EXQUISITELY HETEROGENEOUS

Exquisitely heterogeneous

Combining different food textures to boost palatability

Marco Santagiuliana

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For a science
free from fears

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Chapter I

GENERAL INTRODUCTION

1

1.1 General Introduction

Many foods consumed daily are composed of multiple components which can often display a heterogeneous structure, flavour, and appearance. For example, creamy yoghurts are often combined with crunchy granola pieces, or chocolate pieces are added to biscuits and ice cream. During the consumption of such heterogeneous products, intra-oral sensory variety is delivered by the contrasting and dynamic sensations of texture and flavour. The dynamic texture contrast leads to continuous changes in intensity and quality of perceived texture, which leads to higher liking (Hyde & Witherly, 1993; Szczesniak & Kahn, 1984). Food industry is interested in understanding the key factors responsible for the appreciation of such heterogeneous foods. Due to the intricacy of product appreciation and perception, a multidisciplinary approach is necessary to comprehend the relationship between product heterogeneity and consumer perception. Food sensory perception and palatability are affected by a variety of interconnected factors related to both the product and consumer. Food texture, flavour, and visual appearance of the product are interpreted and integrated by consumers who will evaluate them based on their individual sensitivity and previous experiences. In order to design foods that are appreciated, the complex relations between food characteristics and consumer response should be considered in its entirety.

1.2 From food rheology to texture perception

Rheology is the science that investigates the relationships between forces and deformations in any material. The rheological behaviour of food can be characterized instrumentally and several studies have investigated the correlation between physical properties and specific textural perceptions. For macroscopically homogeneous liquid and solid foods, it is now well-known that rheological properties are the leading factors determining the perceived texture of food by consumers (Lillford, 2018; Van Vliet, 2002). The rheological behaviour of food is investigated differently depending on whether a liquid, semi-solid, or solid product is considered.

For liquid foods, the ratio between shear stress and shear rate defines the shear viscosity, a parameter representing the bulk product rheological behaviour. When the relation between shear stress and shear rate is linear, the liquid is referred to as Newtonian. On the contrary, when the shear viscosity increases or decreases upon shear rate a non-Newtonian behaviour occurs. The majority of liquid foods present a shear thinning behaviour in which the shear viscosity decreases upon shear rate. The shear viscosity has been mainly associated with thickness perception (Hutchings & Lillford, 1988; Malone et al., 2003; Richardson et al., 1989). However, in combination with other lubrication aspects, viscosity of the bulk in liquid food seems to be also involved in the perception of more complex textural attributes as creaminess, fattiness, slipperiness and smoothness (Lillford, 2018; Scholten, 2016).

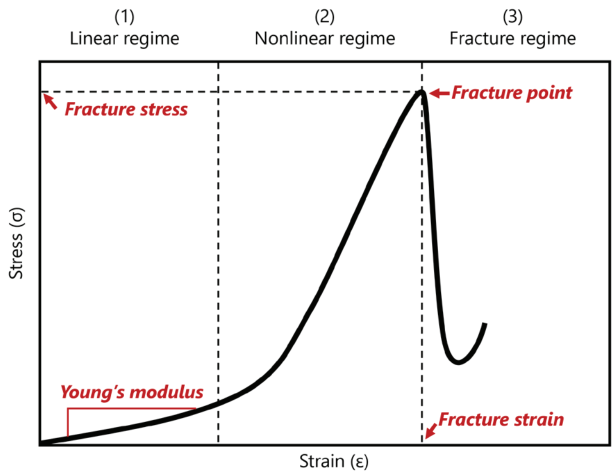


Figure 1.1. Example of a stress-strain relationship of semi-solid or solid food.

