals' skin, which is dependent on factors such as environmental conditions and which makes human fingers unsuitable as 'standard' tribology sliders (Shao et al. 2009).

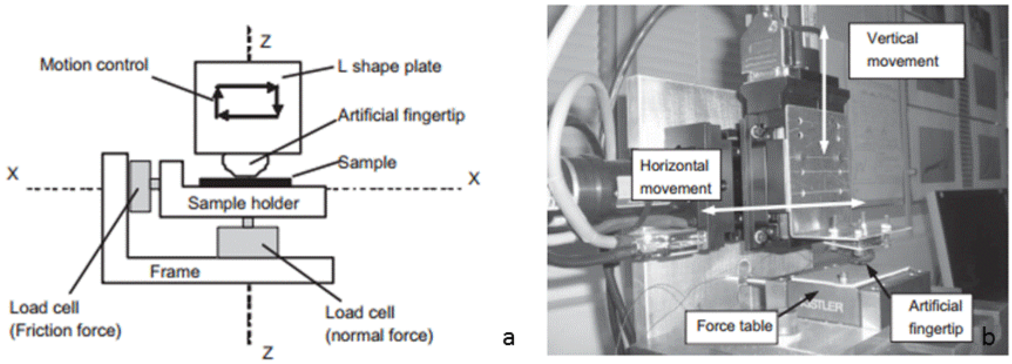


Figure 6.1 (a) Schematic illustration of the friction measurement system and (b) friction measurement with artificial fingertip (Shao et al. 2009).

The artificial fingertip is mounted to the two-axis load cell and the plaque with the surface texture is attached to the table. The operation is based on the motion of an artificial fingertip over the surface of the plaques at force and speed, which correspond to human contact values. The amplitude of frictional force *F* and normal force *N* are recorded against time with a *LabVIEW* system. The coefficient of the friction is then calculated from the equation:

$$\mu = \frac{F}{N} \tag{6.1}$$

where *F* is the amplitude of frictional force and *N* is the normal force.

During the measurements friction coefficients were measured five times for each plaque and the values were averaged.

6.2.2.2 Sensory Assessment of Tactile Sensitivity and Surface Texture

6.2.2.2.1 Participants

A total of 62 participants (31 females and 31 males) were recruited for this study. The participants had no reported medical complications, skin problems or other known health problems that may have influenced the results of the test. The mean age was 33 ± 7 years. All participants were recruited from the campus of the University of Leeds and were either students or university staff. Written consent was obtained from each participant prior to the test. During the initial introduction, the participants were informed of the procedure, but they were not told of the purpose of the investigation. All sensory tests were conducted in a purpose-designed sensory laboratory within the food science and nutrition building at the University of Leeds. Ethical permission was obtained from the faculty ethical committee (MEEC 12-013), and all test procedures followed the ethical rules and regulations as set by the committee.

6.2.2.2.2 Test procedures

To answer the questions asked in the current study these, five different sensory tasks were planned.

Task 1. Roughness discrimination threshold: in air, water, and low, moderate and high viscosity Newtonian solutions at room temperature (25 °C).

Task 2. Roughness discrimination threshold: in water and low, moderate and high viscosity Newtonian solutions at body temperature (37 °C).

Task 3. Scoring of the sensed roughness under different conditions: in air, water and low, moderate and high viscosity Newtonian solutions at room temperature (25 °C).

Task 4. Scoring of the sensed roughness under different conditions: in water and low, moderate and high viscosity Newtonian solutions at room temperature (37 °C).

Task 5. Effect of force load on roughness sensitivity: in water and air at room temperature (25 °C).

Tasks 1 to 4 involved plaques which were submerged in different solutions so that a thin layer of lubricant was presented during the finger tactile test to investigate the effect of the lubricants' viscosity and temperature on the sensation of roughness. These findings were expected to elucidate the sensation dynamics for the skin surface when covered with a liquid (such as a moisturiser) and also to provide an indication of what could be happening inside the mouth during oral processing. Plaques were presented with three-digit blinded codes and were in a randomized balanced presentation order.

The samples were tested under the following subtasks:

1. In air.
2. In water, with the surface placed in a container with water covering the whole surface.
3. In 80 % syrup solution.
4. In 90 % syrup solution.
5. In 100 % syrup solution, as shown in Figure 6.2.

Figure 6.2 Sensory test conditions using different lubricants at a certain temperature.

Syrup (Lyle's Golden Syrup Tate & Lyle, Nottinghamshire, U.K.) was used as a medium in these tasks due to its Newtonian character, displaying a constant viscosity regardless of shear rate, which might considerably vary between individuals. The solutions of 80 % and 90 % syrup were prepared by dilution with distilled water. The syrup solutions were tested for their dynamic viscosities using a Kinexus rheometer (Malvern Instruments, Ltd., Worcestershire, U.K.). The measurements were taken at 25 °C and 37 °C using cone-and-plate geometry CP2/60 (60 mm diameter and 2° angle cone). Viscosity values were constant for a wide range of shear rates, demonstrating the Newtonian nature of the golden syrup. Viscosity tests were conducted three times with samples prepared from different batches, and the mean viscosity values and standard deviations were calculated (Table 6.1).

Table 6.1 Viscosity values of the syrup solutions at different temperatures including the standard deviation of the replicates.

Classifications of the solutions	**Solution**	**Viscosity ± Standard deviation (Pa.s)**
Low viscosity	80 % syrup (25 °C)	0.16 ± 0.02
	80 % syrup (37 °C)	0.07 ± 0.02
Moderate viscosity	90 % syrup (25 °C)	0.88 ± 0.02
	90 % syrup (37 °C)	0.29 ± 0.01
High viscosity	100 % syrup (25 °C)	34.6 ± 1.5
	100 % syrup (37 °C)	6.54 ± 0.29

More specifically for Tasks 1 and 2 participants were asked to stroke their fingertip on the pair of plaques with a constant reference plaque to answer if they are the 'same' or 'different'. The plaques were presented in randomised order. Participants' lowest different detection was taken as individuals' threshold of roughness discrimination, which was then plotted to observe population threshold.

For Tasks 3 and 4 participants were asked to stroke their fingertip on the pair of plaques with a constant reference plaque and scale the perceived roughness in comparison with the reference, in a 0 to 9 scale as shown in Figure 6.3. The reference plaque roughness was accepted as ‘0’. Obtained values for each plaque was then averaged for plotting the perceived roughness against the actual roughness value.

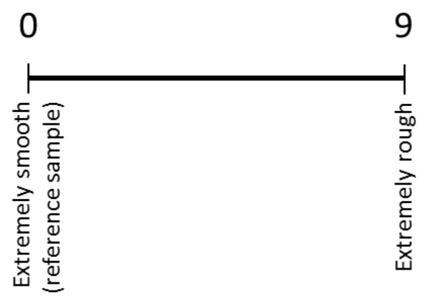


Figure 6.3 Sensory scale used in Task 3 and 4, for scoring the perceived roughness of the plaques, compared with a reference plaque which was described as ‘0’.

For task 5, roughness sensitivity versus applied force load was assessed to determine the effect of force load on sensitivity with four elected plaques (Table 6.2).

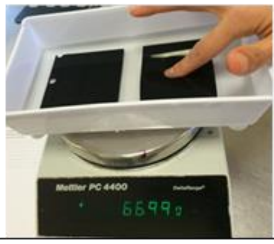
Table 6.2 Actual roughness values for the selected surfaces for pair-wise ranking test.

Surface number	Roughness (µm)
A	0.96
B	1.03
C	1.45
D	2.37

To define the various levels of force loading, two studies were used as reference. A study by Soneda and Nakano (2008) showed that 1 N is the optimum contact load for stimulus detection. Additionally, Adams et al. (2013)

reported that a load force up to 2 N would still be defined as a normal loading force for tactile exploration. It was therefore decided that a force between 0.8 N and 2.2 N would be categorised as a ‘moderate’ touch, a force up to 0.79 N classified as a ‘light’ touch, and a force between 2.21 N and 4 N defined as a ‘hard’ touch. The load force was measured by placing a balance underneath the test material, and the participants were trained to apply the correct range of force prior to the actual tests (Table 6.3).

Table 6.3 Descriptions of force ranges given to the participants (n = 30).

Force load, F_L (g)	$79 < F_L$	$80 < F_L < 220$	$221 < F_L < 400$
Inside air at 25°C			
Inside water at 25°C			

For each task specific number of participants, aim, materials, methods, descriptions, asked sensory question and the testing temperatures have been shown in Table 6.4.

Table 6.4 Details of the sensory assessment tasks applied in the current study.

	Task 1	Task 2	Task 3	Task 4	Task 5
Number of participants	32, (16 female, 16 male)				30, (16 female, 14 male)
Aim	To investigate the roughness discrimination threshold using lubricants with different viscosity and temperature.		To investigate the perceived roughness using lubricants with different viscosity and temperature.		To investigate the importance of force load on the surface roughness discrimination capability.
Material	8 different ABS plaques (1 reference, 7 test sample) (Table 6.5).				4 different ABS plaques (Table 6.2).
Methods	Pair-wise comparison of the constant reference plaque and sample plaques.				Pair-wise ranking with 2 alternative forced choice (2AFC) (Meilgaard et al. 2011). Plaques were compared with pairs in all possible permutations (6 comparisons per force load range).
Descriptions	Plaques were submerged in the lubricant and panellists were asked to slide their fingertip on the surface in order to sense the surface roughness.				Force load levels were divided in three different levels: light, moderate and hard touch. Loading force was controlled with a balance placed underneath the surfaces (Table 6.3).
Sensory Question	'Are they the same or different in terms of surface roughness?'		'What would you scale of the test plaques roughness on a scale of 0 to 9, where reference plaque has the value of 0?' (Figure 6.3)		'Within the described force range, explore the surface roughness of presented two surfaces and select the rougher/smoother plaque.'
Sub-tasks	1. In air. 2. In water. 3. In 80 % syrup solution. 4. In 90 % syrup solution. 5. In 100 % syrup solution.		1. In air. 2. In water. 3. In 80 % syrup solution. 4. In 90 % syrup solution. 5. In 100 % syrup solution.		For each force range: 1. In air. 2. In water.
Test temperature (°C)	25	37	25	37	25

6.2.3 Statistical analysis

Results obtained from Tasks 1 and 2 were plotted with probit analysis to observe log-normal best fitting lines, with the confidence intervals calculated using Microsoft Office Excel 2010 (v14.0). Statistical analysis was conducted in XLSTAT (Microsoft, Mountain View, CA) and Microsoft Office Excel 2010 (v14.0).

6.3 Results and Discussions

6.3.1 Physical Assessment of Surface Texture

6.3.1.1 Ra Measurements

Eight surfaces were selected based on their R_a values. Table 6.5 shows the surface roughness of the selected surfaces and percentage differences from the reference surface (1*). This ratio was used during data analysis and presentation to demonstrate the percentage change required for sensory discrimination.

Table 6.5 Actual roughness values of the plaques, with the calculation steps of the % roughness ratio (* indicates the reference value) (R_a indicates roughness value, where R_a* indicates the roughness of the reference plaque).

Surface number	Roughness (μm)	Difference from the reference (μm)	Difference ratio	% Difference ratio
		$Ra - Ra*$	$\frac{Ra - Ra*}{Ra*}$	$\frac{Ra - Ra*}{Ra*} x\,100$
1*	0.83	0.00	0.00	0.00
2	0.96	0.13	0.16	16.00
3	1.03	0.20	0.24	24.00
4	1.45	0.62	0.75	75.00
5	2.37	1.54	1.86	186.00
6	2.40	1.51	1.90	190.00
7	2.62	1.79	2.16	216.00
8	3.24	2.41	2.91	291.00

6.3.1.2 Coefficients of Friction Measurements

The results of friction coefficients measurement are shown in Figure 6.4. These experiments demonstrate that the measured coefficient of friction values were very similar for selected surfaces.

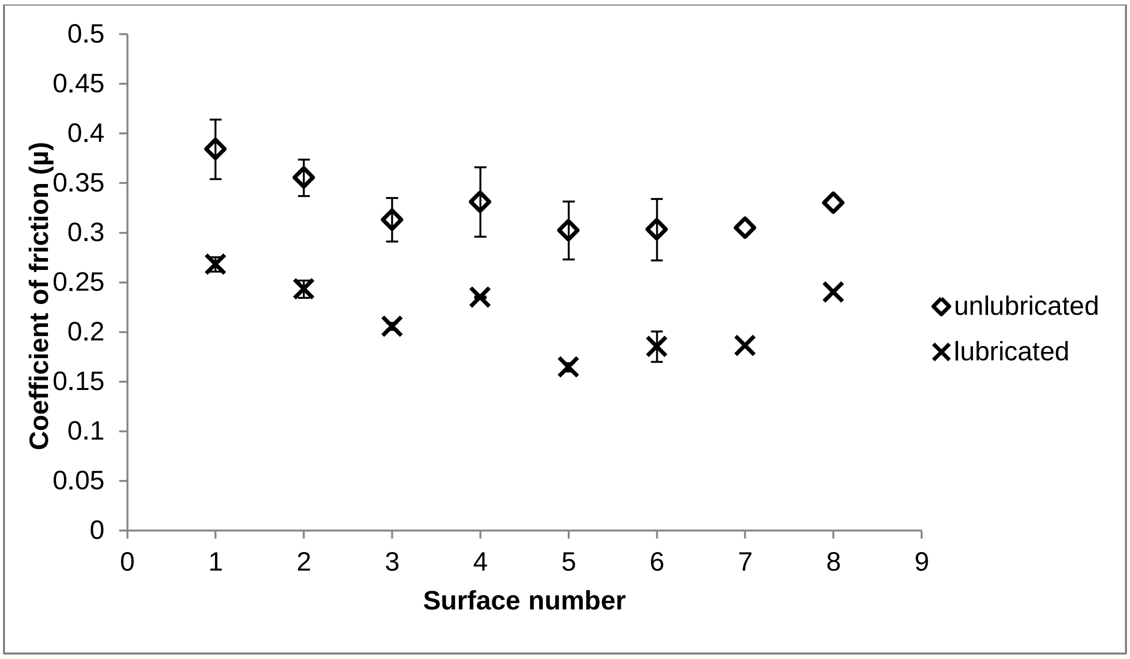


Figure 6.4 Friction coefficient values of the 8 plaques measured with artificial fingertip in air and in water at 25 °C. Surface number was as shown in Table 6.5.

Coefficient of friction is dependent not only on the surface topography but also to the manufactured material property. Hence, the observed similarity within the plaques could be explained due to using same manufactured material. Another possible explanation of the similarity for the coefficients of friction measurements could be due to the instrument used. The artificial fingertip works on a principle of force measurements and with the coefficient of friction calculated from the ratio of these forces. The test surfaces were deliberately selected from similar ones that may have had little differences between them. Noteworthy that artificial fingertip could have a limitation, though it is still an empirical measurement by defined method which with its current application did not detect difference between the used plaques. Hence, in the present study, R_a values were referred as an indicator for the coefficients of friction; which have been shown to correlate (Menezes et al. 2008).

6.3.2 Sensory Assessment of Tactile Sensitivity and Surface Texture

For obtaining a threshold JND is widely used in threshold studies. It is generally accepted that half of the cumulative population response can be used as the threshold value (Meilgaard et al. 2011, Laing 1983, Chaplan et al. 1994, Clark and Mehl 1971). In line with this approach, results of Tasks 1 and 2 were plotted with probit analysis, a log-normalisation process.

For Task 1 obtained cumulative population thresholds for each subtasks has been shown in Figure 6.5.

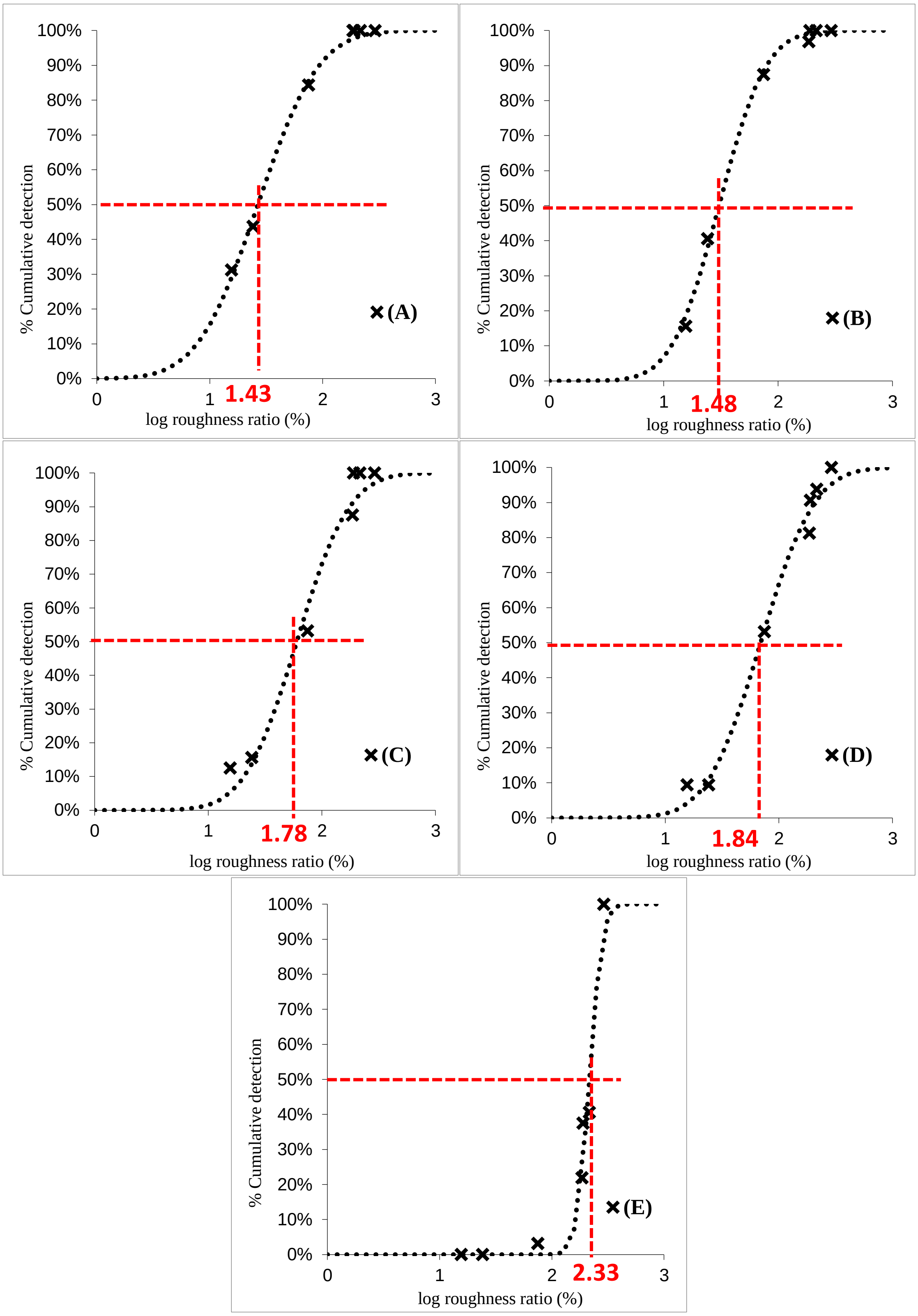


Figure 6.5 Log-normal fitted (probit analysis) (n = 32) cumulative population percentage against the roughness ratio at room temperature (25 °C) for: (A) in air (Median: $10^{1.43}$ = 29 %), (B) in water (Median: $10^{1.48}$ = 30 %), (C) in 80 % syrup (Median: $10^{1.78}$ = 60 %), (D) in 90 % syrup (Median: $10^{1.84}$ = 63 %), and (E) in 100 % syrup (Median: $10^{2.33}$= 216 %).

These results showed that the threshold value for roughness discrimination was at a minimum when the tests were performed in air (Figure 6.5A). The presence of a thin layer of lubricant will lead to a reduced capability for surface discrimination. It was also found that capability for surface discrimination appeared to gradually diminish with increasing viscosity of the fluid. The JND level reached 216 % when a thin layer of highly viscous syrup was present (Figure 6.5E). The JND values for the different fluids are summarised in Table 6.6 and Figure 6.6, where JND as a percentage is plotted against fluid viscosity.

Table 6.6 Obtained Just noticeable difference (JND) values of the subtasks done in task 1 (n = 32) (*Kadoya et al. (1985), **Kestin et al. (1978)).

Conditions	**JND values** **Changes in roughness required to perceive the difference (%)**	**Viscosity (Pa.s)**
Air	29	0.00002*
Water (at 25 °C)	30	0.0009**
80% syrup (at 25 °C)	60	0.16 ± 0.02
90% syrup (at 25 °C)	63	0.88 ± 0.02
100% syrup (at 25 °C)	216	34.6 ± 1.5

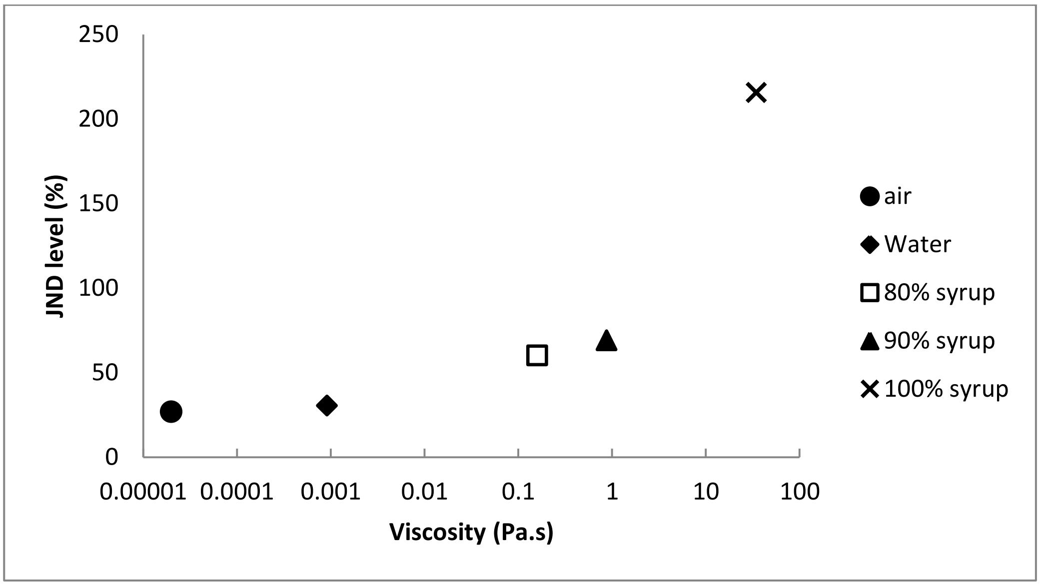


Figure 6.6 Obtained JND levels of the roughness discrimination for different viscosities in logarithmic scale of viscosity at 25 °C (n = 32).

For Task 2 the obtained results were illustrated in Figure 6.7 and listed in Table 6.7.

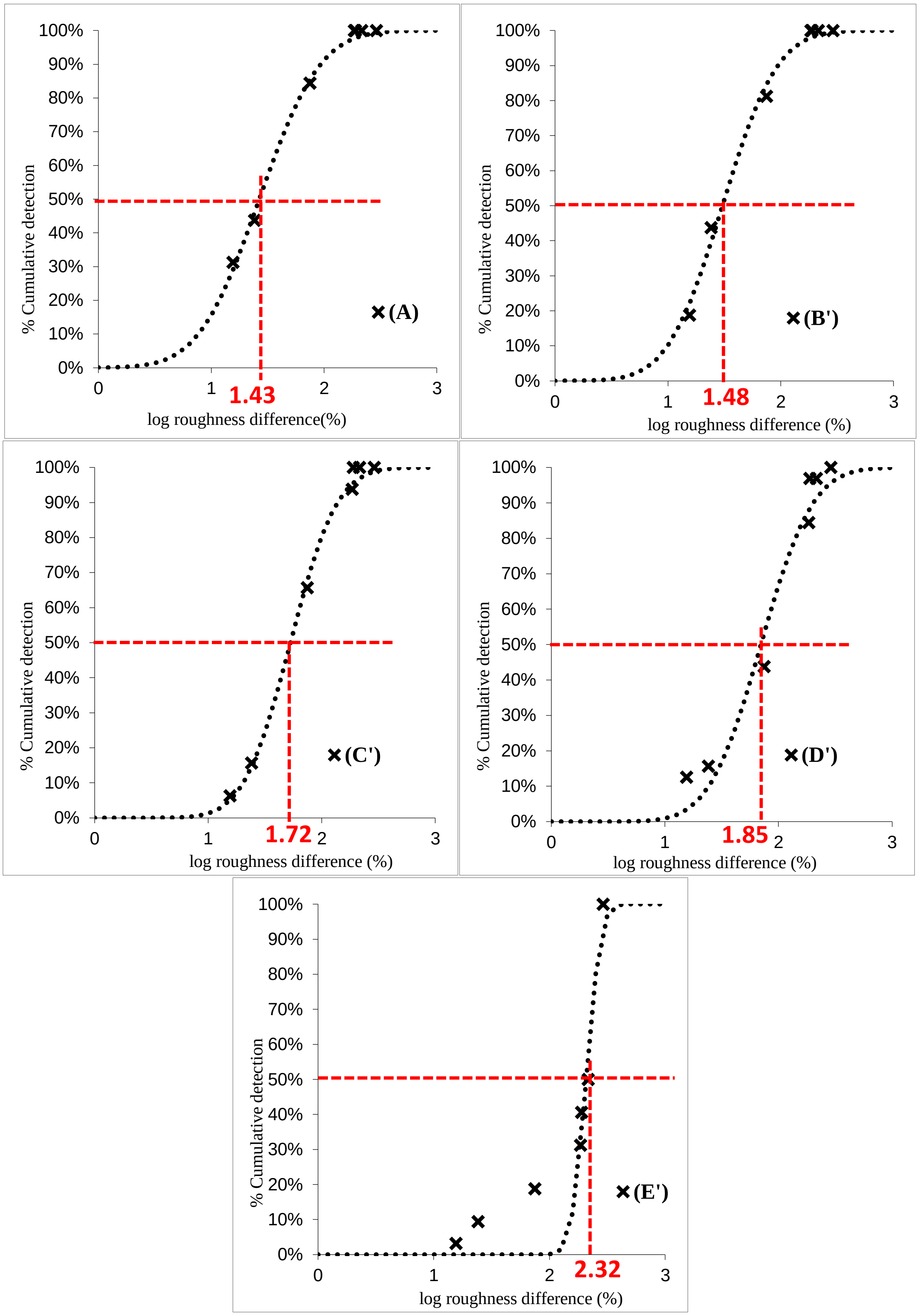


Figure 6.7 Log-normal fitted (probit analysis) (n = 32) cumulative population percentage against the roughness ratio at 37 °C for B', C', D' and E' and 25 °C for A, for (A) in air (Median: $10^{1.43}$ = 29 %), (B') in water (Median: $10^{1.48}$ = 30 %), (C') in 80 % syrup (Median: $10^{1.72}$ = 53 %), (D') in 90 % syrup (Median: $10^{1.85}$ = 70 %), and (E') in 100 % syrup (Median: $10^{2.32}$= 207 %).

The results were similar to those observed in Task 1. JND was at its lowest when there was no fluid present between the finger and the substrate surface. The presence of a fluid layer and increasing fluid viscosity led to increased JND values which also mean loss of sensitivity. These results are summarised in Table 6.7 and shown in Figure 6.8.

Table 6.7 Just noticeable difference (JND) values of the subtasks done in Task 2 (n = 32) (* Kadoya et al. (1985)** Kestin et al. (1978)).

Conditions	**JND values** **Changes in roughness required to perceive the difference (%)**	**Viscosity (Pa.s)**
Air	29	0. 00002*
Water (37 °C)	30	0.0007**
80 % syrup (37 °C)	53	0.07 ± 0.02
90 % syrup (37 °C)	70	0.29 ± 0.01
100 % syrup (37 °C)	207	6.54 ± 0.29

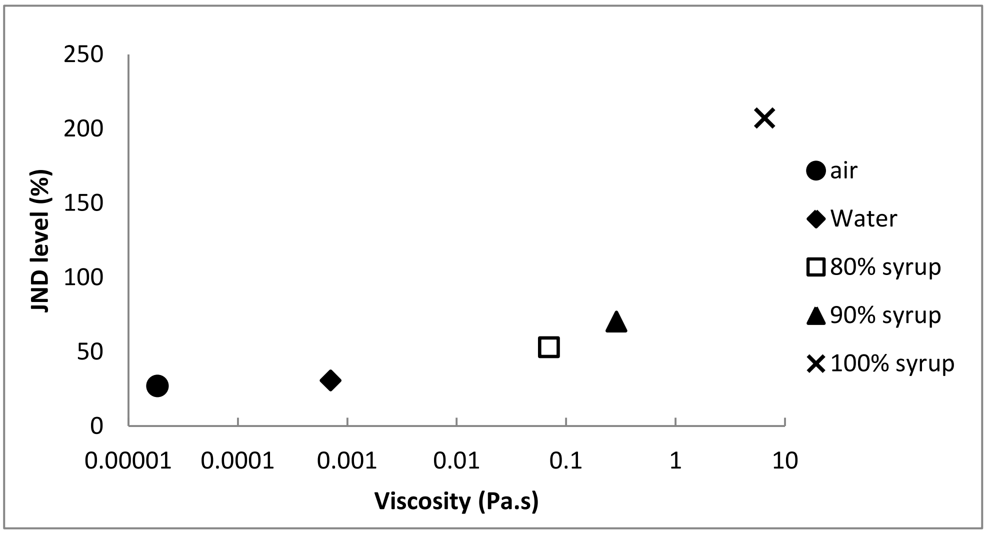


Figure 6.8 Obtained JND levels of the roughness discrimination with different viscosity levels in logarithmic scale at 37 °C (n = 32).

Tasks 1 and 2 showed that the surface roughness discrimination threshold is highly dependent on the viscosity of the lubricant. The threshold value was found to increase with increasing viscosity, regardless of the temperature; there was no statistically significant difference between the sensitivities at 25 °C and 37 °C ($p > 0.05$). This indicates that the reduction of viscosity with temperature does not have a significant effect on the sensitivity, and when the JND values are compared, it can be seen that they are similar for both temperatures. This finding could be explained by the relative nature of the test in which comparisons between pairs of surfaces and set temperatures were in a range that did not affect the sensation. However, only very high or low temperatures would be expected to change the sensation as then the viscosity would be considerably changing.

A more obvious result of these findings was the reduction in sensitivity with viscosity. A possible explanation for this effect on the JND threshold is the influence of a surface-coating lubricant. A study by Ghalme et al. (2013) showed that the viscosity of the lubricant had a significant effect on the sensed roughness. Roughness was defined to be the integral of the deviations from the average of the peaks and valleys on a surface. Lubricants filled those peaks and valleys with different viscosities. During surface exploration with lubricants in the lower viscosity ranges (such as water or 80 % syrup), the liquid could be pushed away from those peaks and valleys, resulting in a good sensation of the actual roughness. With the higher viscosity levels (such as 90 % and 100 % syrup), pushing the solution from those peaks and valleys becomes harder, requiring a force greater than the human capability to feel the true roughness. It is worth noting that with the higher viscosities, the sensation may predominantly be due to only the viscosity of the fluid. This concept was suggested by Osborne Reynolds when he investigated the effects of lubricants on surfaces, calling this ‘hydrodynamic lubrication’ (Christensen and Tonder 1971). Another evidence for this theory of lubrication is the Stribeck curve.

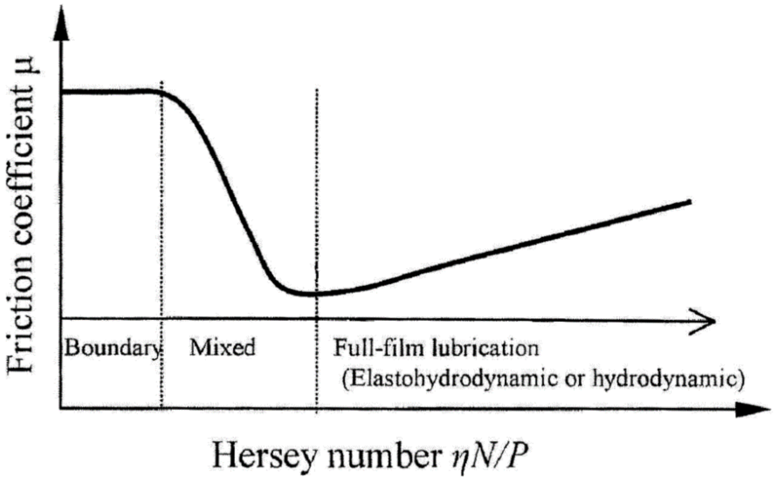


Figure 6.9 Stribeck curve, showing the friction coefficient against the Hersey number with three different regimes, boundary, mixed and full-film lubrication (Woydt and Wäsche 2010). Horizontal axis is the $\eta N/P$, where η stands for viscosity*,* N relative speed of the surfaces and P as the load on the interface per unit.

Stribeck curve, as seen in Figure 6.9 is a plot of friction related to the viscosity, relative speed and load under lubrication. The vertical axis shows the coefficient of friction, and the horizontal axis combines the other variables (viscosity, relative speed of the surfaces and load on the interface). The combination of these three factors is also often referred to as the film thickness or Hersey number and it gives an indication of how close the two surfaces will be. As the horizontal axis moves, this results in increased speed and viscosity and reduced load. The zero point of the horizontal axis refers to static friction. The Stribeck curve shows three different regimes: the boundary, mixed and hydrodynamic regimes. The boundary regime is a combination of low speed and viscosity and high load force, where friction is predominantly determined by physical contact between the two surfaces, and the bulk flow property of the lubricant does not play a role. As speed and viscosity increase or the load decreases, the mixed lubrication phase starts, and the surfaces begin to be covered by a thin film of the lubricant. During the mixed regime, the coefficient of friction is rapidly reduced as a result of decreasing surface contact and greater fluid lubrication. The coefficient of friction reaches its minimum level, and the hydrodynamic lubrication regime is initiated. At this minimum point, the load on the interface is completely supported by the lubricant, and there is almost no solid–solid contact. In the hydrodynamic regime, the two surfaces will have no physical contact but will instead be separated by a thick layer of lubricant. Increased lubricant viscosity and sliding speed and reduced surface load will all lead to an increased thickness of the lubricant layer between the two surfaces. In this case, the interaction between the surfaces will depend on the bulk flow property rather than the actual surface characteristics, so the resistance force sensed will increasingly be determined by the viscosity of the lubricant rather than by surface roughness. With regard to the Stribeck curve, it can be observed that at lower viscosity levels (i.e. water or 80 % syrup), the perceived surface topography will be due to the actual surface properties, but with increasing viscosity (90 % or 100 % syrup), the sensation will be determined by bulk flow behaviour rather than by the surface itself. This suggests that the results from tasks 1 and 2 can be supported with the evidence of the hydrodynamic lubrication theory.

The results of Task 3, which was designed to understand the perceived roughness under different viscosities at room temperature, was plotted in Figure 6.10 as mean values of obtained scores.

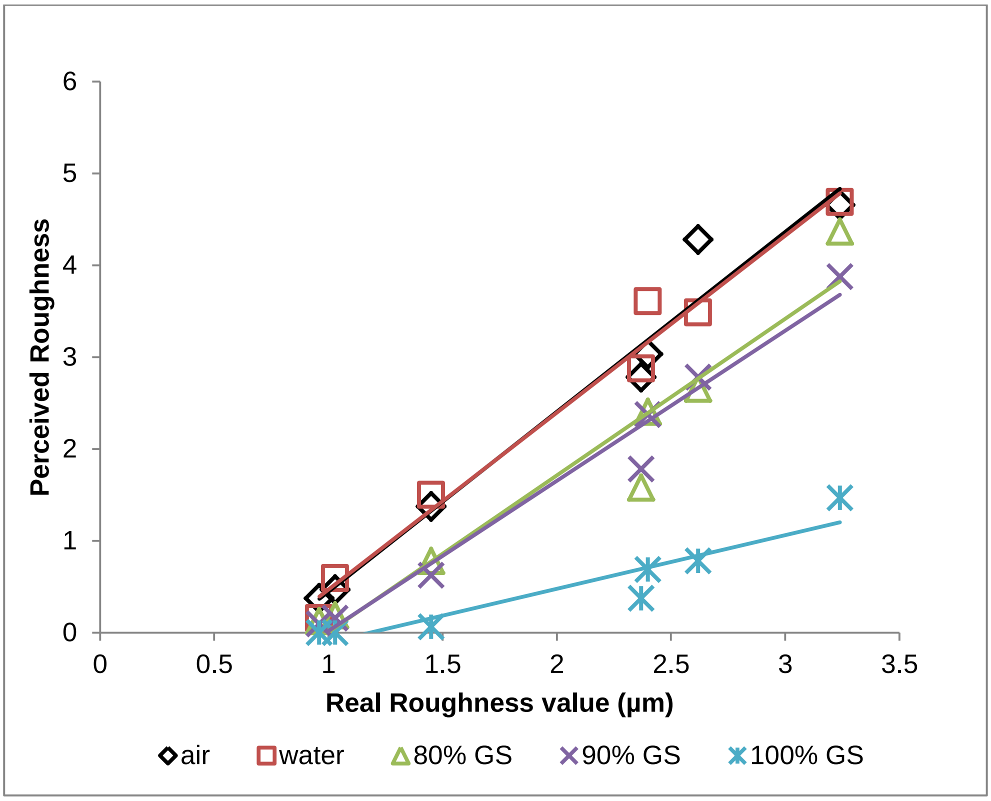


Figure 6.10 Average scores of the roughness values against the real roughness value for the different conditions of air, water, 80 % syrup, 90 % syrup and 100 % syrup, at 25 °C (n = 32).

These results demonstrated that the sensation of the surface roughness was weakened by the presence of a fluid layer between the substrate surface and the skin. The perceived roughness showed good correlation with the actual surface roughness at each concentration ($p < 0.05$). However, this correlation became rather less discriminating (smaller slope) when a layer of syrup was present during the test (Figure 6.10).