For semi-solid and solid foods, the rheological behaviour is characterized considering the relationship between stress (σ) and strain (ε) during deformation. The force per unit area causing the deformation defines the stress, whereas the extension per unit length caused by the applied force represents the strain. The relationship between stress and strain can be categorized in three different regimes (**Figure 1.1**): the first, linear regime (1); the second, nonlinear regime (2); and the third, fracture regime (3). During the first regime, stress and strain follow a linear relation and, therefore, the structure of the material is not affected by the deformation applied. The ratio between stress and strain in the linear regime is defined as Young's modulus, which provides a measure of the stiffness of a semi-solid and solid material. In the second regime, the deformation applied starts to affect the structure of the material and, as a result of this, the relation between stress and strain becomes nonlinear. In the third regime, the deformation applied leads the material to fracture. The linear regime is assessed using small deformation tests, whereas large deformation measurements allow investigating the material in the nonlinear and fracture regimes. Considering the deformations occurring during oral processing, large and fracture measurements are often performed in food to allow a connection with the perceived textural properties by the individual. In solid foods, rheological parameters obtained during large deformation tests as fracture stress and fracture strain have been extensively related to texture (Foegeding & Drake, 2007; Sala et al., 2008). For instance, the fracture stress of food has been associated with perceived hardness in a variety of products ranging from model gels, cheeses, fruits, and vegetables. Similarly, positive correlations between fracture strain of food and perceived deformability, brittleness at first bite and fracturability have been shown (Devezeaux de Lavergne et al., 2017).

Fracture stress and fracture strain are not the only product characteristics influencing texture perception. Physicochemical properties as melting behaviour and serum release are also known material properties able to impact food perception by the consumers. For instance, an increase in temperature to body temperature causes melting of fats and melting of gelatine network in gelled or viscous products, which can lead to a higher perceived creaminess and overrule the effect of fracture properties on perception (Devezeaux de Lavergne et al., 2016; Sala et al., 2008). In the same way, the manifestation of serum release during consumption affects perception of moisture-related sensory attributes (e.g. moist, watery, cooling/refresh) (Çakır et al., 2012; Devezeaux de Lavergne et al., 2016; Gwartney et al., 2002; van den Berg et al., 2007) and juiciness during consumption in model gels, fruits and vegetables, and meat products (van de Velde et al., 2006; van den Berg et al., 2007).

1.3 Dynamics of food texture perception

Perception of food texture occurs in the mouth as a dynamic and complex process. The food mechanical and physicochemical properties that give rise to the different textural sensations undergo a constant modification during consumption as a result of oral processing and mastication. An intricate coordination of muscle activities, jaw and tongue movements allows food manipulation, destruction and mixing with saliva to obtain a bolus that is safe to swallow (van Aken et al., 2007; van Vliet et al., 2009). These dynamic processes play a key role in establishing the food texture profile and they involve parameters related to the consumer and product. Both consumer physiological and food rheological factors, in fact, can affect parameters as bite size, number of chews per bite, consumption time, eating rate, and number of swallows that define the chewing process of food (Chen, 2015; Hiiemae et al., 1996).

From a consumer perspective, physiological factors such as age, sex, and ethnicity have been shown to greatly affect oral processing behaviour of food. For example, a physiological decline caused by ageing is a known source of deterioration of dental status, oral volume, bite force, jaw muscle activity, and tongue pressure. These age-related changes and the related decline in mastication efficiency induce compensation strategies for the elderly (e.g. augmented number of chews before the food is swallowed). Alternatively, physiological differences between male and female adults in terms of maximum bite force, salivary flow, lip and cheek strength have been found, with males having higher values for such parameters than females (Clark & Solomon, 2012; Julien et al., 1996; Palinkas et al., 2010; Percival et al., 1994). These differences result in larger bite sizes, higher eating rates, and shorter chewing cycle durations for males in comparison to females (Hill & McCutcheon, 1984; Nagasawa et al., 1996; Park & Shin, 2015; Youssef et al., 1997).

From a food product perspective, rheological and physicochemical properties have also a determinant role in defining consumer oral processing behaviour. For example, instrumentally measured textural properties characterized via Texture Profile Analysis (TPA; method that acknowledges the temporal dynamics of texture), such as springiness, cohesiveness, and chewiness, have been shown to be positively correlated with average bite sizes and number of chews for a broad range of solid foods (Wee et al., 2018). Similarly, positive correlations between the instrumentally measured hardness of model food gels and number of chews, muscle activity, and jaw opening amplitude were observed (Koç et al., 2014). For liquid, semi-solid and solid foods, rheological properties largely impact bite size, consumption time, and eating rate of consumers, while their effects on chewing rate and chewing cycle duration were found to be limited (Aguayo-Mendoza et al., 2019). When food elements varying in texture are combined within a single bite, oral processing and related perception of a product can be affected (James, 2018; Tang et al., 2017; Tarrega et al., 2016). In this instance, the combination of two gel layers with different mechanical properties resulted in an oral processing behaviour with characteristics in between the chewing patterns of the two layers when consumed separately (Devezeaux de Lavergne et al., 2015). In the same way, addition of toppings (i.e. cheese spread, mayonnaise) to carriers like bread or crackers facilitate mastication and bolus formation (van Eck et al., 2018), affecting sensory perception of the products (van Eck et al., 2019).

1.4 Consumer physiological parameters affecting food texture perception

As the perception of food texture occurs when the product is manipulated in the mouth, it is important to take into consideration that the complex interaction between food stimuli and human body is affected by a relative large inter-individual variability (Engelen & Van Der Bilt, 2008). As a matter of fact, a large deviation in ratings of the same stimulus between subjects can emerge due to differences in several oral physiological parameters. In this thesis, the effect of oral tactile sensitivity, fungiform papillae density, saliva production, and sensitivity to 6-n-propylthiouracil (PROP) have been considered to explain the variability of perceived texture in heterogeneous foods containing microparticles.

1.4.1 Oral tactile sensitivity

Contrary to other sensorial perceptions (e.g. taste, smell), the perception of food texture cannot be related to a single type of specialized sensor due to its intrinsic multimodal nature. However, oral tactile sensations are considered to be the main factor contributing to perception of food texture. Such tactile sensations are perceived thanks to specialized mechanoreceptor nerve fibers present in the surfaces of oral mucosa (i.e. tongue and palate) (Prescott & Bartoshuk, 2016). During food consumption, these nerve fibers generate signals that are sent to the brain where they will be integrated to express the perception of the different textural sensations (e.g. grittiness, smoothness, creaminess). It is known that individuals differ in their oral tactile sensitivity and this is expected to influence perceived texture of food. Several methods allow characterizing the subject sensitivity towards tactile stimuli in mouth. For instance, tasks of oral form or letter recognition (Essick et al., 1999; Jacobs et al., 1998), two-point or size discrimination tests (Johnson & Phillips, 1981) and force/pressure perception on the tongue (Pigg et al., 2010) have been proposed as methods to characterize individual mechanosensory acuity. The latter test consists of the ability to perceive and recognize the pressure applied by Von Frey monofilaments, which are very thin nylon fibers able to deliver different forces when the surface of the tongue is touched. With such a method, different sensitivities were found in different locations of the tongue as the anterior part of the tongue is more sensitive than the posterior part (Yackinous & Guinard, 2001). Probably as a result of the complexity of texture perception and the different sensations related to that, several studies have failed in finding any correlation between the individual's tactile sensitivity and food texture perception (Aktar et al., 2015a; Nachtsheim & Schlich, 2013).