For Task 4, same test procedures as in Task 3 was repeated at body temperature (37 °C). The results were obtained by calculating the mean scores and are shown in Figure 6.11

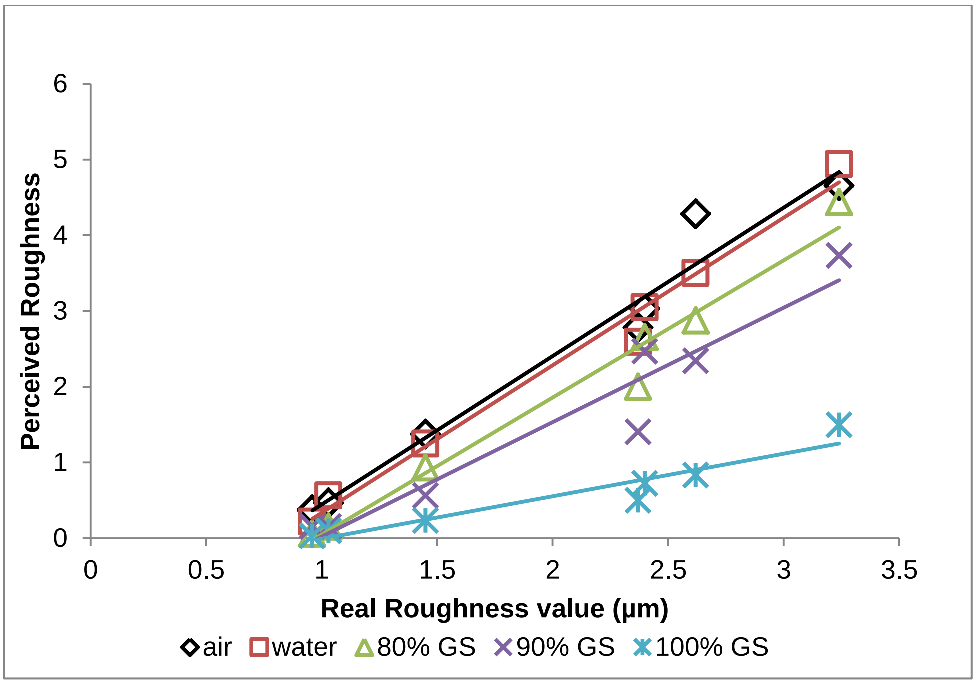


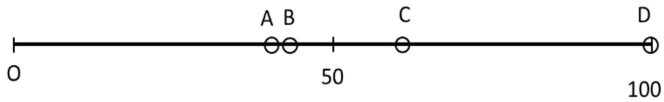
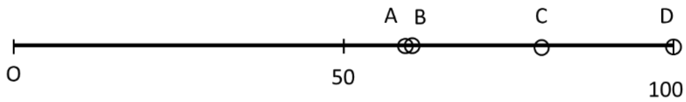
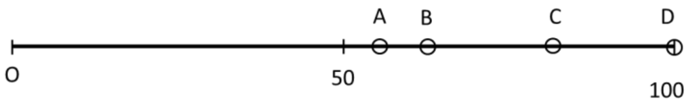
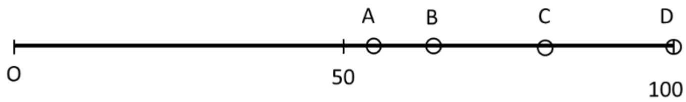
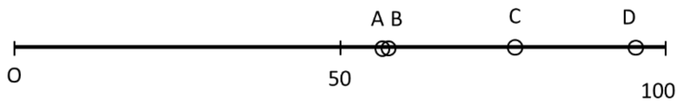
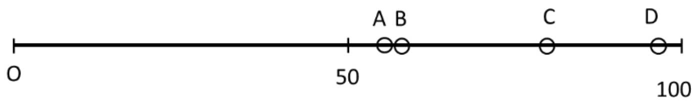
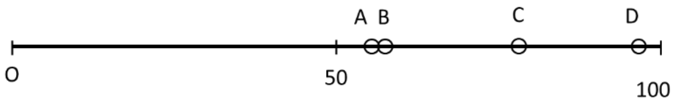
Figure 6.11 Average scores of the roughness values against the real roughness value for the different conditions of air, water, 80 % syrup, 90 % syrup and 100 % syrup at 37 °C (n = 32).

As with task 3, the perceived roughness showed a good correlation with the actual roughness ($p < 0.05$), which was rather flattened by increasing the viscosity of the lubricant.

The results of Tasks 3 and 4 were not significantly different, i.e. temperature did not have a significant effect on the perceived roughness ($p > 0.05$). These findings clearly showed that the perception of roughness is dependent on properties of the lubricant. Moreover, as previously mentioned, the Stribeck curve is clear evidence to certain finding, by claiming the importance of the lubricant viscosity of the sensation aspect. It can therefore be claimed with confidence that with lubricants with lower viscosities, perception is mainly determined by the actual surface characteristics but that when the lubricant's viscosity increases, then the lubricant moves into the hydrodynamic regime, and the sensed roughness is then mainly dependent on the bulk flow properties of the lubricant rather than the actual surface topography.

On the other hand Task 5, focused on the effect of force load on the roughness perception. The participants were asked to choose the rougher/smoother surface, and the ranking tests were analysed based on their selection. The results were analysed using the method of Meilgaard et al. (2011) and are presented in Table 6.8.

Table 6.8 Actual roughness scale and calculated scales by ranking test for the test in air and inside water at room temperature for 3 force ranges, light, moderate and hard touch (n = 30). The results were converted to percentage values.

<table>
<tr><th colspan="2">Actual roughness scale (physical)</th></tr>
<tr><td colspan="2"></td></tr>
<tr><th colspan="2">Testing of roughness in under normal conditions ‘air’</th></tr>
<tr><td>Force range</td><td>Observed scale</td></tr>
<tr><td>Light touch</td><td></td></tr>
<tr><td>Moderate touch</td><td></td></tr>
<tr><td>Hard touch</td><td></td></tr>
<tr><th colspan="2">Testing of roughness inside water (25 ^oC)</th></tr>
<tr><td>Force range</td><td>Observed scale</td></tr>
<tr><td>Light touch</td><td></td></tr>
<tr><td>Moderate touch</td><td></td></tr>
<tr><td>Hard touch</td><td></td></tr>
</table>

Each participant made 36 judgements in pairwise comparisons, making a total of 1080 decisions for the whole test. The resulting scales showed that the participants were not able to discriminate surfaces A and B using a light touch. Notably, the participants' capability to discriminate surfaces was reduced in water. More interesting findings were obtained when the correct/incorrect identification was counted for the rougher/smoother surface, with a clearly poorer surface discrimination capability in the presence of water, as shown in Figure 6.12.

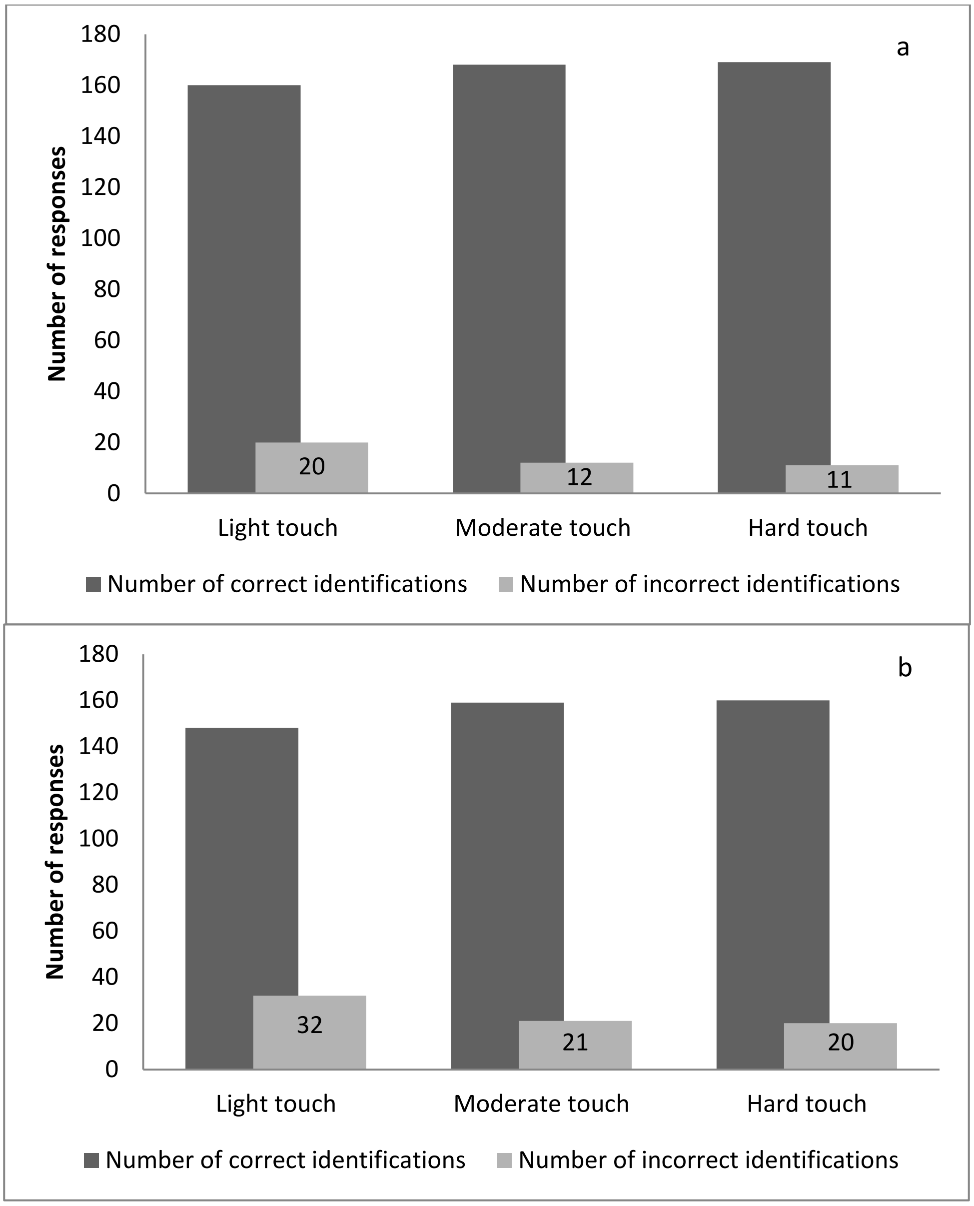
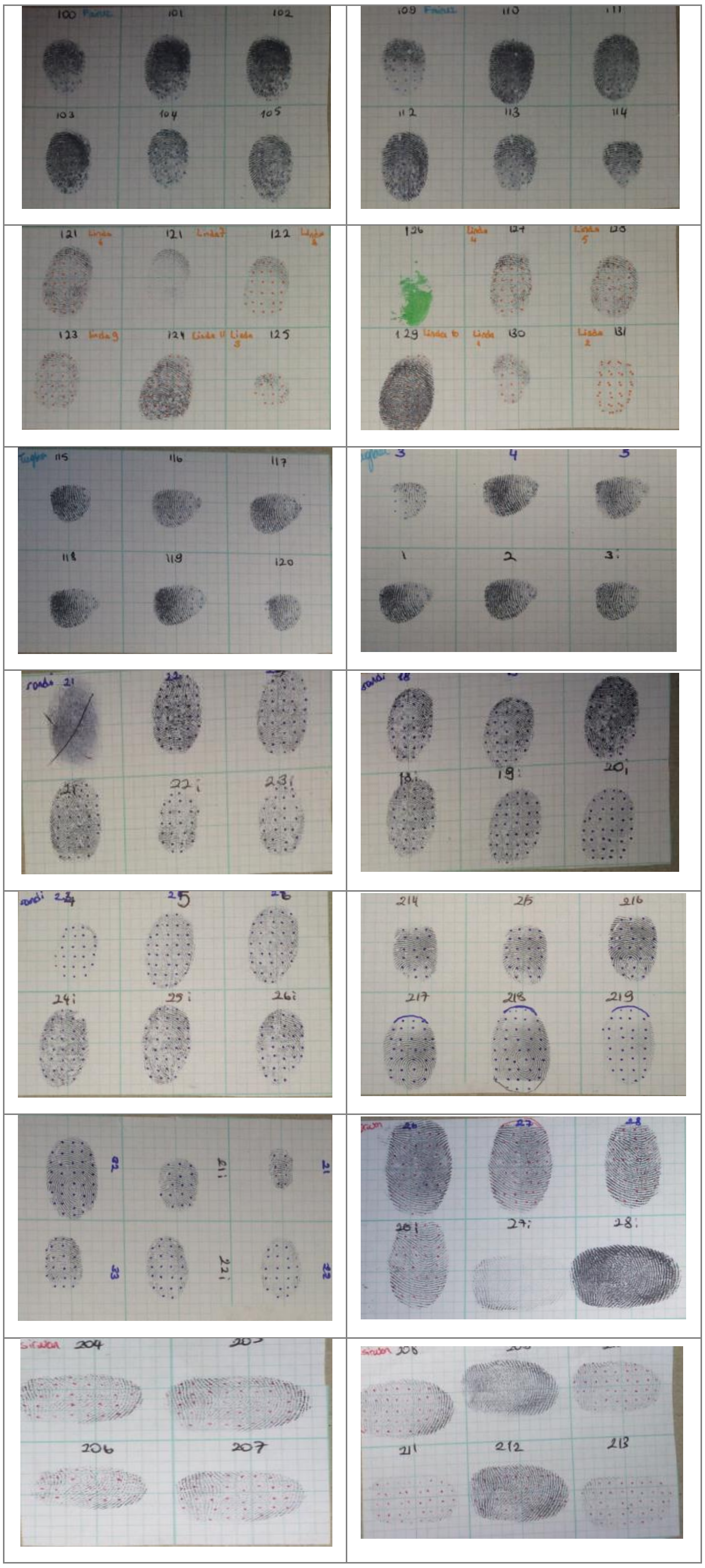


Figure 6.12 Number of correct/incorrect identification during the ranking tests done for observing the surface texture properties with three different force ranges at room temperature, in air (a) and, in water (b) (n = 30).

It is clear from these graphs that the probability of making an error during the selection of the rougher/smoother surface under certain force levels significantly decreased with increased force ($p < 0.001$). It can therefore be concluded that increasing the force load increased sensitivity but that there was no significant difference between the sensitivities at the moderate and higher levels of force.

A possible reason for this finding was suggested as the increased contact area of the fingertip under an increased load. This hypothesis was investigated by measuring the fingertip contact area for 6 people (3 females and 3 males) while applying different ranges of forces. The selected participants were asked to press their fingertip on the inkpad and then apply a force on the graph paper placed on top of the scale (Table 6.9). The fingertip area was calculated by visually counting of the boxes and was plotted against the force load as shown in Figure 6.13.

Table 6.9 Actual fingertip prints, which were printed on a graph paper (after pressing the fingertip on inkpad) with controlled force loads (on the scale). Each fingertip was coded and the force was noted for calculation (n = 6).



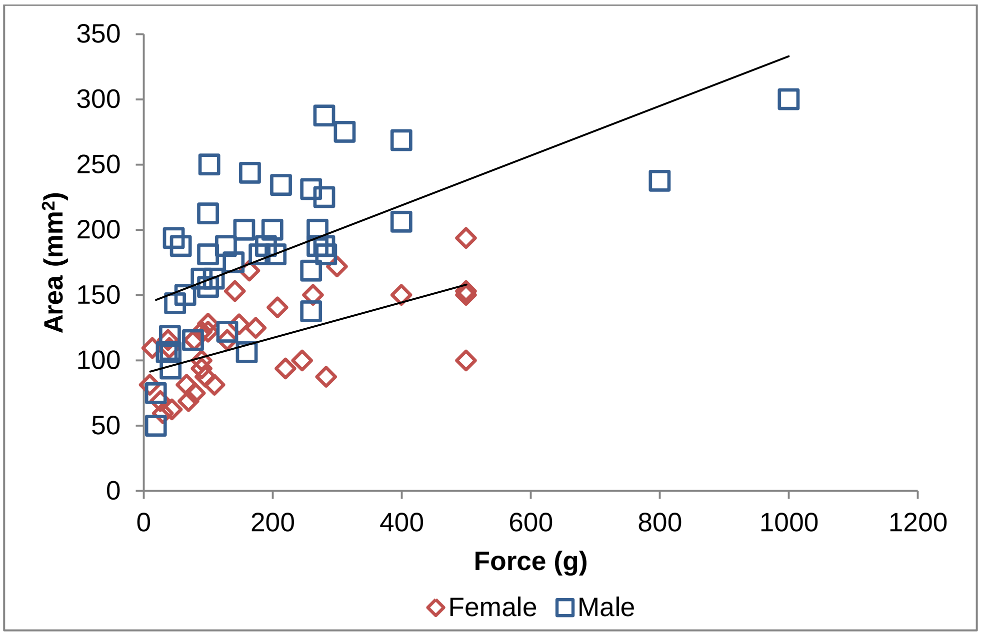


Figure 6.13 Area of the fingertip during different force loads applied for female and male subjects (n = 6).

This graph shows that the fingertip contact area with the substrate increases with increased force load. Assuming that the skin has a constant density of mechanoreceptors, an increased contact area would mean a large increase in the number of mechanoreceptors involved in surface texture detection, which would certainly assist in the correct recognition and assessment of surface roughness. This can be considered in terms of Hertz's law of friction as below:

$$F = \mu L \quad (6.2)$$

where, *F* is the resistance force, μ is the coefficient of friction and *L* is the load force. This law is also known as the Amontons' law of friction.

This equation shows that there is a direct relationship between the force load and the friction force, with their ratio giving the coefficient of friction. The coefficient of friction is a term commonly used for the characterisation of surface topography. Its magnitude largely depends on surface roughness, with greater surface roughness expected to have a higher coefficient of friction (Menezes et al. 2008). In the present study, the coefficient of friction values obtained using the artificial fingertip did not show the expected pattern;

nevertheless, it is still assumed that roughness is related to the coefficient of friction.

In this regard, when two surfaces are compared using a certain load force, the perceived difference in resistive frictional forces between the two surfaces will be directly proportional to the difference in the coefficient of friction between the two surfaces and to the applied surface load (Equation 6.3). As the difference in the coefficient of friction is a fixed value dependent on surface properties, the sensed resistance difference between the two surfaces will largely depend on the applied load. The higher the load force, the larger will the difference in sensed resistance will become, which would be beneficial for a more efficient surface discrimination.

$$\Delta F = (\mu_{2-}\, \mu_1) \,.\, L \qquad (6.3)$$

Increased discrimination at a higher surface load can further be explained by the graph shown in Figure 6.14. In this case, the threshold value, which is unknown and being investigated in this study, can be compared with the value of ΔF. When ΔF exceeds the threshold value, only then would the difference between the roughness/friction coefficients of the two surfaces be discriminable. It is obvious that higher load forces would increase the value of ΔF and therefore increase the probability of the surfaces as being perceived as having different roughness.

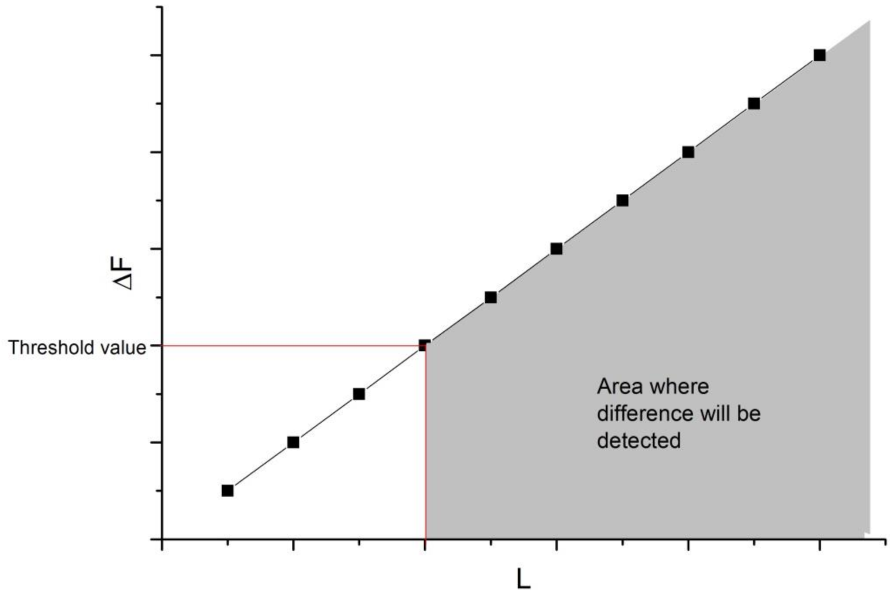


Figure 6.14 Relationship between *F* and *L*, according to the Hertz law of lubrication and the integration of the threshold value.