1.4.2 Fungiform papillae density

The perception of oral stimuli intensity and the consequent determination of food preferences always involves the individual chemoreceptor systems. During oral consumption, the compounds present in food are sensed thanks to receptors located in taste pores. These are peripheral structures specialized in taste stimuli detection, which can be found on the tongue and other parts of the oral mucosa. Historically, as taste pores could be mainly located within gustatory papillae, the individual taste pores density has been estimated by calculating the number of papillae present on the tongue. Papillae are visible bulges on the surface of the tongue, which vary in their shapes and can be categorized in four types: fungiform, filiform, circumvallate, and foliate (Nuessle et al., 2015). Among these types, fungiform papillae (FP) have commonly been designated as main indicators of taste pore density and related to individual sensitivity (Miller & Reedy, 1990). Individuals vary considerably in their number of fungiform papillae present on the tongue surface; in fact, fungiform papillae densities (FPD) ranging from 0 to over 200 papillae/cm^2 are reported in the literature (Fischer et al., 2013; Piochi et al., 2018; Zhang et al., 2009). Considering that fungiform papillae are innervated by both gustatory and somatosensory nerves, studies have suggested that these tongue structures are sensitive to both taste (i.e. bitter, sour, sweet, salty and umami) and mechanical stimuli (Whitehead et al., 1985; Zahm & Munger, 1985). A possible relation might exist between FPD and individual textural sensitivity, as oral mechanoreceptors of the mucosa are situated in the same connective tissue of papillae (Watanabe, 2004).

1.4.3 Saliva production

Saliva is a human body fluid continuously secreted by salivary glands and dispersed in the oral cavity. Its constant presence in our mouth ensures both body protection by the local microbiota and an aqueous medium essential for food processing and perception. The high amount of water (99%) of saliva allows the present electrolytes, immunoglobulins, enzymes (α-amylase, etc.) and mucins to be included into the forming bolus (Humphrey & Williamson, 2001). Such an incorporation process not only facilitates the breakdown of the product by enzymes, but it also contributes to the food perception by digesting (i.e. increase in sweetness when starches are broken down to saccharides by α-amylase) and dissolving components present in it. Tastants, in particular, are in fact transported by the saliva to taste buds where they can be perceived. During mastication, saliva acts as a lubricant that reduces friction between oral mucosa and food and facilitates oral movement and swallowing. The amount and composition of saliva incorporated into the foods during mastication depend on the structure and texture of food products and it affects the dynamic product perception (Carpenter, 2013). Saliva incorporation can change bolus consistency thanks to its dilution effect and lubrication properties, influencing significantly the perception of attributes such as adhesiveness and hardness (Pascua et al., 2013).

1.4.4 Sensitivity to 6-n-propylthiouracil (PROP)

The ability to taste bitter compounds has a great role in individual perception and choice of food (Prodi et al., 2004). Over the last two decades, the bitter taste response in population has been investigated using 6-n-propylthiouracil (PROP) (Bakke & Vickers, 2008; Dinehart et al., 2006; Masi et al., 2015; Zhao & Tepper, 2007). Sensitivity to PROP bitterness has been used as a genetic marker as its perception is an inherited characteristic that depends on the gene TAS2R38. Depending on the dominant variant of the gene receptor form, individual sensitivity to PROP bitterness varies (Duffy et al., 2004). Based on their PROP bitterness intensity ratings, subjects can be classified into three groups. Non-tasters (NT) are subjects who perceive PROP as weak or tasteless, medium tasters (MT) perceive PROP as moderately bitter, and supertasters (ST) are those who perceive it as extremely bitter. Sensitivity to PROP bitterness has been related to a higher perception of other compounds such as sucrose, citric acid, sodium chloride, quinine caffeine, and monosodium glutamate (Hayes & Duffy, 2008; Pankratz et al., 2014; Prescott et al., 2001). Possible relationships have been found between PROP bitterness and other chemosthetic or tactile sensations as pungency from capsaicin or astringency from alum (Bajec & Pickering, 2008; Prescott & Swain-Campbell, 2000).

1.5 Consumer expectations and texture perception

Besides the role of product properties and consumer physiology in sensory perception and liking of food, the expectations consumers possess toward a certain product are also of great importance in shaping their responses (Skaczkowski et al., 2016). Expectations can be generally defined as “subjective notions of things to come” and they are linked to the concept of anticipation (Deliza, 1995). The confirmation or disconfirmation of consumers’ expectations (i.e. anticipated properties) in terms of appearance, flavour and texture, have a central role in determining product acceptance or rejection. Consumers form their expectations based on a variety of factors pertaining to the product characteristics, the environment, and previous experiences. For instance, visual or olfactory properties of the product can provide external sensorial cues that help to generate expectations of the actual food sensory profile in the mind of the consumers. However, such product-related information is affected by the context in which the product is being evaluated and the condition of the surroundings (e.g. presentation or plate style). Additionally, person’s frame of reference, and knowledge are known factors affecting generation of consumer expectations (Aaron et al., 1994; Harrar & Spence, 2013; Michel et al., 2015; Okamoto & Dan, 2013; Piqueras-Fiszman et al., 2012; Spence et al., 2012; Stewart & Goss, 2013; Wansink et al., 2005; Yeomans et al., 2008).