6.4 Implications for Roughness Sensation during Oral Processing

The results of the fingertip roughness sensation tasks provide an opportunity for estimating oral conditions. Previous findings reported in this thesis, for elasticity and firmness perception, in particular, have shown that the tongue and fingertip have similar discrimination sensitivities, whereas for viscosity tongue showing a slightly higher sensitivity. On the other hand, tactile sensation tests (touch sensitivity and 2PD tests) have demonstrated that the tongue having a slightly higher sensitivity. These findings suggest that textural results obtained only by fingertip assessments could give a prediction of oral conditions, while noting that the tongue could have a slightly higher sensitivity. Furthermore, in this study, the effect of temperature was also tested (at body temperature and room temperature) and was found to be negligible, at least for roughness perception. Therefore, the results obtained in this study could be used for estimating oral roughness sensation under different conditions.

Given this, it is possible that roughness sensation in the mouth would be reduced with a surface coating such as gravy sauce, honey. If a food producer aims to mask roughness, then it would be reasonable to use a high viscosity medium to cover the surface, which would reduce the sensation of roughness during oral processing. The results of the present study also showed that higher force loads increase the sensation of roughness. This can be applied to oral processing by claiming that increased oral forces (i.e. tongue pressure) may increase the sensation of roughness. A consumer could therefore increase or decrease the force load during oral processing according to whether they wanted or did not want to sense the roughness. It should be noted that these statements are an estimation based on the experimental findings and that oral processing is a much more complicated procedure than fingertip roughness sensation. In this area, further investigations are necessary to confirm or contradict our findings.

6.5 Limitations

As discussed earlier, the coefficient of friction values obtained using the artificial fingertip were similar for the test surfaces. This may mean that the artificial fingertip also has a threshold as roughness and that the coefficient of friction would be expected to correlate. It was therefore necessary to use roughness values in the analysis instead of the actual coefficient of friction values.

While the findings of these experiments are valid, there were some noted limitations worth discussing. The experiments were performed using surfaces that had been designed as car crash pad patterns for interior car materials. They were selected due to their good durability under certain conditions such as in heat or water. However, for threshold tests using JND, investigators are advised to use samples that have similar differences. In the present study, the materials were not produced with this aim; therefore, the given threshold values should be considered to be ranges rather than exact values, due to unavailability of an alternative.

Additionally, during the assessment of the force load on sensitivity (Task 5), a balance was used to control the force applied by the participants. Even though the participants were trained prior to the tests, it was not possible to apply a single constant force throughout the surface exploration. To minimise this load force fluctuation, wide ranges of force were defined.

6.6 Conclusion

These sets of tests were conducted to observe the participants' sensitivity in discriminating surface textures under different conditions. A number of textured plaques originally produced as a car crash pad were used in this study.

The results showed that increasing the viscosity of surface lubricants reduced the sensitivity of roughness perception. This finding was supported by the lubrication theory as shown using the Stribeck curve.

These experiments were repeated for two different temperatures: room temperature and body temperature. The main motivation for this was to predict the perceived roughness during oral processing. The previous experiments reported in this thesis showed that the tongue and fingertip had similar texture discrimination capabilities, and this was used as evidence to support using fingertip assessments for estimating the oral conditions for roughness. It should be noted that such estimation of the tongue's roughness sensation is not supported by concrete evidence but can only be used as an estimate.

Another aspect of this study was to observe whether or not different loaded force during sliding the fingertip over the surfaces would stimulate a better subjective assessment of texture. To investigate this, the sensitivity of roughness–smoothness perception was tested for a variety of load forces on the textured surfaces with a set of ranking tests. It has been claimed that during texture perception, the amount of force load is adjusted according to the topography of the surface, which could prevent individuals from applying very high forces on soft surfaces, such as squeezing a piece of cake (Phillips and Johnson 1981, Adams et al. 2013). In the present study, the surfaces used had similar topographical properties to avoid the natural limitation of force loading (Skedung et al. 2011). The participants were trained before the experiments to apply the specified force load levels, and each participant was successful at controlling their force load within a given range. The results of the ranking tests (Taks 5) showed that the probability of mistakes in choosing the rougher/smoother surface decreased with increasing force loads. This was supported by the measurements of fingertip contact area for different force loads, which showed that the area of the fingertip increased with increasing force. This could mean that the density of the mechanoreceptors also increased, thereby reducing errors in rougher/smoother selection. This is also supported by the Hertz law of lubrication, which states that increasing the load force will increase the sensible difference, which should be equal to or greater than the threshold value. These observations remained with the tests in water at room temperature. However, a wet–dry study remains outside the scope of research in this field as tactile receptors do not directly respond to water (Kandel et al. 2000). The findings of the present study also indicate that water does not result in a dramatic change in roughness sensation. However, when different surface coatings were used, i.e. different concentrations of syrup solution, these resulted in significantly reduced threshold levels with increasing viscosity values.

Chapter 7
Conclusions and Future Work

7.1 Summary of the Thesis and Implications of the Findings

With increasing interest in oral processing, the dynamics and limits of texture sensation are receiving widespread attention. The main aim of this thesis was to determine the discrimination thresholds for certain textural attributes and to provide an insight into the texture sensation limits of the fingers and mouth (specifically the tongue). The results presented in this thesis were obtained from normal healthy adults; therefore, it should be noted that these results are perceived magnitudes by healthy individuals and have been computed to predict the behaviour of the general population. This final chapter summarises the key results and conclusions obtained from the work presented and offers recommendations for future research.

Chapter 1 of this thesis contained the aim and objectives along with the motivations for conducting this research, including the research gap.

Chapter 2 gave a general introduction and provided a literature review of texture, texture assessments and texture sensation mechanisms. In general, along with taste, the textural properties of foods have been accepted to be the main determinative factors affecting consumer satisfaction and business success. Fortunately, there are a variety of instrumental and sensory approaches for investigating texture such as using texture analysers, rheometers or sensory tests such as descriptive or discrimination tests. However, the link between instrumental observation and perceived texture is still ill-defined. During the last few decades, model-based approaches (such as Weber’s law) have been employed to relate instrumental assessments to perceived texture, but in some cases, these have not been sufficient to demonstrate the correlation. Chapter 2 also discussed the sensation of texture, describing how texture perception is provided by the skin with various mechanoreceptors involved in different perceptions.

Chapter 3 investigated the viscosity texture sensation of the fingertip and tongue using Newtonian fluid samples. In addition, touch sensitivity was measured for the fingertip and tongue to collect data about their tactile sensitivities. The results revealed difference between the tongue and fingertip in terms of touch sensation and viscosity discrimination tasks, where the tongue was found to be slightly more sensitive in detecting the change in viscosity than the fingertip (detecting a 10% lower increase in viscosity).

Chapter 4 unified instrumental and sensory panel experimental results to establish the sensation thresholds for firmness, touch sensation, two-point discrimination (2PD) and muscle strength, including for oral processing. These experiments were designed to measure an individual's firmness discrimination capability with the fingertip and tongue and to assess an individual's touch sensitivity, 2PD capability and muscle strength (tongue strength, finger grip and hand grip capabilities). The fingertip and tongue were found to have similar discrimination thresholds of 13.3 % and 11.1 %, respectively. Touch sensitivity and 2PD capabilities for the tongue were higher than those for the fingertip. No significant correlation was observed between these modalities.

Chapter 5 described an investigation of the elasticity discrimination capability of the fingertip and tongue. Additionally, static and dynamic touch sensitivity and 2PD capabilities were assessed with the fingertip and tongue. The results showed that the tongue and fingertip had similar sensitivities (1.1 % and 2.7 %, respectively). With the touch sensitivity and 2PD capabilities, the tongue was a little more sensitive than the fingertip. The tactile sensitivity tests were performed both statically and dynamically, showing static testing procedures to be much more sensitive.

Chapter 6 covered a detailed examination of surface roughness properties tested with the fingertip. As well as touch sensitivity and 2PD, this chapter included the testing of changes in sensitivity under different force load levels and using lubricants with different viscosities. These tests were performed at room temperature and body temperature. The results obtained showed that an increase in the force load during roughness exploration increased the sensitivity, while the viscosity of the lubricant was found to negatively affect the sensitivity. Temperature did not show any significant effect in these tasks. These results were used to estimate oral roughness sensation.

These findings will provide essential information for the food industry, which needs information on controlling food quality, in particular for safe as well as tasty products with textural properties that are constant across different batches. With a deep insight into perception limits for the selected attributes of food quality, operators can control actual structural properties and expected perceptions. This confirmation of textural quality could give an indication of sensible or insensible changes in the product, allowing the manufacturer to place the products in the market with confidence.

Another potential use of these findings is in the interest of vulnerable people and food manufacturers preparing food for them. Vulnerable individuals (such as some elderly, mentally disabled or dysphagic people) can often suffer due to the texture of foods. To gain a full picture of sensation, initially, it is necessary to understand the sensation limits of healthy individuals and then, to use those findings to predict the requirements of vulnerable populations, taking into account the expected variation between the healthy and vulnerable populations.

The main research questions listed in the first chapter of this thesis have been answered within the acknowledged limitations of each chapter. The first question was whether texture perception was determined by tactile sensation. The studies of selected attributes showed that tactile sensation does not directly correlate with perception, which could be due to the complex nature of tactile sensation and dynamic texture perception. The general assumption about tactile sensation and texture perception cannot be ignored, but the results do not provide any evidence to support such a relationship. The second question was whether the finger and tongue had similar tactile and texture sensitivities. The results showed that for texture tongue and fingertip had similar sensitivities excluding the viscosity, whereas for tactile sensitivity tongue was more sensitive. This finding about texture sensitivity of fingertip and tongue gave us confidence for conducting the experiments with the fingertip in Chapter 6 and then using these for estimating oral perception. This also answered the third question about using results for the finger for predicting oral perception.

These findings will attract the interest of vulnerable people, food producers for these individuals, oral processing scientists and food manufacturers. The vulnerable population includes some elderly, mentally disabled and dysphagic people. These individuals often suffer during eating and may not have access to the same selection of foods as healthy people. These individuals sometimes report that they do not enjoy eating and that they eat just because they have to. Increasing population age is another factor that food scientists should take into account, understanding the needs of elderly people and customising their foods accordingly. Another vulnerable group is mentally disabled individuals without the capability to control their oral processing or swallowing. For their benefit, they need to be fed using food with a special texture to prevent them from choking. To understand texture, they need investigations with co-operation from other disciplines such as the medical sciences and the food industry. Again, the first steps towards this ideal future plan should be to understand the limits of texture perception. Dysphagic patients have swallowing impairment. They suffer from difficulty in swallowing and similarly to other vulnerable groups, they need food of a special texture to eat safely. As reported by Steele et al. (2015), caregivers who prepare food for these vulnerable individuals have difficulty in describing the texture; therefore, it would be useful if the texture of foods was printed on food labels in the market. This would allow vulnerable individuals to shop and select foods according to their texture and consume them without safety concerns. However, all these plans for the future are being studied, and the perspective of the present study was to establish perception limits, which could then be used as an indication of texture to be printed on the food labels.

Oral processing scientists could also benefit from these findings. An aim of these scientists is to find a realistic correlation between machinery and sensory assessments to eliminate the need for challenging sensory tests, which are still the most informative methods available. The top objective from this perspective is to produce a realistic mathematical model that can be used for calculating the perception of any attribute (i.e. taste, flavour and texture). This plan for the distant future will only be possible if we can establish perception limits for those attributes and use these to compute a physical model. Experiments described in this thesis gave the sensation limits for viscosity, elasticity, firmness and roughness attributes, but to create that mathematical model, many more attributes need to be tested, and food scientists, anatomists, mechanical engineers and modelling experts will need to cooperate.

Another main implication of this study is for the food industry. In the food industry, food texture is not only important in controlling machinery maintenance but also for business success. As discussed earlier, texture along with taste is important in deciding a consumer's like or dislike of a product, so the industry should be producing acceptable products with a consistent texture. When a producer provides an unusual but acceptable texture for a particular product, they may have the privilege of becoming the leading brand. However, if this innovative texture is unacceptable, the product will most probably leave the market. The texture of the final product is determined by ingredients (such as thickeners and emulsifiers); therefore, the producer has to use specific amounts of these. The information provided in this study can give them the flexibility to change the relative amount of these substances, and if the final texture differs from the previous texture to a degree that is below the threshold levels obtained in this study, then they can confidently put the new recipe into production. This application gives them flexibility over texture-providing ingredients.

7.2 Recommendations and Future Work

The results obtained in this study have demonstrated some exciting new findings. They have also provided inspiration for possible further exploration in a number of areas:

1. Developing sensory methodologies: The sensory method used in chapters 3, 4 and 5 was simple pairwise comparison asking whether or not the participant could sense any difference. The reason for choosing this method was to eliminate the need for a complicated process of ranking/scaling to obtain the simplest threshold value. The response about the sensation was immediately observed after the comparison, avoiding the bias that may occur with complicated judgement processes. However, chapter 6 showed that pairwise ranking and scoring also showed a difference in the threshold, in this case the difference between

different conditions for the same attribute. Therefore, the introduction and trial of new methodologies for determining sensation thresholds could be useful to confirm our findings and also to develop a better understanding if possible.

2. Involving different population groups: In this thesis it was stated that discrimination tests should be conducted with untrained members of the general population to observe general sensation. However, performing similar tests of texture sensation with blind individuals who may have better fingertip sensation, for instance, could provide special information regarding the question of whether texture perception is an innate or developed skill. Alternatively, recruiting from an elderly population could reveal the effects of ageing on texture sensation, and these observations may prove to be useful. Furthermore, it may be possible to gain further insight into whether or not texture perception is a learnt skill that develops with experience. Similarly, cross-cultural studies involving cultures where hands or chopsticks are used for eating could be interesting for observing differences in texture perception related to cultural habits. Lastly, a further group of participants could be from a vulnerable population, such as dysphagic patients, who experience oral processing problems such as swallowing disorders. If a future study could be performed in a clinical environment with these individuals, it would reveal the actual sensation limits of these patients, allowing the provision of food of the correct texture to certain individuals.

3. Testing different texture attributes: The literature gap regarding texture perception, influenced the design of this study, resulting in the selection of least complicated textural attributes, especially those which did not involve teeth during oral processing, such as syrup and gels. The sample selection was also carefully designed to avoid any bias from individual differences such as variations in oral shear rates. In this regard, a similar approach could be applied with non-Newtonian fluids, but this would need a good control of an individuals' oral shear rate to ensure that all participants operate within a narrow range. In addition,

testing different attributes such as crunchiness or astringency that involve senses other than tactile could be challenging but interesting for the next stage of research.

4. Theoretical modelling of texture sensation during oral processing: The findings obtained for each textural attribute could be further analysed, and based on the experimental results, a mathematical model could be constructed, which then could be used as a prediction model of consumer perception. A model able to make such predictions would be welcomed in the food sciences and would change the direction of future studies.

References

Abbott, J., Massie, D., Upchurch, B. and Hruschka, W. (1995) 'Nondestructive sonic firmness measurement of apples', *Transactions of the ASAE,* 38(5), 1461-1466.

Adams, M. J., Briscoe, B. J. and Johnson, S. A. (2007) 'Friction and lubrication of human skin', *Tribology Letters,* 26(3), 239-253.

Adams, M. J., Johnson, S. A., Lefèvre, P., Lévesque, V., Hayward, V., André, T. and Thonnard, J. L. (2013) 'Finger pad friction and its role in grip and touch', *Journal of The Royal Society Interface,* 10(80), 1-19.

Adler, E., Hoon, M. A., Mueller, K. L., Chandrashekar, J., Ryba, N. J. P. and Zuker, C. S. (2000) 'A Novel Family of Mammalian Taste Receptors', *Cell,* 100(6), 693-702.

Agrawal, K. R., Lucas, P. W., Bruce, I. C. and Prinz, J. F. (1998) 'Food properties that influence neuromuscular activity during human mastication', *Journal of Dental Research,* 77(11), 1931-1938.

Akay, D., Chen, X., Barnes, C. and Henson, B. (2012) 'ANFIS modeling for predicting affective responses to tactile textures', *Human Factors and Ergonomics in Manufacturing & Service Industries,* 22(3), 269-281.

Aktar, T., Chen, J., Ettelaie, R. and Holmes, M. (2015a) 'Evaluation of the Sensory Correlation between Touch Sensitivity and the Capacity to Discriminate Viscosity', *Journal of Sensory Studies,* 30(2), 98-107.

Aktar, T., Chen, J., Ettelaie, R. and Holmes, M. (2015b) 'Tactile sensitivity and the capability of soft-solid texture discrimination', *Journal of Texture Studies*, in press.

Alcantara, M. R. (2005) 'About rheology', [online], available: http://www.iq.usp.br/mralcant/About_Rheo.html [accessed 28 May 2015].

Alsanei, W. A. and Chen, J. (2014) 'Studies of the oral capabilities in relation to bolus manipulations and the ease of initiating bolus flow', *Journal of Texture Studies,* 45(1), 1-12.

Alsanei, W. A., Chen, J. and Ding, R. (2015) 'Food oral breaking and the determining role of tongue muscle strength', *Food Research International,* 67, 331-337.

Bahn, S., Lee, C., Lee, J. H. and Yun, M. H. (2007) 'A statistical model of relationship between affective responses and product design attributes for capturing user needs' in Aykin, N., ed. *Usability and Internationalization, Pt 2, Proceedings: Global and local user interfaces*, 305-313.

Baker, R. A., Berry, N. and Hui, Y. H. (1996) 'Fruit preserves and jams in processing fruits science and tecnology' in Barwal, V. S. and Kalia, M., eds., *Biology, principles, and applications*, Switzerland: Technomic Publishing Co. Inc.

Barnes, C. J., Childs, T. H. C., Henson, B. and Southee, C. H. (2004) 'Surface finish and touch - a case study in a new human factors tribology', *Wear,* 257(7-8), 740-750.

Barnes, H. A., Hutton, J. F. and Walters, K. (1989) *An introduction to rheology,* Anserdam, New York: Elsevier.

Bell-Krotoski, J. and Tomancik, E. (1987) 'The repeatability of testing with Semmes-Weinstein monofilaments', *The Journal of Hand Surgery,* 12(1), 155-161.

Benjamins, J., Vingerhoeds, M. H., Zoet, F. D., de Hoog, E. H. A. and van Aken, G. A. (2009) 'Partial coalescence as a tool to control sensory perception of emulsions', *Food Hydrocolloids,* 23(1), 102-115.

Bennett, J. M. (1992) 'Recent developments in surface roughness characterization', *Measurement Science and Technology,* 3(12), 11-19.

Bensmaia, S. J. and Hollins, M. (2003) 'The vibrations of texture', *Somatosensory and Motor Research,* 20(1), 33-43.

Bensmaia, S. J. and Hollins, M. (2005) 'Pacinian representations of fine surface texture', *Perception and Psychophysics,* 67(5), 842-854.

Bergmann Tiest, W. M. (2010) 'Tactual perception of material properties', *Vision Research,* 50(24), 2775-2782.

Bergmann Tiest, W. M. and Kappers, A. M. L. (2006) 'Analysis of haptic perception of materials by multidimensional scaling and physical measurements of roughness and compressibility', *Acta Psychologica,* 121(1), 1-20.

Bi, J. (2008) *Sensory Discrimination Tests and Measurements: Statistical Principles, Procedures and Tables,* Ames, IA: Wiley-Blackwell.

Blair, G. W. S. and Coppen, F. M. V. (1941) '273. The consistency of cheese curd at the pitching point and its bearing on the firmness and quality of the finished cheese', *Journal of Dairy Research,* 12(1), 44-54.

Blake, D. T., Hsiao, S. S. and Johnson, K. O. (1997) 'Neural coding mechanisms in tactile pattern recognition: The relative contributions of slowly and rapidly adapting mechanoreceptors to perceived roughness', *Journal of Neuroscience,* 17(19), 7480-7489.