Such a complexity behind the single term "expectations" can be simplified by distinguishing them based on either the object of the expectancy/anticipation (i.e. what the consumer is expecting) or the cause of the induced expectancy (i.e. what trigger the expectancy formation). In the first instance, expectations can be categorized on sensory-based expectations, which are the beliefs that the stimulus/ food product will possess certain sensory attributes, each at certain intensities (e.g. sweet fruit; crispy chips) and hedonic-based expectations, which are beliefs that the product will be liked/disliked to a certain degree (Cardello, 1994). Alternatively, expectations can be distinguished based on the eliciting cause into preconceived or "real-time" expectations. Preconceived expectations are those that are generated thanks to previous experiences with the product, familiarity, and stereotypes. For instance, one could describe how vanilla ice cream tastes without seeing or tasting it or could define negative expectations towards a specific food if this was proved already to be disliked in the past. Conversely, real-time expectations are those that are generated during the consumption of the food product. These can be further distinguished in visually-elicited expectations (e.g. cues generating from packaging, info labelling, product visual characteristics, serving vessel) and oral-elicited expectations (e.g. texture properties) (Szczesniak, 2002).

Expectations and actual product perception do not always match and this creates a cognitive contrast in the consumer that might affect product perception and liking. Theoretical psychological models have been developed to explain the effects of the level of expectations and magnitude of contrast on acceptability of foods (**Figure 1.2**) (Anderson, 1973). Four major theories have been established over the years: (1) assimilation; (2) contrast; (3) generalized negativity; (4) assimilation/contrast.

The assimilation theory (1) suggests that when a mismatch occurs between expectations and actual product performance (i.e. product texture), consumers will try to assimilate (i.e. minimize) such a difference by changing their perceptions, thus bringing it closer to their expectations. Conversely, the contrast theory (2) proposes that possible differences between product performance and expectations are enlarged by consumers. For instance, the disparity between expected and actual stimulus properties results in an exaggeration of the difference, leading to a substantial reduction in consumer satisfaction. The generalized negativity theory (3) assumes that any discrepancy between consumer expectations and product performance will necessarily result in lower hedonic response than the optimal expectation match. Finally, the assimilation/contrast theory (4) proposes a hybrid model in which consumer satisfaction/dissatisfaction follows the principles of assimilation theory when a product is only slightly different from the expectations (either positive or negative). Under conditions of highly positive or negative disconfirmation of expectations, the principles of contrast theory will be followed. Therefore, this theory proposes that actual sensory or hedonic attributes of the product differ only slightly from expectations, the consumer will minimize such a discrepancy, but if the difference is larger this will cause a contrast effect.

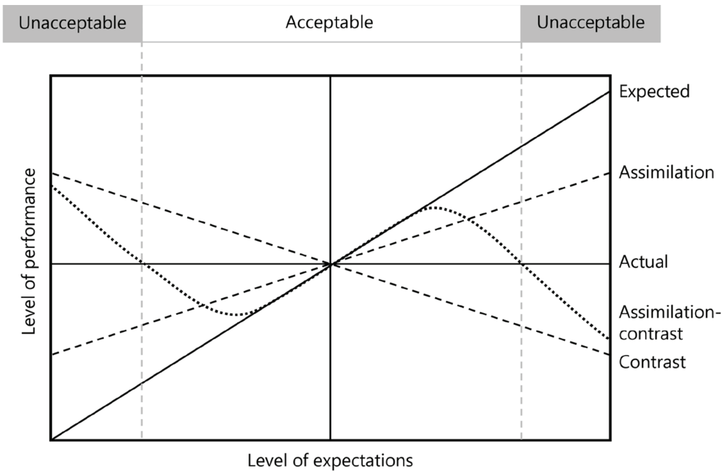


Figure 1.2. Representation of effect of (dis)confirmation of consumer's expectations on perception and liking according to three psychological theories by Anderson (1973). Figure taken from Piqueras-Fiszman and Spence (2015).

When textural properties are concerned, consumers tend to comment on them only when these are inconsistent with their expectations (Szczesniak, 2002). Variations from the expected levels of textural attributes can be a sign of compromised product freshness (e.g. staled bread) and, for such a reason, texture is an important yet subtle indicator of product quality. For familiar products, however, the confirmation of expectation may also result in consumer boredom (Piqueras-Fiszman & Spence, 2015). A continuous stimulation with sensorial properties may, in fact, lead to consumer's familiarisation, which does not increase interested or hedonic appraisal of food. The introduction of small modifications in a product (i.e. addition of particles providing a new structure, flavour, and appearance) might be used to create new products which are perceived more interesting by the consumers (assimilation effect). The level of modifications introduced in a food product should be balanced as large and discrepant variations from the expected profile might result in consumers' rejection since these might induce negative arousal (i.e. contrast effect) due to potentially harmful stimuli or neophobic feelings (Pliner & Hobden, 1992; Koza et al., 2005). Additionally, product familiarity and product-related experience with food influences the interpretation of sensorial information that determines product perception and appreciation (Chocarro et al., 2009; Deliza et al., 1996; Grunert et al., 2004).

1.6 Rationale and thesis outline

Very little knowledge is available on the factors responsible for the perception and appreciation of heterogeneous foods by consumers. To gain insights on the variables to take into consideration when designing palatable foods composed by different structural elements, the interdependencies between food heterogeneity, food expectations, oral processing and sensitivity, sensory perception and liking should be investigated. A multidisciplinary approach is required to understand the relationship between product heterogeneity and consumer perception (**Figure 1.3**).

A broad comprehension can be achieved by firstly investigating which food properties are responsible for the recognition and perception of heterogeneity in food. As the stimulus interpretation of such properties depends on both prior and real-time expectations the consumer have, these should be characterized together to understand appreciation of food heterogeneity. In fact, the recognition of the same stimulus could lead to opposite reactions (i.e. assimilation vs contrast effect; liking vs disliking) depending on whether the presence of heterogeneities and their properties are expected or not in a food product.

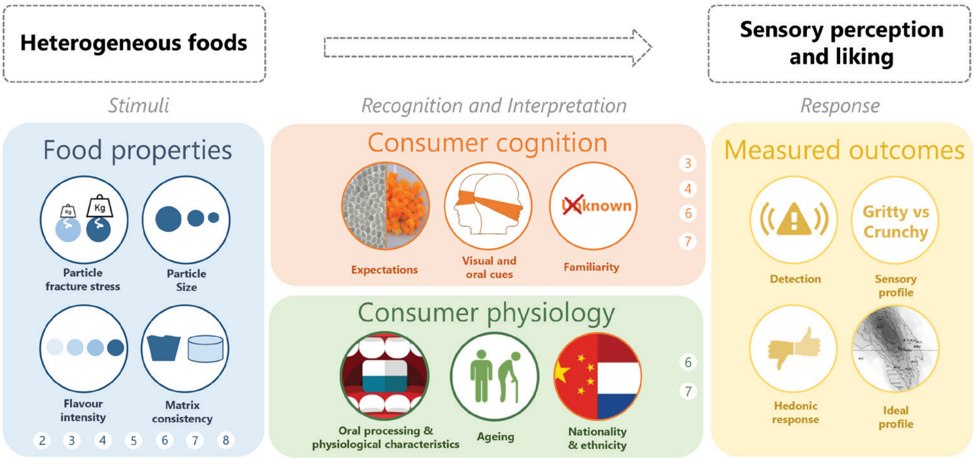


Figure 1.3. Schematic overview of this thesis. Numbers indicate chapters in this thesis.