Bock, R. D. and Jones, L. V. (1968) *The measurement and prediction of judgment and choice,* Sanfransisco, CA: Holden-Day.

Boland, A. B., Buhr, K., Giannouli, P. and van Ruth, S. M. (2004) 'Influence of gelatin, starch, pectin and artificial saliva on the release of 11 flavour compounds from model gel systems', *Food Chemistry,* 86(3), 401-411.

Bourne, M. C. (1966) 'A classification of objective methods for measuring texture and consistency of foods', *journal of Food Science,* 31, 1011-1020.

Bourne, M. C. (1978) 'Texture profile analysis', *Journal of Food Technology,* 33, 62-66.

Bourne, M. C. (1982) 'Effect of temperature on firmness of raw fruits and vegetables', *journal of Food Science,* 47(2), 440-444.

Bourne, M. C. (2002) 'Food Texture and Viscosity, Concept and Measurement' in, 2 ed., London: Academic Press.

Bourne, M. C. and Mondy, N. (1967) 'Measurement of whole potato firmness with a universal testing machine', *Food Technology,* 21(10), 1387-1410.

Boyar, M. M. and Kilcast, D. (1986) 'Review food texture and dental science ', *Journal of Texture Studies,* 17(3), 221-252.

Brill, N., Tryde, G., Edwards, C. and Thomas, H. (1974) 'Age changes in the two-point discrimination threshold in human oral mucosa', *Journal of Oral Rehabilitation,* 1(4), 323-333.

Brown, J. (1974) 'Recognition assessed by rating and ranking', *British Journal of Psychology,* 65(1), 13-22.

Brown, J. A., Foegeding, E. A., Daubert, C. R. and Drake, M. A. (2003) 'Changes in rheological and sensorial properties of young cheeses as related to maturation', *Journal of Dairy Science,* 86, 3054-3067.

Bukowska, M., Essick, G. K. and Trulsson, M. (2010) 'Functional properties of low-threshold mechanoreceptive afferents in the human labial mucosa', *Experimental Brain Research,* 201(1), 59-64.

Butler, S. G., Stuart, A., Leng, X., Wilhelm, E., Rees, C., Williamson, J. and Kritchevsky, S. B. (2011) 'The Relationship of Aspiration Status With Tongue and Handgrip Strength in Healthy Older Adults', *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences,* 66A(4), 452-458.

Cao, L. X., Vorburger, T. V., George Lieberman, A. and Lettieri, T. R. (1991) 'Light-scattering measurement of the rms slopes of rough surfaces', *Appl Opt,* 30(22), 3221-7.

Capra, N. (1995) 'Mechanisms of oral sensation', *Dysphagia,* 10(4), 235-247.

Cardello, A. V. (1996) 'The role of the human senses in food acceptance' in Meiselman, H. L. and Macfie, H. J. H., eds., *Food choice, acceptance and consumption*, London: Blackpie A & P, 1-82.

Carello, C. and Turvey, M. T. (2004) 'Physics and psychology of the muscle sense', *Current Directions in Psychological Science,* 13(1), 25-28.

Cascio, C. J. and Sathian, K. (2001) 'Temporal cues contribute to tactile perception of roughness', *Journal of Neuroscience,* 21(14), 5289-5296.

Chandhok, P. and Bagust, J. (2002) 'Differences between the cutaneous two-point discrimination thresholds of chiropractic students at different stages in a 5-year course', *Journal of Manipulative and Physiological Therapeutics,* 25(8), 521-525.

Chandrashekar, J., Hoon, M. A., Ryba, N. J. P. and Zuker, C. S. (2006) 'The receptors and cells for mammalian taste', *Nature,* 444(7117), 288-294.

Chaplan, S. R., Bach, F. W., Pogrel, J. W., Chung, J. M. and Yaksh, T. L. (1994) 'Quantitative assessment of tactile allodynia in the rat paw', *Journal of Neuroscience Methods,* 53(1), 55-63.

Chen, J. (2007) 'Surface texture of foods: Perception and characterization', *Critical Reviews in Food Science and Nutrition,* 47(6), 583-598.

Chen, J. (2013) 'Instrumental assessment of food sensory quality a practical guide foreword' in Kilcast, D., ed. *Instrumental assessment of food sensory quality: A practical guide*, Cambridge: Woodhead Publ Ltd, 207-208.

Chen, J. and Lolivret, L. (2011) 'The determining role of bolus rheology in triggering a swallowing', *Food Hydrocolloids,* 25(3), 325-332.

Chen, J. and Stokes, J. R. (2012) 'Rheology and tribology: Two distinctive regimes of food texture sensation', *Trends in Food Science & Technology,* 25(1), 4-12.

Chen, X. J., Shao, F., Barnes, C., Childs, T. and Henson, B. (2009) 'Exploring Relationships between Touch Perception and Surface Physical Properties', *International Journal of Design,* 3(2), 67-76.

Childs, T. and Henson, B. (2007) 'Human tactile perception of screen-printed surfaces: Self-report and contact mechanics experiments', *IMechE Proceedings,* 221(3), 427-441.

Cholewaik, R. W. and Collins, A. A. (2003) 'Vibro tactile localization on the arm: Effects of place, space, and age', *Journal of Perception and Psychophysics,* 65, 1058-1077.

Christensen, C. M. (1981) 'Drug induced xerostomia and effects on taste perception', *Journal of Dental Research,* 60, 614-614.

Christensen, H. and Tonder, K. (1971) 'The Hydrodynamic Lubrication of Rough Bearing Surfaces of Finite Width', *Journal of Lubrication Technology,* 93(3), 324-329.

Cichero, J. A. and Halley, P. J. (2006) 'Variations of the normal swallow' in Cichero, J. A. and Murdoch, B. E., eds., *Dysphagia: Foundation, theory and practice*, Chichester: John Wiley & Sons, 47-91.

Cichero, J. A., Jackson, O., Halley, P. J. and Murdoch, B. E. (2000) 'How thick is thick? Multicenter study of the rheological and material property characteristics of mealtime fluids and videofluoroscopy fluids', *Dysphagia,* 15(4), 188-200.

Clark, W. C. and Mehl, L. (1971) 'Thermal pain: A sensory decision theory analysis of the effect of age and sex on d', various response criteria, and 50% pain threshold', *Journal of Abnormal Psychology,* 78(2), 202-212.

Cornford, S. J. (1963) 'Volume and Crumb Firmness Measurements in Bread and Cake', *British Baking Industries Research Association Rept,* 68.

Craig, J. (1972) 'Difference threshold for intensity of tactile stimuli', *Perception & Psychophysics,* 11(2), 150-152.

Craig, J. and Lyle, K. (2001) 'A correction and a comment on Craig and Lyle ', *Perception & Psychophysics,* 64(3), 504-506.

Craig, J. C. and Johnson, K. O. (2000) 'The Two-Point Threshold: Not a Measure of Tactile Spatial Resolution', *Current Directions in Psychological Science,* 9(1), 29-32.

Darden, M. A. and Schwartz, C. J. (2009) 'Investigation of skin tribology and its effects on the tactile attributes of polymer fabrics', *Wear,* 267(5–8), 1289-1294.

Davies, G. A. and Stokes, J. R. (2005) 'On the gap error in parallel plate rheometry that arises from the presence of air when zeroing the gap', *Journal of Rheology,* 49(4), 919-922.

Davies, G. A. and Stokes, J. R. (2008) 'Thin film and high shear rheology of multiphase complex fluids', *Journal of Non-Newtonian Fluid Mechanics,* 148(1-3), 73-87.

Davis, C. H. (1997) 'A robust threshold retracking algorithm for measuring ice-sheet surface elevation change from satellite radar altimeters', *Geoscience and Remote Sensing, IEEE Transactions on,* 35(4), 974-979.

Dell, T. s. (2015) 'MS Glossary', [online], available: http://www.oocities.org/thjuland/gloss1.html [accessed 07/03/2015].

Delwiche, M. and Sarig, Y. (1991) 'A probe impact sensor for fruit firmness measurement', *Transactions of the ASAE (USA)*.

Dennis Flanagan, Horea Ilies, Brendan O'Brien, Anne McManus and Beau Larrow (2012) 'Jaw Bite Force Measurement Device', *Journal of Oral Implantology,* 38(4), 361-364.

Dépeault, A., Meftah, E. M. and Chapman, C. E. (2009) 'Tactile perception of roughness: Raised-dot spacing, density and disposition', *Experimental Brain Research,* 197(3), 235-244.

Deurenberg, P. and Deurenberg-Yap, M. (2009) 'Ageing and changes in body composition: the importance of valid measurements' in GROOT, M. R. L. D., ed. *Food for the ageing population*, FL, USA: Woodhead Publishing Limited and CRC Press LLC.

Døving, A. and Måge, F. (2002) 'Methods of Testing Strawberry Fruit Firmness', *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science,* 52(1), 43-51.

Døving, A., Måge, F. and Vestrheim, S. (2005) 'Methods for Testing Strawberry Fruit Firmness', *Small Fruits Review,* 4(2), 11-34.

Dowson, D. (1998) *History of Tribology,* 2nd ed.*,* New York: John Wiley.

Drake, B. K. (1963) 'Food Crushing Sounds. An Introductory Study', *journal of Food Science,* 28(2), 233-241.

Dresselhuis, D. M., de Hoog, E. H. A., Cohen Stuart, M. A., Vingerhoeds, M. H. and van Aken, G. A. (2008) 'The occurrence of in-mouth coalescence of emulsion droplets in relation to perception of fat', *Food Hydrocolloids,* 22(6), 1170-1183.

Eck, J., Kaas, A. L., Mulders, J. L. J. and Goebel, R. (2013) 'Roughness perception of unfamiliar dot pattern textures', *Acta Psychologica,* 143(1), 20-34.

Ekman, G., Hosman, J. and Lindstrom, B. (1965) 'Roughness, smoothness, and preference: A study of quantitative relations in individual subjects', *Journal of Experimental Psychology,* 70(1), 18-26.

Elkharraz, G., Thumfart, S., Akay, D., Eitzinger, C. and Henson, B. (2014) 'Making Tactile Textures with Predefined Affective Properties', *Affective Computing, IEEE Transactions on,* 5(1), 57-70.

Emmons, D. B. and Price, W. V. (1959) 'A Curd Firmness Test for Cottage Cheese1', *Journal of Dairy Science,* 42(3), 553-556.

Engelen, L. (2012) 'Oral receptors ' in Chen, J. and Engelen, L., eds., *Food Oral Processing, Fundamentals of Eating and Sensory Perception*, Oxford: Wiley- Blackwell, 15-43.

Engelen, L. and de Wijk, R. A. (2012) 'Oral Processing and Texture Perception' in Chen, J. and Engelen, L., eds., *Food Oral Processing Fundamentals of Eating and Sensory Perception*, Oxford: Wiley-Blackwell, 157-176.

Engelen, L. and Van Der Bilt, A. (2008) 'Oral physiology and texture perception of semisolids', *Journal of Texture Studies,* 39(1), 83-113.

Esselen, W. B., Jr., Hart, W. J., Jr. and Fellers, C. R. (1967) 'Further Studies on the Use of Calcium Chloride to Maintain Firmness in Canned and Frozen Apples', *Fruit products journal,* 27, 8-18.

Fechner, G. T. (1860) *Elemente der Psychophysik, Volume 1,* Leipsic Breitkopf und Härtel.

Felt, P. (1999) 'The National Dysphagia Diet: the science and practice', *Nutrition Clinical Practice,* 14, 455-478.

Ferreira, M. C., Rodrigues, L. and Fels, K. (2004) 'New method for evaluation of cutaneous sensibility in diabetic feet: preliminary report', *Revista do Hospital das Clínicas,* 59, 286-290.

Field, G. D., Sampath, A. P. and Rieke, F. (2005) 'Retinal processing near absolute threshold: From behavior to mechanism', *Annual Review of Physiology,* 67(1), 491-514.

Foegeding, E. A. (2007) 'Rheology and sensory texture of biopolymer gels', *Current Opinion in Colloid & Interface Science,* 12(4–5), 242-250.

Foegeding, E. A., Brown, J., Drake, M. and Daubert, C. R. (2003) 'Sensory and mechanical aspects of cheese texture', *International Dairy Journal,* 13(8), 585-591.

Foegeding, E. A., Daubert, C. R., Drake, M. A., Essick, G., Trulsson, M., Vinyard, C. J. and Van De Velde, F. (2011) 'A comprehensive approach to understanding textural properties of semi and soft solid foods', *Journal of Texture Studies,* 42(2), 103-129.

Frederiksen, H., Hjelmborg, J., Mortensen, J., McGue, M., Vaupel, J. W. and Christensen, K. (2006) 'Age trajectories of grip strength: Cross-sectional and longitudinal data among 8,342 Danes aged 46 to 102', *Annals of Epidemiology,* 16(7), 554-562.

Friedman, H. H., Whitney, J. E. and Szczesniak, A. S. (1963) 'The Texturometer: A New Instrument for Objective Texture Measurement', *journal of Food Science,* 28(4), 390-396.

Frijters, J. E. R. (1988) 'Sensory difference testing and the measurement of sensory discriminability' in Piggot, J. R., ed. *Sensory analysis of foods*, 2nd ed., London: Elsevier Aplied Science, 134-154.

Fujiki, T., Takano-Yamamoto, T., Tanimoto, K., Sinovcic, J. N. P., Miyawaki, S. and Yamashiro, T. (2001) 'Deglutitive movement of the tongue under local anesthesia', *American Journal of Physiology - Gastrointestinal and Liver Physiology,* 280, 1070-1075.

Gambareli, F. R., Serra, M. D., Pereira, L. J. and Gaviao, M. B. D. (2007) 'Influence of measurement technique, test food, teeth and muscle force interactions in masticatory performance', *Journal of Texture Studies,* 38(1), 2-20.

Garay, P. N. (1996) *Pump Application Desk Book,* 3rd ed., New Jersey: Fairmont Press Prentice-Hall.

Garcia, J. M., Chambers, I. V. E. and Molander, M. (2005) 'Thickened LiquidsPractice Patterns of Speech-Language Pathologists', *American Journal of Speech-Language Pathology,* 14(1), 4-13.

Garrido, J. I., Lozano, J. E. and Genovese, D. B. (2015) 'Effect of formulation variables on rheology, texture, colour, and acceptability of apple jelly: Modelling and optimization', *LWT - Food Science and Technology,* 62(1, Part 1), 325-332.

Gee, M. G., Tomlins, P., Calver, A., Darling, R. H. and Rides, M. (2005) 'A new friction measurement system for the frictional component of touch', *Wear,* 259, 1437-1442.

Gentil, M. and Tournier, C. L. (1998) 'Differences in fine control of forces generated by the tongue, lips and fingers in humans', *Archives of Oral Biology,* 43(7), 517-523.

Gerhardt, L. C., Strässle, V., Lenz, A., Spencer, N. D. and Derler, S. (2008) 'Influence of epidermal hydration on the friction of human skin against textiles', *Journal of The Royal Society Interface,* 5(28), 1317-1328.

Gescheider, G. A. (1997) *Psychophysics: the fundamentals,* New Jersey: Lawrence Erlbaum Associates Publishers.

Ghalme, S. G., Mankar, A. and Bhalerao, Y. J. (2013) 'Effect of lubricant viscosity and surface roughnesson coefficient of friction in rolling contact', *Tribology in Industry,* 35(4), 330-336.

Gibson, J. J. (1962) 'Observations on active touch', *Psychological Review,* 69, 477-491.

Gillenson, S. P., Parets, N., Bear-Lehman, J. and Stanton, D. B. (1998) 'The effect of wrist position on testing light touch sensation using the Semmes-Weinstein pressure aesthesiometer: A preliminary study', *Journal of Hand Therapy,* 11(1), 27-31.

Gitis, N. and Sivamani, R. (2004) 'Tribometrology of Skin', *Tribology Transactions,* 47(4), 461-469.

Goldstein, E. B. (2010) 'Sensation and Perception. 8th edition', *Wadsworth, Belmont, CA*.

Gordon, J. and Ghez, C. (1991) 'Muscle receptors and spinal reflexes: the stretch reflex', *Principles of neural science,* 3, 565-580.

Grohmann, B., Spangenberg, E. R. and Sprott, D. E. (2007) 'The influence of tactile input on the evaluation of retail product offerings', *Journal of Retailing,* 83(2), 237-245.

Guilford, J. P. (1954) *Psychometric methods,* New York: McGraw-Hill.

Guinard, J.-X. and Mazzucchelli, R. (1996) 'The sensory perception of texture and mouthfeel', *Trends in Food Science & Technology,* 7(7), 213-219.

Guinard, J.-X., Zoumas-Morse, C. and Walchak, C. (1997) 'Relation Between Parotid Saliva Flow and Composition and the Perception of Gustatory and Trigeminal Stimuli in Foods', *Physiology & Behavior,* 63(1), 109-118.

Hall, C. B. (1964) 'Firmness and Color of Some Tomato Varieties during Ripening and According to Harvest Dates', *American society for horticultural science,* 84, 507-512.

Haller, M. H., Harding, P. L. and Rose, D. H. (1932) 'The Interrelation of Firmness, Dry Weight, and Respiration in Strawberries', *American society for horticultural science,* 29, 330-341.

Harker, F. R., Maindonald, J., Murray, S. H., Gunson, F. A., Hallett, I. C. and Walker, S. B. (2002) 'Sensory interpretation of instrumental measurements 1: texture of apple fruit', *Postharvest Biology and Technology,* 24(3), 225-239.

Hatschek, E. (1928) *The Viscosity of Liquids, International textbooks of exact science,* New York: D. Van Nostrand company.

Haut, I. C., Webster, J. E., and Cochran, G. W. (1935) 'The Influence of Commercial Fertilizers upon the Firmness and Chemical Composition of Strawberries and Tomatoes', *American society for horticultural science,* 33, 405-411.

Hayakawa, F., Kazami, Y., Nishinari, K., Ioku, K., Akuzawa, S., Yamano, Y., Baba, Y. and Kohyama, K. (2013) 'Classification of Japanese Texture Terms', *Journal of Texture Studies,* 44(2), 140-159.

Hecht, S. (1924) 'The visual discrimination of intensity and the weber-fechner law', *The Journal of General Physiology,* 7(2), 235-267.

Henson, B., Barnes, C., Livesey, R., Childs, T. and Ewart, K. (2006) 'Affective Consumer Requirements: A Case Study of Moisturizer Packaging', *Concurrent Engineering: Research and Applications,* 14(3), 187-196.

Hershko, V., Weisman, D. and Nussinovitch, A. (1998) 'Method For Studying Surface Topography and Roughness of Onion and Garlic Skins For Coating Purposes', *journal of Food Science,* 63(2), 317-321.

Hiiemae, K. M. and Palmer, J. B. (1999) 'Food transport and bolus formation during complete feeding sequences on foods of different initial consistency', *Dysphagia,* 14(1), 31-42.

Holbrook, M. B. and Hirschman, E. C. (1982) 'The experiential aspects of consumption - consumer fantasies, feelings, and fun', *Journal of Consumer Research,* 9(2), 132-140.

Hollins, M. and Bensmaïa, S. J. (2007) 'The coding of roughness', *Canadian ournal of experimental psychology (Revue Canadienne de psychologie expérimentale),* 61(3), 184-195.

Hollins, M., Bensmaïa, S. J. and Roy, E. A. (2002) 'Vibrotaction and texture perception', *Behavioural Brain Research,* 135(1–2), 51-56.

Hollins, M., Faldowski, R., Rao, S. and Young, F. (1993) 'Perceptual dimensions of tactile surface texture: A multidimensional scaling analysis', *Perception & Psychophysics,* 54(6), 697-705.

Hollins, M. and Risner, S. R. (2000) 'Evidence for the duplex theory of tactile texture perception', *Perception & Psychophysics,* 62(4), 695-705.

Hoon, M. A., Adler, E., Lindemeier, J., Battey, J. F., Ryba, N. J. P. and Zuker, C. S. (1999) 'Putative Mammalian Taste Receptors: A Class of Taste-Specific GPCRs with Distinct Topographic Selectivity', *Cell,* 96(4), 541-551.

Hurling, R., Rodell, J. and Hunt, H. (1996) 'Fiber diameter and fish texture', *Journal of Texture Studies,* 27(6), 679-685.

Hutchings, J. B. and Lillford, P. J. (1988) 'The perception of food texture - the philosophy of the breakdown path', *Journal of Texture Studies,* 19(2), 103-115.

International Organization for Standardization (1981) 'Sensory analysis vocabulary, Part 4', 5492.

Jackman, R., Marangoni, A. and Stanley, D. (1990) 'Measurement of tomato fruit firmness', *HortScience,* 25(7), 781-783.

Janssen, A. M., Terpstra, M. E. J., De Wijk, R. A. and Prinz, J. F. (2007) 'Relations between rheological properties, saliva-induced structure breakdown and sensory texture attributes of custards', *Journal of Texture Studies,* 38(1), 42-69.

Janssen, A. M., van de Pijpekamp, A. M. and Labiausse, D. (2009) 'Differential saliva-induced breakdown of starch filled protein gels in relation to sensory perception', *Food Hydrocolloids,* 23(3), 795-805.

Jerosch-Herold, C. (2005) 'Assessment of sensibility after nerve injury and repair: a systematic review of evidence for validity, reliability and responsiveness of tests', *The Journal of Hand Surgery: British & European Volume,* 30(3), 252-264.

Jobling, A. (1991) 'An introduction to rheology', *Polymer International,* 21(1), 61-67.

Johnson, K. O. (2001) 'The roles and functions of cutaneous mechanoreceptors', *Current Opinion in Neurobiology,* 11(4), 455-461.

Johnson, K. O. and Phillips, J. R. (1981) 'Tactile spatial resolution. I. Two-point discrimination, gap detection, grating resolution, and letter recognition', *Journal of Neurophysiology,* 46(6), 1177-1192.

Johnson, K. O., Yoshioka, T. and Vega Bermudez, F. (2000) 'Tactile functions of mechanoreceptive afferents innervating the hand', *Journal of Clinical Neurophysiology,* 17(6), 539-558.

Jordan, P. W. (2000) *Designing Pleasurable Products: An Introduction to the New Human Factors,* London, New York: Taylor & Francis.

Joris Hage, J., Steen, L. P. E. v. d. and de Groot, P. J. M. (1995) 'Difference in sensibility between the dominant and nondominant index finger as tested using the semmes-weinstein monofilaments pressure aesthesiometer', *The Journal of Hand Surgery,* 20(2), 227-229.

Jowitt, R. (1974) 'The terminology of food texture ', *Journal of Texture Studies,* 5, 351-358.

Kadoya, K., Matsunaga, N. and Nagashima, A. (1985) 'Viscosity and thermal conductivity of dry air in the gaseous phase ', *Journal of Physical and Chemical Reference Data,* 14(4), 947-970.

Kahrimanovic, M., Bergmann Tiest, W. M. and Kappers, A. M. L. (2009) 'Context effects in haptic perception of roughness', *Experimental Brain Research,* 194(2), 287-297.

Kandel, E. R., Schwartz, J. H. and Jessell, T. M. (2000) *Principles of Neural Science,* 4th ed.*,* New York McGraw-Hill.

Karkkainen, H., Piippo, P. and Tuominen, M. (2001) 'Ten tools for customer-driven product development in industrial companies', *International Journal of Production Economics,* 69(2), 161-176.

Katz, D. (1925) *Der aufbau der tastwelt. Zeitschrift fur Psychologie,* Leipzig: Barth.

Katz, D. and Krueger, L. E. (1989) *The World of Touch,* Hillsdale, England Lawrence Erlbaum Associates, Inc.

Kestin, J., Sokolov, M. and A., W. W. (1978) 'Viscosity of liquid water in the range -8^{o}C to 150^{o}C', *Journal of Physical and Chemical Reference Data,* 7(3), 941-948.

Khalid, H. M. and Helander, M. G. (2006) 'Customer emotional needs in product design', *Concurrent Engineering-Research and Applications,* 14(3), 197-206.

Khazaei, J. and Mann, D. (2004) 'Effects of Temperature and Loading Characteristics on Mechanical and Stress-Relaxation Properties of Sea Buckthorn Berries. Part 2. Puncture Tests', *Agricultural engineering international: The CIGR Ejournal,* 6.

Kilcast, D. (1999) 'Sensory techniques to strudy food texture' in Rosenthal, A. J., ed. *Food texture: Measurement and perception*, Gaithersburg, MD: Aspen Publishers Inc., 30-60.

Kilcast, D. and Clegg, S. (2002) 'Sensory perception of creaminess and its relationship with food structure', *Food Quality and Preference,* 13(7–8), 609-623.

Kilcast, D. and Eves, A. (1991) *Feeding and the Texture of Foods, Integrating texture and phsiology - techniques,* New York NY: Cambridge University Press.

Kim, M.-A. and Lee, H.-S. (2012) 'Investigation of operationally more powerful duo-trio test protocols: Effects of different reference schemes', *Food Quality and Preference,* 25(2), 183-191.

Klatzky, R. and Lederman, S. (1999) 'Tactile roughness perception with a rigid link interposed between skin and surface', *Perception & Psychophysics,* 61(4), 591-607.

Klatzky, R., Lederman, S., Hamilton, C., Grindley, M. and Swendsen, R. (2003) 'Feeling textures through a probe: Effects of probe and surface geometry and exploratory factors', *Perception & Psychophysics,* 65(4), 613-631.

Klatzky, R., Lederman, S. and Metzger, V. (1985) 'Identifying objects by touch: An “expert system”', *Perception & Psychophysics,* 37(4), 299-302.

Kohyama, K. and Nishi, M. (1997) 'Direct measurement of biting pressures for crackers using a multiple-point sheet sensor', *Journal of Texture Studies,* 28(6), 605-617.

Kramer, A. (1955) 'Food quality and quality control' in Blanck, ed. *Handbook of food and agriculture*, New York: Reinhold Publication Company.

Kramer, A. (1964) 'Definition of texture and its measurement in vegetable products', *Journal of Food Technology,* 19, 37-45.

Kramer, A. (1973) 'Food texture- definition, measurement and relation to other food quality attributes' in A. Kramer and Szczesniak, A. S., eds., *Texture measurements of foods*, Dordrecht, Holland: D. Reidel Publishing.

Kramer, A. and Szczesniak, A. S. (2012) *Texture Measurement of Foods: Psychophysical Fundamentals; Sensory, Mechanical, and Chemical Procedures, and their interrelationships,* Springer Netherlands.

Kramer, A. and Twigg, B. A. (1959) 'Principles and instrumentation for the physical measurements of food quality with special reference to fruit and vegetable products', *Advances in Food Research,* 9, 153-220.

Kramer, A. and Twigg, B. A. (1970) *Fundamentals of quality control for the food industry* 2ed., Westport, Connecticut Avi Publishing Company.

Krueger, L. (1970) 'David Katz’s Der Aufbau der Tastwelt (The world of touch): A synopsis', *Perception & Psychophysics,* 7(6), 337-341.

Kutter, A., Hanesch, C., Rauh, C. and Delgado, A. (2011) 'Impact of proprioception and tactile sensations in the mouth on the perceived thickness of semi-solid foods', *Food Quality and Preference,* 22(2), 193-197.

LaBelle, R. L. and Woodams, E. E. (1964) 'Recovery of Montmorency Cherries from Repeated Bruising', *American society for horticultural science,* 84, 103-107.

Laguna, L., Sarkar, A., Artigas, G. and Chen, J. (2015) 'A quantitative assessment of the eating capability in the elderly individuals', *Physiology & Behavior,* 147, 274-281.

Laing, G. G. (1983) 'Natural sniffing gives optimum perception of odours by humans', *Perception,* 12(2), 99-117.

Laming, D. (1986) *Sensory analysis,* Orlando, FL: Academic Press.

Lawless, H., Vanne, M. and Tuorila, H. (1997) 'Categorization of english and finnish texture terms among consumers and food professionals', *Journal of Texture Studies,* 28(6), 687-708.

Lawless, H. T. and Heymann, H. (1998) *Sensory evaluation of food: principles and practices,* New York, NY: Chapman and Hall.

Lederman, S. J. and Klatzky, R. L. (1987) 'Hand movements: A window into haptic object recognition', *Cognitive Psychology,* 19(3), 342-368.

Lederman, S. J. and Klatzky, R. L. (1990) 'Haptic classification of common objects: Knowledge-driven exploration', *Cognitive Psychology,* 22(4), 421-459.

Lee, H. S. and van Hout, D. (2009) 'Quantification of sensory and food quality: the R-index analysis', *journal of Food Science,* 74(6), R57-64.

Lee, H. S., van Hout, D. and Hautus, M. J. (2007) 'Comparison of performance in the A–Not A, 2-AFC, and same–different tests for the flavor discrimination of margarines: The effect of cognitive decision strategies', *Food Quality and Preference,* 18(6), 920-928.

Lenfant, F., Loret, C., Pineau, N., Hartmann, C. and Martin, N. (2009) 'Perception of oral food breakdown. The concept of sensory trajectory', *Appetite,* 52(3), 659-667.

Lewis, R., Menardi, C., Yoxall, A. and Langley, J. (2007) 'Finger friction: Grip and opening packaging', *Wear,* 263(7–12), 1124-1132.

Lillford, P. J. (1991) 'Texture and acceptability of human foods.' in Vincent, J. F. V. and Lillford, P. J., eds., *Feeding and the Texture of Food (Society for Experimental Biology Seminar Series No. 44)*, Cambridge: Cambridge University Press, 231-244.

Liu, X., Chan, M. K., Hennessey, B., Rübenach, T. and Alay, G. (2005) 'Quantifying touch-feel perception on automotive interiors by a multi-function tribological probe microscope', *Journal of Physics: Conference Series,* 13(1), 357-361.

Liu, X., Yue, Z., Cai, Z., Chetwynd, D. G. and Smith, S. T. (2008) 'Quantifying touch–feel perception: tribological aspects', *Measurement Science and Technology,* 19(8), 1-9.

Logemann, J. A., Gensler, G., Robbins, J., Lindblad, A. S., Brandt, D., Hind, J. A., Kosek, S., Dikeman, K., Kazandjian, M., Gramigna, G. D., Lundy, D., McGarvey-Toler, S. and Miller Gardner, P. J. (2008) 'A Randomized Study of Three Interventions for Aspiration of Thin Liquids in Patients With Dementia or Parkinson's Disease', *Journal of Speech, Language, and Hearing Research,* 51(1), 173-183.

Lucas, P. W., Prinz, J. F., Agrawal, K. R. and Bruce, I. C. (2002) 'Food physics and oral physiology', *Food Quality and Preference,* 13(4), 203-213.

Lundborg, G. (2000) 'A 25-year perspective of peripheral nerve surgery: Evolving neuroscientific concepts and clinical significance', *The Journal of Hand Surgery,* 25(3), 391-414.

Macefield, V. G., Häger-Ross, C. and Johansson, R. S. (1996) 'Control of grip force during restraint of an object held between finger and thumb: Responses of cutaneous afferents from the digits', *Experimental Brain Research,* 108(1), 155-171.

Macosko, C. W. (1994) *Rheology: principles, measurements and applications,* New York: Wiley.

Maeyama, T. and Plattig, K.-H. (1989) 'Minimal two-point discrimination in human tongue and palate', *American Journal of Otolaryngology,* 10(5), 342-344.

Marlow, C. D., Winkelmann, R. K. and Gibilisco, J. A. (1965) 'General sensory innervation of the human tongue', *The Anatomical Record,* 152(4), 503-511.

Meilgaard, M. C., Civille, G. V. and Carr, B. T. (1991) *Sensory evaluation techniques* 1st ed., Boca Raton, FL: CRC Press.

Meilgaard, M. C., Civille, G. V. and Carr, B. T. (2007) *Sensory Evaluation Techniques,* 3rd ed., Boca Raton: Taylor & Francis.

Meilgaard, M. C., Civille, G. V. and Carr, B. T. (2011) *Sensory Evaluation Techniques,* 4th ed., Boca Raton: Taylor & Francis.

Menezes, P., Kishore and Kailas, S. (2008) 'Influence of roughness parameters on coefficient of friction under lubricated conditions', *Sadhana,* 33(3), 181-190.

Menier, C., Forget, R. and Lambert, J. (1996) 'Evaluation of two-point discrimination in children: Reliability, effects of passive displacement and voluntary movement', *Developmental Medicine & Child Neurology,* 38(6), 523-537.

Meyers, M. A. and Chawla, K. K. (2008) *Mechanical behaviour of materials,* 2nd ed., Cambridge, UK: Cambridge University Press.

Mills, R. H. (1999) 'Rheology Overview: Control of Liquid Viscosities in Dysphagia Management', *Nutrition in Clinical Practice,* 14(5), 52-56.

Minato, A., Ono, T., Miyamoto, J. J., Honda, E.-i., Kurabayashi, T. and Moriyama, K. (2009) 'Preferred chewing side-dependent two-point discrimination and cortical activation pattern of tactile tongue sensation', *Behavioural Brain Research,* 203(1), 118-126.

Modler, H., Larmond, M., Lin, C., Froehlich, D. and Emmons, D. (1983) 'Physical and Sensory Properties of Yogurt Stabilized with Milk Proteins 1, 2', *Journal of Dairy Science,* 66(3), 422-429.

Mohsenin, N. N. (1970) 'Physical properties of plant and animal materials, Volume I' in *Structure physical characteristics and mechanical properties*, New York: Gordon and Breach Science Publishers, .

Morrison, G. R. (1982) 'Measurement of flavour thresholds', *Journal of the Institute of Brewing,* 88(3), 170-174.

Muller, H. G. (1969) 'Mechanical properties, rheology, and haptaesthesis of food', *Journal of Texture Studies,* 1(1), 38-42.

National Dysphagia Diet: Standardization For Optimal Care (2002) 'National Dysphagia Diet Task Force ', 1400.

Natural History Museum (2015) 'Sensory homunculus', [online], available: http://piclib.nhm.ac.uk/results.asp?image=041490 [accessed 16 September 2014].

Nelson, G., Chandrashekar, J., Hoon, M. A., Feng, L., Zhao, G., Ryba, N. J. P. and Zuker, C. S. (2002) 'An amino-acid taste receptor', *Nature,* 416(6877), 199-202.

Nelson, G., Hoon, M. A., Chandrashekar, J., Zhang, Y., Ryba, N. J. P. and Zuker, C. S. (2001) 'Mammalian Sweet Taste Receptors', *Cell,* 106(3), 381-390.

North Coast Medical Inc. (2013) 'North Coast Medical & Rehabilitation Products, Touch-Test® Sensory Evaluators', [online], available: https://www.ncmedical.com/item_1278.html [accessed 13 November 2013].

Nybom, N. (1962) 'New Principle for Measuring Firmness of Fruits', *Horticulture research,* 2, 1-17.

Okada, T., Grunfeld, E., Shallo-Hoffmann, J. and Bronstein, A. M. (1999) 'Vestibular perception of angular velocity in normal subjects and in patients with congenital nystagmus', *Brain,* 122(7), 1293-1303.

Oliveira, G. H. H., Corrêa, P. C., Botelho, F. M. and Oliveira, P. L. R. (2015) 'Mechanical properties of tomatoes subjected to an induced compression during storage', *Journal of Texture Studies,* 46(4), 293-301.

Ono, T., Iwata, H., Hori, K., Tamine, K., Kondoh, J., Hamanaka, S. and Maeda, Y. (2009) 'Evaluation of tongue-, jaw-, and swallowing-related muscle coordination during voluntarily triggered swallowing', *Int J Prosthodont,* 22(5), 493-8.

Ormerod, T., Maskill, L. and Ball, L. J. (1997) ' Information reuse and design expertise' in Langley, P. and Shafto, M. G., eds., *Proceedings of the Nineteenth Annual Conference of the Cognitive Science Society*, Stanford, CA: Lawrence Erlbaum Associates.

Pangborn, R. M., Gibbs, Z. M. and Tassan, C. (1978) 'Effect of hydrocolloids on apparent viscosity and sensory properties of selected beverages', *Journal of Texture Studies,* 9(4), 415-436.

Paoletti, F., Moneta, E., Bertone, A. and Sinesio, F. (1993) 'Mechanical properties and sensory evaluation of selected apple cultivars', *LWT-Food Science and Technology,* 26(3), 264-270.

Pascua, Y., Koç, H. and Foegeding, E. A. (2013) 'Food structure: Roles of mechanical properties and oral processing in determining sensory texture of soft materials', *Current Opinion in Colloid & Interface Science,* 18(4), 324-333.

Pedreschi, F., Aguilera, J. M. and Brown, C. A. (2000) 'Characterization of food surfaces using scale-sensitive fractal analysis', *Journal of Food Process Engineering,* 23(2), 127-143.

Peleg, M. (1980) 'A note on the sensitivity of fingers, tongue and jaws as mechanical testing instruments', *Journal of Texture Studies,* 10(3), 245-251.

Peleg, M. (2006) 'On fundamental issues in texture evaluation and texturization: A view', *Food Hydrocolloids,* 20(4), 405-414.

Penfield, W. and Rasmussen, T. (1950) *The cerebral cortex of man,* New York: Macmillan.

Perfetti, T. A. and Gordin, H. H. (1985) 'Just noticeable difference studies of mentholated cigarette products', *Tobacco Science,* 57, 20-29.

Periyasamy, R., Manivannan, M. and Narayanamurthy, V. B. R. (2008) 'Changes in Two Point Discrimination and the law of mobility in Diabetes Mellitus patients', *Journal of Brachial Plexus and Peripheral Nerve Injury,* 3(3), 1-9.

Perkinelmer (2001) 'Mechanical properties of films and coatings', [online], available: http://www.perkinelmer.com/CMSResources/Images/44-74269APP_RelaxationofPVC.pdf [accessed 29 May 2015].

Phillips, J. R. and Johnson, K. O. (1981) 'Tactile spatial resolution. III. A continuum mechanics model of skin predicting mechanoreceptor responses to bars, edges, and gratings', *Journal of Neurophysiology,* 46(6), 1204-1225.

Pont, S. C., Kappers, A. M. L. and Koenderink, J. J. (1999) 'Similar mechanisms underlie curvature comparison by static and dynamic touch', *Perception & Psychophysics,* 61(5), 874-894.

Ponte, J. G., Titcomb, S. T. and Cotton, R. H. (1962) 'Flour as a factor in bread firming', *Cereal Chemistry,* 39(6), 437-445.

Prakash, S., Tan, D. D. Y. and Chen, J. S. (2013) 'Applications of tribology in studying food oral processing and texture perception', *Food Research International,* 54(2), 1627-1635.

Prinz, J. F. and Lucas, P. W. (1997) 'An optimization model for mastication and swallowing in mammals', *Proceedings of the Royal Society B: Biological Sciences,* 264(1389), 1715-1721.

Quevedo, R. and Aguilera, J. M. (2004) 'Characterization of food surface roughness using the glistening points method', *Journal of Food Engineering,* 65(1), 1-7.

Rao, M. A. (2007) *Rheology of Fluid and Semisolid Foods: Principles and Applications,* 2nd ed.*,* New York: Springer.

Reiner, M. (1964) 'The Deborah Number', *Physics today,* 17(1), 62-63.