Since the addition of heterogeneity (e.g. particles) can provide a different visual appearance, texture and flavour to the product, the visual and oral properties of the combined elements are expected to be of utmost relevance to determine perception and appreciation of the food. Such an addition is also expected to influence dynamic perception and oral processing of the product. Finally, as differences in perception of a heterogeneous product might raise when consumers vary in their physiological (e.g. age) or psychological characteristics (e.g. familiarity), such consumers' features should be taken into consideration in order to obtain a complete picture of the fundamental aspects that determine the response to a heterogeneous food product.

The **aim** of this thesis is to determine the effect of structural heterogeneity on expected and perceived sensory properties and liking of foods in different consumer groups. In detail, this thesis aims to investigate how food and consumer characteristics affect sensory perception and liking of heterogeneous foods by engineering structural heterogeneities at different length scales. A combination of model and real food products were used to establish the effect of physical and physicochemical properties of complex, heterogeneous food matrices on sensory perception and liking in relation to consumer characteristics.

In **Chapter 2**, bi-layer gel-based model foods were engineered to investigate the relation between physical food properties and the perception of texture contrast. Specifically, the key mechanical and physicochemical properties of semi-solid foods required to trigger the detection of texture contrast were explored. Properties of the gels were designed to examine the effect of fracture stress, fracture strain, syneresis, and melting behaviour on perceived texture contrast in heterogeneous products.

As the majority of heterogeneous foods contain dispersed particles rather than layers, **Chapter 3** aimed to understand the combined influence of size and fracture stress of added particles in food on sensory perception and hedonic response. K-carrageenan gel particles were developed to vary independently of their size (millimetre range) and fracture stress. These were added to liquid model soups and semi-solid model gels to determine the effect of matrix consistency on perceived texture contrast in particle-filled foods.

Both flavour of the added particles and consumer's expectations generated by visual and oral sensorial cues were assumed to be of great relevance for the perception and appreciation of heterogeneous products and these factors were investigated in **Chapter 4**. Real carrots, model carrots and model chicken particles differing in particle size, fracture stress, and/or carrot flavour concentration were designed to vary the visual and sensorial properties of chicken soup, a product that is normally known to be heterogeneous in its texture. The effects of such product modifications on expected, perceived and ideal sensory properties and liking were characterized through a consumer test.

The experiment summarized in **Chapter 5** was designed to decouple how visual and oral cues influence sensory perception and liking of novel, heterogeneous foods. Heterogeneous processed cheeses were prepared by adding model or real bell pepper pieces varying in size, fracture stress, and concentration to homogeneous processed cheese matrices. These were evaluated in three consecutive test conditions in which products were tasted while being blindfolded, judged only from visual appearance and evaluated during normal condition. By those means, the influence of exteroceptive (visual) and interoceptive (oral) cues on sensory perception and liking of novel, heterogeneous foods was determined.

Chapter 6 aimed to determine how addition of particles to a viscous food influences the consumer oral processing behaviour by video recording the participants during consumption. In this study, model peach particles varying in size, fracture stress and concentration were added to yoghurt. While chapters 2, 3, 4 and 5 focussed on a rather homogeneous group of subjects with respect to age and ethnicity, this chapter investigated the sensory perception and chewing behaviour of consumer groups differing in age. The expected, perceived and ideal sensory properties of the heterogeneous yoghurts were determined and compared between the two groups.

The comparison of perceived texture between different consumer groups was further expanded considering participants with different nationalities and ethnicity in **Chapter 7**. Precisely, this chapter aimed to unveil how product familiarity and physiological characteristics of consumers affect detectability of microparticles of Dutch, Caucasian and Chinese, Asian women. Participants were characterized for product familiarity, salivary flow rates, propylthiouracil (PROP) status, point pressure thresholds measured with Von Frey filaments, and fungiform papillae density. These parameters were related to average particle size detection thresholds causing grittiness sensations.