Richardson, N. J. and Booth, D. A. (1993) 'Multiple physical patterns in judgements of the creamy texture of milks and creams', *Acta Psychologica,* 84(1), 93-101.

Robbins, J., Nicosia, M. A., Hind, J. A., Gill, G. D., Blanco, R. and Logemann, J. A. (2002) 'Defining physical properties of fluids for dysphagia evaluation and treatment. Perspectives on swallowing and swallowing disorders', *Dysphagia,* 11, 9-16.

Rohm, H. (1990) 'Consumer awareness of food texture in austria', *Journal of Texture Studies,* 21(3), 363-374.

Rose, S. and Nelson, J. (1954) 'STUDIES WITH RADIO-IODINATED INSULIN', *Australian Journal of Experimental Biology and Medical Science,* 32(3), 429-436.

Rosenthal, A. J. (1999) 'Relation between instrumental and sensory measures of food texture' in Rosenthal, A. J., ed. *Food texture: Measurement and perception*, Gaithersburg, MD: Aspen Publishers Inc., 1-16.

Rosenthal, A. J. (2010) 'Texture profile analysis – how important are the parameters?', *Journal of Texture Studies,* 41(5), 672-684.

Ross, C. F. and Hoye, C. L. (2012) 'Breaking and Mastication of Solid Foods' in J. Chen and Engelen, L., eds., *Food Oral Processing*, Oxford: Wiley-Blackwell, 95-109.

Rossetti, D., Bongaerts, J. H. H., Wantling, E., Stokes, J. R. and Williamson, A. M. (2009) 'Astringency of tea catechins: More than an oral lubrication tactile percept', *Food Hydrocolloids,* 23(7), 1984-1992.

Rossetti, D., Yakubov, G. E., Stokes, J. R., Williamson, A. M. and Fuller, G. G. (2008) 'Interaction of human whole saliva and astringent dietary compounds investigated by interfacial shear rheology', *Food Hydrocolloids,* 22(6), 1068-1078.

Rousseau, B. t., Rogeaux, M. and O'Mahony, M. (1999) 'Mustard discrimination by same–different and triangle tests: aspects of irritation, memory and τ criteria', *Food Quality and Preference,* 10(3), 173-184.

Russ, J. (1986) *Computer-assisted microscopy: the measurement and analysis of images,* New York: Plenum Press.

Russell, J. A. (2003) 'Core affect and the psychological construction of emotion', *Psychological Review,* 110(1), 145-172.

Ruth, T. (1951) 'Sensory mechanisms' in Stevens, S. S., ed. *Handbook of Experimental Psychology*, New York: Wiley, 121-153

Samur, E., Colgate, J. E. and Peshkin, M. A. (2009) 'Psychophysical evaluation of a variable friction tactile interface', *Human vision and electronic imaging XIV,* 7240, 1-9.

Schierbauni, F. (1964) 'Starch ' in Wazer, J. R., van, J. W., Lyons, K. Y. and E., C. R., eds., *Viscosity and flow measurement. A laboratory handbook of rheology*, New York: Interscience Publishers, 371-372.

Schmidt, R., Schmelz, M., Torebjörk, H. E. and Handwerker, H. O. (2000) 'Mechano-insensitive nociceptors encode pain evoked by tonic pressure to human skin', *Neuroscience,* 98(4), 793-800.

Schmidt, R. F. (1986) *Fundamentals of Sensory Physiology,* 3rd ed., Berlin: Springer-Verlag.

Schott, G. D. (1993) 'Penfield's homunculus: a note on cerebral cartography', *Journal of Neurology, Neurosurgery, and Psychiatry,* 56(4), 329-333.

Schramm, L. L. (2005) *Emulsions, Foams, and Suspensions: Fundamentals and Applications,* Weinheim: Wiley-VCH.

Schreuders, T. A. R., Selles, R. W., van Ginneken, B. T. J., Janssen, W. G. M. and Stam, H. J. (2008) 'Sensory Evaluation of the Hands in Patients with Charcot-Marie-Tooth Disease Using Semmes-Weinstein Monofilaments', *Journal of Hand Therapy,* 21(1), 28-35.

Schutz, H. G. and Pilgrim, F. J. (1957) 'Differential sensitivity in gustation', *Journal of Experimental Psychology,* 54(1), 41-48.

Shama, F. and Sherman, P. (1973) 'Identification of stimuli controlling the sensory evaluation of viscosity II. oral methods', *Journal of Texture Studies,* 4(1), 111-118.

Shao, F., Childs, T. H. C., Barnes, C. J. and Henson, B. (2010) 'Finite element simulations of static and sliding contact between a human fingertip and textured surfaces', *Tribology International,* 43(12), 2308-2316.

Shao, F., Childs, T. H. C. and Henson, B. (2009) 'Developing an artificial fingertip with human friction properties', *Tribology International,* 42(11-12), 1575-1581.

Sherman, P. (1969) 'A texture profile of foodstuffs based on well-defined rheological properties', *journal of Food Science,* 34, 458-470.

Ship, J. A. (1999) 'The Influence of Aging on Oral Health and Consequences for Taste and Smell', *Physiology & Behavior,* 66(2), 209-215.

Shorter Oxford English Dictionary (2007) 'Texture', 507.

Silletti, E., Vingerhoeds, M., van Aken, G. and Norde, W. (2008) 'Rheological Behavior of Food Emulsions Mixed with Saliva: Effect of Oil Content, Salivary Protein Content, and Saliva Type', *Food Biophysics,* 3(3), 318-328.

Skedung, L., Danerlöv, K., Olofsson, U., Michael Johannesson, C., Aikala, M., Kettle, J., Arvidsson, M., Berglund, B. and Rutland, M. W. (2011) 'Tactile perception: Finger friction, surface roughness and perceived coarseness', *Tribology International,* 44(5), 505-512.

Smith, A. M. and Scott, S. H. (1996) 'Subjective scaling of smooth surface friction', *Journal of Neurophysiology,* 75(5), 1957-1962.

Smith, C., Logemann, J., Burghardt, W., Zecker, S. and Rademaker, A. (2006) 'Oral and Oropharyngeal Perceptions of Fluid Viscosity Across the Age Span', *Dysphagia,* 21(4), 209-217.

Smith, C. H., Logemann, J. A., Burghardt, W. R., Carrell, T. D. and Zecker, S. G. (1997) 'Oral sensory discrimination of fluid viscosity', *Dysphagia,* 12(2), 68-73.

Soneda, T. and Nakano, K. (2008) 'Investigation of the vibration detectability of human fingers supported by the observation of contact zones', *Proceedings of the 2nd International Conference on Advanced Tribology (iCAT 2008), Singapore*, 3-5.

Spence, C., Levitan, C., Shankar, M. and Zampini, M. (2010) 'Does Food Color Influence Taste and Flavor Perception in Humans?', *Chemosensory Perception,* 3(1), 68-84.

Srinivasan, M. A. and LaMotte, R. H. (1995) 'Tactual discrimination of softness', *Journal of Neurophysiology,* 73(1), 88-101.

Steele, C. (2005) 'Searching for Meaningful Differences in Viscosity', *Dysphagia,* 20(4), 336-338.

Steele, C., Alsanei, W., Ayanikalath, S., Barbon, C. A., Chen, J., Cichero, J. Y., Coutts, K., Dantas, R., Duivestein, J., Giosa, L., Hanson, B., Lam, P., Lecko, C., Leigh, C., Nagy, A., Namasivayam, A., Nascimento, W., Odendaal, I., Smith, C. and Wang, H. (2015) 'The Influence of Food Texture and Liquid Consistency Modification on Swallowing Physiology and Function: A Systematic Review', *Dysphagia,* 30(1), 2-26.

Steele, C., James, D., Hori, S., Polacco, R. and Yee, C. (2014) 'Oral Perceptual Discrimination of Viscosity Differences for Non-Newtonian Liquids in the Nectar- and Honey-Thick Ranges', *Dysphagia,* 29(3), 355-364.

Steffe, J. F. (1996) *Rheological methods in food process engineering,* 2nd ed.*,* Michigan: Freeman Press.

Stern, M. K. and Johnson, J. H. (2010) 'Just Noticeable Difference' in Weiner, I. B. and Craighead, W. E., eds., *The Corsini Encyclopedia of Psychology*, New York: John Wiley & Sons, Inc.

Stevens, S. S. (1966) 'On the operation known as judgement', *American Scientist,* 54(4), 385-401.

Stevens, S. S. (1975) *Psychophysics: introduction to its perceptual, neural, and social prospects,* California: John Wiley & Sons.

Stokes, J. R. (2012) '‘Oral’ Rheology' in J. Chen and Engelen, L., eds., *Food Oral Processing*, Oxford: Wiley-Blackwell, 225-263.

Stokes, J. R. and Davies, G. A. (2007) 'Viscoelasticity of human whole saliva collected after acid and mechanical stimulation', *Biorheology,* 44(3), 141-160.

Stokes, J. R. and Frith, W. J. (2008) 'Rheology of gelling and yielding soft matter systems', *Soft Matter,* 4(6), 1133-1140.

Stone, H. (1963) 'Determination of odor difference limens for three compounds', *Journal of Experimental Psychology,* 66(5), 466-473.

Stone, H. and Sidel, J. L. (2004) *Sensory evaluation practices,* 3rd ed., Orlando, FL: Academic Press.

Sund-Levander, M., Forsberg, C. and Wahren, L. K. (2002) 'Normal oral, rectal, tympanic and axillary body temperature in adult men and women: a systematic literature review', *Scandinavian Journal of Caring Sciences,* 16(2), 122-128.

Swets, J. A. (1964) 'Is there a sensory threshold?' in Swets, J. A., ed. *Signal Detection and Recognition by Human Observers*, New York: Wiley.

Szczesniak, A. S. (1963) 'Classification of textural characteristics', *journal of Food Science,* 25, 385-389.

Szczesniak, A. S. (1973) 'Instrumental Methods of Texture Measurement' in Kramer, A. and Szczesniak, A. S., eds., *Texture measurements of foods*, Boston: D. Reidel Publishing Company.

Szczesniak, A. S. (1979) 'Classification of mouthfeel characteristics of beverages ' in Sherman, P., ed. *Food Texture and Rheology*, London: Academic Press, 1-20.

Szczesniak, A. S. (2002) 'Texture is a sensory property', *Food Quality and Preference,* 13(4), 215-225.

Szczesniak, A. S. and Bourne, M. C. (1969) 'SENSORY EVALUATION OF FOOD FIRMNESS', *Journal of Texture Studies,* 1(1), 52-64.

Szczesniak, A. S. and Khan, E. L. (1971) 'Consumer awareness and attitudes to food texture I. Adults', *Journal of Texture Studies,* 2, 280-295.

Szczesniak, A. S. and Kleyn, D. H. (1963) 'Consumer awareness of texture and other food attributes', *Journal of Food Technology,* 27, 74-77.

Talbot, W. H., Darian-Smith, I., Kornhuber, H. H. and Mountcastle, V. B. (1968) 'The sense of flutter-vibration: comparison of the human capacity with response patterns of mechanoreceptive afferents from the monkey hand', *Journal of Neurophysiology,* 31(2), 301-334.

te Nijenhuis, K., McKinley, G. H., Spiegelberg, S., Barnes, H. A., Aksel, N., Heymann, L. and Odell, J. A. (2007) 'Non-Newtonian Flows' in Tropea, C., Yarin, A. and Foss, J. F., eds., *Springer Handbook of Experimental Fluid Mechanics*, Berlin, Heidelberg: Springer-Verlag.

Thai, C. and Shewfelt, R. (1990) 'Peach quality changes at different constant storage temperatures: empirical models', *Transactions of the ASAE,* 33(1), 227-233.

The Institute for Perception (2003) 'IFPrograms User's manual', 27-28.

Thomas, T. R. (1999) *Rough surfaces,* 2nd ed.*,* London: Imperial College Press.

Trampisch, U. S., Franke, J., Jedamzik, N., Hinrichs, T. and Platen, P. (2012) 'Optimal Jamar Dynamometer Handle Position to Assess Maximal Isometric Hand Grip Strength in Epidemiological Studies', *The Journal of Hand Surgery,* 37(11), 2368-2373.

Treutwein, B. (1995) 'Adaptive psychophysical procedures', *Vision Research,* 35(17), 2503-2522.

Trueman, M. and Jobber, D. (1998) 'Competing through design', *Long Range Planning,* 31(4), 594-605.

Trulsson, M. and Johansson, R. S. (2002) 'Orofacial mechanoreceptors in humans: encoding characteristics and responses during natural orofacial behaviors', *Behavioural Brain Research,* 135(1–2), 27-33.

Tseng, W. Y., Fisher, J. S., Prieto, J. L., Rinaldi, K., Alapati, G. and Lee, A. P. (2009) 'A slow-adapting microfluidic-based tactile sensor', *Journal of Micromechanics and Microengineering,* 19(8), 1-8.

Urdang, L. (1968) *Random House Dictionary of The English Language,* New York: Random House.

Valbo, A. B. and Johansson, R. S. (1978) 'The tactile sensory innervation of the glabrous skin of the human hand' in Gordon, G., ed. *Active touch*, New York: Oxford University Press.

Valente, M., Leardi, R., Self, G., Luciano, G. and Pain, J. P. (2009) 'Multivariate calibration of mango firmness using vis/NIR spectroscopy and acoustic impulse method', *Journal of Food Engineering,* 94(1), 7-13.

van Boven, R. and Johnson, K. (1994) 'The limit of tactile spatial resolution in humans: grating orientation discrimination at the lip, tongue, and finger', *Neurology,* 44(12), 2361-2361.

van Vliet, T. (1999) 'Rheological classification of foods and instrumental techniques for their study' in Rosenthal, A. J., ed. *Food texture: measurement and perception*, Gaithersburg, MD: Aspen Publishers Inc., 65-97.

Vickers, Z. (1991) 'Sound perception and food quality', *Journal of Food Quality,* 14(1), 87-96.

Vingerhoeds, M. H., Blijdenstein, T. B. J., Zoet, F. D. and van Aken, G. A. (2005) 'Emulsion flocculation induced by saliva and mucin', *Food Hydrocolloids,* 19(5), 915-922.

Voisey, P. W. (1975) 'SELECTING DEFORMATION RATES IN TEXTURE TESTS *', *Journal of Texture Studies,* 6(2), 253-257.

Voisey, P. W. and Emmons, D. B. (1966) 'Modification of the Curd Firmness Test for Cottage Cheese1', *Journal of Dairy Science,* 49(1), 93-96.

Walker, G. (2004) 'Texture Analysis', [online], available: http://sst-web.tees.ac.uk/external/U0000504/Notes/Sensory/Texture.html [accessed 30 May 2015].

Warde, A. and Martens, L. (2000) *Eating Out: Social Differentiation, Consumption and Pleasure,* Cambridge: Cambridge University Press.

Wearmouth, W. G. (1952) 'Some Effects of Variations in Temperature on the Firmness of Cheddar Cheese', *Dairy Industry,* 17, 994.

Weinstein, S. (1968) 'Intensive and extensive aspects of tactile sensitivity as a function of body part, sex and laterability' in Kenshalo, D. R., ed. *The Skin Senses*, Springfield, IL: Plenum Press, 195-222.

Weisenberger, J. M. (2001) 'Cutaneous Perception' in Goldstein, E. B., ed. *Blackwell Handbook of Perception*, Oxford: Blackwell Publishers Ltd.

White, G. W. (1970) 'Rheology in food research', *International Journal of Food Science & Technology,* 5(1), 1-32.

Wiggermann, N. E., Werner, R. A. and Keyserling, W. M. (2012) 'The Effect of Prolonged Standing on Touch Sensitivity Threshold of the Foot: A Pilot Study', *Journal of physical medicine and rehabilitation,* 4(2), 117-122.

Wilkinson, C., Dijksterhuis, G. B. and Minekus, M. (2000) 'From food structure to texture', *Trends in Food Science & Technology,* 11(12), 442-450.

Wood, F. W. (1968) 'Psychophysical studies on the consistency of liquid foods', *Society of Chemical Industry, Monograph,* 27, 40-49.

World Health Organization (2015) *Obesity and overweight, 311,* Geneva: World Helth Organisation

Woydt, M. and Wäsche, R. (2010) 'The history of the Stribeck curve and ball bearing steels: The role of Adolf Martens', *Wear,* 268(11), 1542-1546.

Yoshioka, T., Craig, J. C., Beck, G. C. and Hsiao, S. S. (2011) 'Perceptual Constancy of Texture Roughness in the Tactile System', *The Journal of Neuroscience,* 31(48), 17603-17611.

Appendix A Ethical Approval

Performance, Governance and Operations
Research & Innovation Service
Charles Thackrah Building
101 Clarendon Road
Leeds LS2 9LJ
Tel: 0113 343 4873
Email: j.m.blaikie@leeds.ac.uk

UNIVERSITY OF LEEDS

Tugba Aktar
School of Food Science and Nutrition
University of Leeds
Leeds, LS2 9JT

MEEC Faculty Research Ethics Committee
University of Leeds

4 November 2015

Dear Tugba

Title of study	**Studies of the oro-tactile sensation and food texture perception**
Ethics reference	**MEEC 12-013**

I am pleased to inform you that the application listed above has been reviewed by the MaPS and Engineering joint Faculty Research Ethics Committee (MEEC FREC) and following receipt of your response to the Committee's initial comments, I can confirm a favourable ethical opinion as of the date of this letter. The following documentation was considered:

Document	*Version*	*Date*
MEEC 12-013 Ethic Form Tugba Aktar.doc	1	30/11/12
MEEC 12-013 information sheet for ethic.docx	1	30/11/12
MEEC 12-013 consent_form.doc	1	30/11/12
MEEC 12-013 ethical response.doc	1	29/01/13

Committee members made the following comments about your response:

- The proposed 'health screening' by the secretary, in order to fulfil the exclusion criteria in C8, now appears to have been removed and therefore, providing a full list of ingredients is made available to participants before enrolling in the study, then the committee is happy with this. It was suggested you amend and possibly reword the email in Point 2 slightly to correct the grammar and make it more readable before sending it out.

Please notify the committee if you intend to make any amendments to the original research as submitted at date of this approval, including changes to recruitment methodology. All changes must receive ethical approval prior to implementation. The amendment form is available at

http://researchsupport.leeds.ac.uk/index.php/academic_staff/good_practice/managing_approved_projects-1/applying_for_an_amendment-1.

Please note: You are expected to keep a record of all your approved documentation, as well as documents such as sample consent forms, and other documents relating to the study. This should be kept in your study file, which should be readily available for audit purposes. You will be given a two week notice period if your project is to be audited. There is a checklist listing examples of documents to be kept which is available at

http://researchsupport.leeds.ac.uk/index.php/academic_staff/good_practice/managing_approved_projects-1/ethics_audits-1.

Yours sincerely

Jennifer Blaikie

Senior Research Ethics Administrator,

Research & Innovation Service

On behalf of Professor Gary Williamson,

Chair, MEEC FREC

CC: Student's supervisor(s)

Appendix B Questionnaire for Sensory Evaluations

B.1 Chapter 3 Sensory Evaluation Form

Sensory Evaluation of Human Sensat**ion**

- **Personal information:**

  Name: **Age:** **Gender:** Female Male

  Weight (kg): **Height (cm):** **Ethnicity:**

  Date: _ / _ / ___

- **Task (1) Instructions:**
  - Please put the blind fold and make sure you cannot see.
  - Put your hand on your knee in a relaxed position with your index finger waiting for the experiment.
  - Give a response when you feel a touch on your finger tip

  finger

- **Task (2) Instructions:**
  - Please put the blind fold and make sure you cannot see.
  - Open your mouth when you hear the ready sound and keep your tongue in a relaxed position.
  - Give a response when you feel a touch on your tongue.

  tongue

- **Task (3) Instructions:**
  - Please put the blind fold and make sure you cannot see.
  - Sanitize your hands with the sanitizer provided.
  - Rest your hand.
  - A control and a sample will be disposed each time and you should report if they are the same or different in terms of **thickness.**
  - When the liquid is disposed apply a shear force with your thumb finger to your index finger by rubbing them to each other and answer the following question verbally

Is the thickness/consistency of the sample; same or different than the control?

	Finger
Control - 319	
Control - 618	
Control - 765	
Control - 192	

Control - 675	
Control - 219	
Control - 261	
Control - 972	
Control - 819	
Control - 120	

- **Task (4) Instructions:**
    - With the provided sample set start from left to right in the presented order.
    - The blank spoon is the control sample and you will need to compare the samples each time with the control.
    - You should dispose the whole spoon to the middle of your tongue.
    - When you dispose the liquid you should apply a shear force by your tongue to your palate (Circular movements by your tongue to your palate).
    - Take the control and rinse your mouth with water and try the sample
    - You can spit out the sample as swallowing is not essential in this study.
    - After each comparison pair, eat a salty biscuit and drink water to neutralize your taste.
    - During the test please ignore the difference in the taste as much as you can, since the samples could taste different but might have same thickness.
    - Write down in each box if you think and feel the sample is the same with the control or not.

	Tongue
Control – 319	
Eat a biscuit and rinse your mouth with water.	
Control - 618	
Eat a biscuit and rinse your mouth with water.	
Control - 765	
Eat a biscuit and rinse your mouth with water.	
Control - 192	
Eat a biscuit and rinse your mouth with water.	
Control - 675	
Eat a biscuit and rinse your mouth with water.	
Control - 219	
Eat a biscuit and rinse your mouth with water.	
Control - 261	

Eat a biscuit and rinse your mouth with water.	
Control - 972	
Eat a biscuit and rinse your mouth with water.	
Control - 819	
Eat a biscuit and rinse your mouth with water.	
Control - 120	
Eat a biscuit and rinse your mouth with water.	

(S=same/ D=different)

- **Important:**

Please, ask for more information, if you have any inquiries regarding this test **BEFORE** starting the evaluation.

General Comments:

Thank you! ☺

B.2 Chapter 4 Sensory Evaluation Form

Sensory Evaluation of Human Sensation

- **Personal information:**

  Name: **Age:** **Gender:** Female Male

  Weight (kg): **Height (cm):** **Ethnicity:**
  Date: __ / __ / ___

  Contact details:

- **Task (1) Instructions:**
  - Please put the blind fold and make sure you cannot see.
  - Put your hand on your knee in a relaxed position with your index finger waiting for the experiment.
  - Give a response when you feel a touch on your finger tip

finger	

- **Task (2) Instructions:**
  - Please put the blind fold and make sure you cannot see.
  - Open your mouth when you hear the ready sound and keep your tongue in a relaxed position.
  - Give a response when you feel a touch on your tongue.

tongue	

- **Task (3) Instructions:**
  - You will be asked to sense the firmness of the gel with your dominant index finger tip by compressing on the sample until you break the structure.
  - During the test you will be blindfolded.
  - Test the firmness of the control and then the sample and make comparison in between the pairs only.
  - Answer whether you feel the firmness of the samples are the same or not.

	Finger
Control – 518	
Control – 313	
Control – 298	
Control – 796	
Control – 108	

Control – 604	
Control – 254	
Control – 985	

(S=same/ D=different)

- **Task (4) Instructions:**
  - With the provided sample set start from left to right in the presented order.
  - The blank spoon is the control sample and you will need to compare the samples each time with the control in each pair.
  - Dispose the control apply a compression on the gel until you break with your hard palate, to test the firmness. Rinse your mouth with water. Do the same with the sample.
  - Answer whether you feel the firmness of the control and sample as they are the same or not.
  - Spit out the gels as swallowing is not essential in this study.
  - Write down in each box if you think and feel the sample is the same with the control or not.

	Tongue
Control – 518	
Control – 313	
Control – 298	
Control – 796	
Control – 108	
Control – 604	
Control – 254	
Control – 985	

(S=same/ D=different)

Important:

Please, ask for more information, if you have any inquiries regarding this test **BEFORE** starting the evaluation.

General Comments:

Thank you! ☺

B.3 Chapter 5 Sensory Evaluation Form

Sensory Evaluation of Human Sensation

- **Personal information:**

  Name: **Age:** **Gender:** Female Male

  Weight (kg): **Height (cm):** **Ethnicity:**

  Date: __ / __ / ___

  Contact details:

- **Task (1) Instructions: Finger touch sensitivity**
  - Please put the blind fold and make sure you cannot see.
  - Put your hand on your knee in a relaxed position with your index finger waiting for the experiment.
  - Give a response when you feel a touch on your finger tip

finger	

- **Task (2) Instructions: Tongue touch sensitivity**
  - Please put the blind fold and make sure you cannot see.
  - Open your mouth when you hear the ready sound and keep your tongue in a relaxed position.
  - Give a response when you feel a touch on your tongue.

tongue	

- **Task (3) Instructions: MITP**
  - Please put the disposable, individual bulb in to the middle of your tongue
  - Squeeze the bulb with your hard palate and tongue as much as you can
  - Repeat the process for 5 times (rest between the replicates)

- **Task (4) Instructions: Finger gripping force**
  - Please place the sensor between your thumb and index fingertip
  - Squeeze the sensor as much as you can
  - Repeat the process for 5 times (rest between the replicates)

- **Task (5) Instructions: Hand gripping force**
  - Please hold the hand held dynamometer with asked hand as shown by the investigator
  - Squeeze the sensor as much as you can

- Repeat the process for 5 times (rest between the replicates)

Right hand:
Left hand:

- **Task (6) Instructions: Elasticity discrimination (finger)**
  - You will be asked to sense the elasticity of the gel with your dominant index finger tip.
  - During the test you will be blindfolded.
  - Test the elasticity by applying a compression force on the gel and try not to break it (new sample will be given in the case of sample breaking)
  - Answer whether you feel the firmness of the samples are the same or not.

	Finger
Control – 518	
Control – 313	
Control – 298	
Control – 796	
Control – 108	
Control – 604	
Control – 254	
Control – 985	

(S=same/ D=different)

- **Task (7) Instructions: Elasticity discrimination (tongue)**
  - With the provided sample set start from left to right in the presented order.
  - The blank spoon is the control sample and you will need to compare the samples each time with the control in each pair.
  - Dispose the control apply a compression on the gel until you feel the elasticity (Try not to break it) with your hard palate. Rinse your mouth with water. Do the same with the sample (if sample is broken a new one will be provided)
  - Answer whether you feel the elasticity of the control and sample as they are the same or not.
  - Spit out the gels as swallowing is not essential in this study.

	Tongue
Control – 518	
Control – 313	
Control – 298	
Control – 796	
Control – 108	
Control – 604	
Control – 254	
Control – 985	

(S=same/ D=different)

Important:

Please, ask for more information, if you have any inquiries regarding this test **BEFORE** starting the evaluation.

General Comments:

Thank you! ☺

B.4 Chapter 6 Sensory Evaluation Form

Sensory Evaluation of Human Roughness Sensation

- **Personal information:**

Name: **Age:** **Gender:** Female Male

Weight (kg): **Height (cm):** **Date:** _ / _ / __

- **Task (1): Touch sensitivity**

Finger	

- **Task (2): 2-point discrimination**

Finger	

- **Task (3) Roughness Discrimination dry:**

	Finger
Control –618	
Control –319	
Control – 765	
Control – 480	
Control - 247	
Control - 118	
Control - 142	

(S=same/ D=different)

- **Task (4) Roughness Discrimination wet:**

	Finger
Control –618	
Control –319	
Control – 765	
Control – 480	
Control - 247	
Control - 118	
Control - 142	

Each panellist receives 6 pairs in balanced random order. **Light Touch**						
Panellist no.	Order of presentation and serving code (rough sensed in a circle) **DRY**					
	1	2	3	4	5	6
1	AB	CD	AC	BC	BD	AD
2	CD	BC	AD	AB	AC	BD
3	BD	AB	BC	CD	AD	AC
4	AD	BD	AB	AC	BC	CD
5	BC	AC	BD	AD	CD	AB
6	AC	AD	CD	BD	AB	BC
7	AB	BC	CD	AC	BD	AD
8	BC	CD	AD	BD	AB	AC
9	CD	AD	BC	AB	AC	BD
10	AD	BD	AC	CD	BC	AB
11	BD	AC	AB	AD	CD	BC
12	AC	AB	BD	BC	AD	CD
13	BC	BD	CD	AC	AB	AD
14	AD	BC	AB	CD	BD	AC
15	CD	AD	BC	AB	AC	BD
16	AC	CD	BD	AD	BC	AB
17	BD	AB	AC	BC	AD	CD
18	AB	AC	AD	BD	CD	BC
19	AD	AC	AB	BD	BC	CD
20	AB	CD	BD	AD	AC	BC
21	CD	AC	BC	AB	AD	BD
22	AD	AB	CD	BC	BD	AC
23	BC	BD	AD	AC	CD	AB
24	BD	BC	AC	CD	AB	AD
25	AB	BC	CD	AC	AD	BD
26	BC	CD	AD	BD	AC	AB
27	CD	AB	BC	AD	BD	AC
28	BD	AD	AC	CD	AB	BC
29	AC	BD	AB	BC	CD	AD
30	AD	AC	BD	AB	BC	CD

Each panellist receives 6 pairs in balanced random order. **Mod Touch**						
Panellist no.	Order of presentation and serving code (rough sensed in a circle) **DRY**					
	1	2	3	4	5	6
1	AB	CD	AC	BC	BD	AD
2	CD	BC	AD	AB	AC	BD
3	BD	AB	BC	CD	AD	AC
4	AD	BD	AB	AC	BC	CD
5	BC	AC	BD	AD	CD	AB
6	AC	AD	CD	BD	AB	BC
7	AB	BC	CD	AC	BD	AD
8	BC	CD	AD	BD	AB	AC
9	CD	AD	BC	AB	AC	BD
10	AD	BD	AC	CD	BC	AB
11	BD	AC	AB	AD	CD	BC
12	AC	AB	BD	BC	AD	CD
13	BC	BD	CD	AC	AB	AD
14	AD	BC	AB	CD	BD	AC
15	CD	AD	BC	AB	AC	BD
16	AC	CD	BD	AD	BC	AB
17	BD	AB	AC	BC	AD	CD
18	AB	AC	AD	BD	CD	BC
19	AD	AC	AB	BD	BC	CD
20	AB	CD	BD	AD	AC	BC
21	CD	AC	BC	AB	AD	BD
22	AD	AB	CD	BC	BD	AC
23	BC	BD	AD	AC	CD	AB
24	BD	BC	AC	CD	AB	AD
25	AB	BC	CD	AC	AD	BD
26	BC	CD	AD	BD	AC	AB
27	CD	AB	BC	AD	BD	AC
28	BD	AD	AC	CD	AB	BC
29	AC	BD	AB	BC	CD	AD
30	AD	AC	BD	AB	BC	CD

Each panellist receives 6 pairs in balanced random order. **Hard touch**						
Panellist no.	Order of presentation and serving code (rough sensed in a circle) **DRY**					
	1	2	3	4	5	6
1	AB	CD	AC	BC	BD	AD
2	CD	BC	AD	AB	AC	BD
3	BD	AB	BC	CD	AD	AC
4	AD	BD	AB	AC	BC	CD
5	BC	AC	BD	AD	CD	AB
6	AC	AD	CD	BD	AB	BC
7	AB	BC	CD	AC	BD	AD
8	BC	CD	AD	BD	AB	AC
9	CD	AD	BC	AB	AC	BD
10	AD	BD	AC	CD	BC	AB
11	BD	AC	AB	AD	CD	BC
12	AC	AB	BD	BC	AD	CD
13	BC	BD	CD	AC	AB	AD
14	AD	BC	AB	CD	BD	AC
15	CD	AD	BC	AB	AC	BD
16	AC	CD	BD	AD	BC	AB
17	BD	AB	AC	BC	AD	CD
18	AB	AC	AD	BD	CD	BC
19	AD	AC	AB	BD	BC	CD
20	AB	CD	BD	AD	AC	BC
21	CD	AC	BC	AB	AD	BD
22	AD	AB	CD	BC	BD	AC
23	BC	BD	AD	AC	CD	AB
24	BD	BC	AC	CD	AB	AD
25	AB	BC	CD	AC	AD	BD
26	BC	CD	AD	BD	AC	AB
27	CD	AB	BC	AD	BD	AC
28	BD	AD	AC	CD	AB	BC
29	AC	BD	AB	BC	CD	AD
30	AD	AC	BD	AB	BC	CD

Each panellist receives 6 pairs in balanced random order. **LIGHT TOUCH**						
Panellist no.	Order of presentation and serving code (rough sensed in a circle) **WET**					
	1	2	3	4	5	6
1	AB	CD	AC	BC	BD	AD
2	CD	BC	AD	AB	AC	BD
3	BD	AB	BC	CD	AD	AC
4	AD	BD	AB	AC	BC	CD
5	BC	AC	BD	AD	CD	AB
6	AC	AD	CD	BD	AB	BC
7	AB	BC	CD	AC	BD	AD
8	BC	CD	AD	BD	AB	AC
9	CD	AD	BC	AB	AC	BD
10	AD	BD	AC	CD	BC	AB
11	BD	AC	AB	AD	CD	BC
12	AC	AB	BD	BC	AD	CD
13	BC	BD	CD	AC	AB	AD
14	AD	BC	AB	CD	BD	AC
15	CD	AD	BC	AB	AC	BD
16	AC	CD	BD	AD	BC	AB
17	BD	AB	AC	BC	AD	CD
18	AB	AC	AD	BD	CD	BC
19	AD	AC	AB	BD	BC	CD
20	AB	CD	BD	AD	AC	BC
21	CD	AC	BC	AB	AD	BD
22	AD	AB	CD	BC	BD	AC
23	BC	BD	AD	AC	CD	AB
24	BD	BC	AC	CD	AB	AD
25	AB	BC	CD	AC	AD	BD
26	BC	CD	AD	BD	AC	AB
27	CD	AB	BC	AD	BD	AC
28	BD	AD	AC	CD	AB	BC
29	AC	BD	AB	BC	CD	AD
30	AD	AC	BD	AB	BC	CD

Each panellist receives 6 pairs in balanced random order. **MOD TOUCH**						
Panellist no.	Order of presentation and serving code (rough sensed in a circle) **WET**					
	1	2	3	4	5	6
1	AB	CD	AC	BC	BD	AD
2	CD	BC	AD	AB	AC	BD
3	BD	AB	BC	CD	AD	AC
4	AD	BD	AB	AC	BC	CD
5	BC	AC	BD	AD	CD	AB
6	AC	AD	CD	BD	AB	BC
7	AB	BC	CD	AC	BD	AD
8	BC	CD	AD	BD	AB	AC
9	CD	AD	BC	AB	AC	BD
10	AD	BD	AC	CD	BC	AB
11	BD	AC	AB	AD	CD	BC
12	AC	AB	BD	BC	AD	CD
13	BC	BD	CD	AC	AB	AD
14	AD	BC	AB	CD	BD	AC
15	CD	AD	BC	AB	AC	BD
16	AC	CD	BD	AD	BC	AB
17	BD	AB	AC	BC	AD	CD
18	AB	AC	AD	BD	CD	BC
19	AD	AC	AB	BD	BC	CD
20	AB	CD	BD	AD	AC	BC
21	CD	AC	BC	AB	AD	BD
22	AD	AB	CD	BC	BD	AC
23	BC	BD	AD	AC	CD	AB
24	BD	BC	AC	CD	AB	AD
25	AB	BC	CD	AC	AD	BD
26	BC	CD	AD	BD	AC	AB
27	CD	AB	BC	AD	BD	AC
28	BD	AD	AC	CD	AB	BC
29	AC	BD	AB	BC	CD	AD
30	AD	AC	BD	AB	BC	CD

Each panellist receives 6 pairs in balanced random order. **HARD TOUCH**						
Panellist no.	Order of presentation and serving code (rough sensed in a circle) **WET**					
	1	2	3	4	5	6
1	AB	CD	AC	BC	BD	AD
2	CD	BC	AD	AB	AC	BD
3	BD	AB	BC	CD	AD	AC
4	AD	BD	AB	AC	BC	CD
5	BC	AC	BD	AD	CD	AB
6	AC	AD	CD	BD	AB	BC
7	AB	BC	CD	AC	BD	AD
8	BC	CD	AD	BD	AB	AC
9	CD	AD	BC	AB	AC	BD
10	AD	BD	AC	CD	BC	AB
11	BD	AC	AB	AD	CD	BC
12	AC	AB	BD	BC	AD	CD
13	BC	BD	CD	AC	AB	AD
14	AD	BC	AB	CD	BD	AC
15	CD	AD	BC	AB	AC	BD
16	AC	CD	BD	AD	BC	AB
17	BD	AB	AC	BC	AD	CD
18	AB	AC	AD	BD	CD	BC
19	AD	AC	AB	BD	BC	CD
20	AB	CD	BD	AD	AC	BC
21	CD	AC	BC	AB	AD	BD
22	AD	AB	CD	BC	BD	AC
23	BC	BD	AD	AC	CD	AB
24	BD	BC	AC	CD	AB	AD
25	AB	BC	CD	AC	AD	BD
26	BC	CD	AD	BD	AC	AB
27	CD	AB	BC	AD	BD	AC
28	BD	AD	AC	CD	AB	BC
29	AC	BD	AB	BC	CD	AD
30	AD	AC	BD	AB	BC	CD

B.5 Chapter 6 Sensory Evaluation Form

Age:	Weigh:	Height:

Task 1: Roughness threshold in air and scoring

Are they the same or different, if different can you score it from 0 to 9 (618 = 0)

s/d?		
	618	118
score	0	

*if same skip scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

s/d?		
	618	546
score	0	

*if same skip scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

s/d?		
	618	480
score	0	

*if same skip scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

s/d?		
	618	247
score	0	

*if same skip scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

s/d?		
	618	142
score	0	

*if same skip scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

s/d?		
	618	319
score	0	

*if same skip scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

s/d?		
	618	765
score	0	

*if same skip scoring

Age:	Weight	Height

Task 2: Roughness threshold in water (25C) and scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	118
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	546
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	480
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	247
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	142
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	319
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	765
score	0	

Age:	Weight	Height

Task 3: Roughness threshold in water (37C) and scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	319
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	765
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	247
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	480
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	142
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	118
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	546
score	0	

Age:	Weight:	Height:

Task 4: Roughness threshold in 100% GS (25C) and scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	765
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	247
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	319
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	142
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	480
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	118
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	546
score	0	

Age:	Weight:	Height:

Task 5: Roughness threshold in 100% GS (37C) and scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	546
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	480
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	319
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	142
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	118
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	247
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	765
score	0	

Age:	Weight:	Height:

Task 6: Roughness threshold in 90 % GS (25C) and scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	142
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	319
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	480
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	546
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	118
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	765
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	247
score	0	

Age:	Weight:	Height:

Task 7: Roughness threshold in 90% GS (37C) and scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	480
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	319
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	118
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	546
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	765
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	142
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	247
score	0	

Age:	Weight:	Height:

Task 8: Roughness threshold <u>in 80% GS (25C)</u> and scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	142
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	765
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	319
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	546
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	118
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	480
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	247
score	0	

Age:	Weight:	Height:

Task 9: Roughness threshold in 80% GS (37C) and scoring

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	319
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	765
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	546
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	142
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	118
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	247
score	0	

Are they the same or different, if different can you score it from 0 to 9 (*618 = 0)

*if same skip scoring

s/d?		
	618	480
score	0	