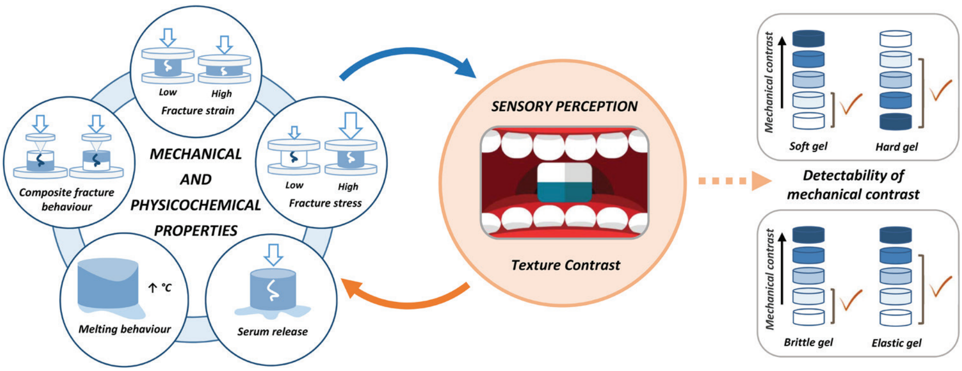
In **Chapter 8**, the addition of macroparticles or fat to common food was investigated as a possible strategy to perceptually compensate for negative texture perceptions as grittiness. Cellulose beads were added as model particles to quark to induce grittiness. Two macroparticle types were used: granola pieces and model peach gel pieces (from chapter 6). Fat concentration of quark was also varied. Both static and dynamic perception of such products were characterized.

Finally, **Chapter 9** summarizes the findings presented in the different chapters and provides an integrated discussion regarding the complex relationship between food characteristics of heterogeneous foods and consumer response. The significance of these results and related implications together with an outlook for further research are also provided.

Chapter 2

HETEROGENEITY TO THE LIMIT

MECHANICAL PROPERTIES AFFECT DETECTABILITY OF PERCEIVED TEXTURE CONTRAST IN HETEROGENEOUS FOOD GELS



This chapter is based on:

Santagiuliana, M., Piqueras-Fiszman, B., van der Linden, E., Stieger, M., Scholten, E., Mechanical properties affect detectability of perceived texture contrast in heterogeneous food gels. *Food Hydrocolloids* 80, 2018, p. 254-263.

Abstract

This study investigated the influence of mechanical and physicochemical properties of semi-solid model foods on the detection and temporal perception of texture contrast. Gel-based model foods consisting of two layers were used to systematically vary mechanical contrast and physicochemical properties within bi-layer gels. Fracture stress (σ_F) and strain (ε_F) were modified by changing the concentration of various gelling agents (agar, κ-carrageenan, and gelatine). The physicochemical properties of gels varied with respect to syneresis and melting behaviour depending on the type of gelling agent. The detection limit of perceived texture contrast of bi-layer gels was determined using ranking tests. Subjects ranked gels in order of increasing perceived heterogeneity as a measure of texture contrast. The detection limit of texture contrast varied between brittle and elastic gels and between soft (low σ_F) and hard (high σ_F) gels. In soft and brittle agar gels, heterogeneity was perceived already when the difference in fracture stress between layers was small ($\Delta\sigma_F \geq 5$ kPa). In soft and elastic gels (κ-carrageenan, gelatine) and hard gels, heterogeneity was perceived only when the difference in fracture stress between the layers was large ($\Delta\sigma_F \geq 12$ kPa). The perceived heterogeneity intensity over time was investigated by time-intensity profiling. During mastication, gelatine gels were perceived for a longer period of time with a higher heterogeneity intensity than agar and κ-carrageenan gels. We conclude that mainly mechanical properties of gels impact detectability of mechanical contrast as perceived texture contrast (heterogeneity), whereas a combination of mechanical and physicochemical properties influence the dynamic perception of heterogeneity over time.

2.1 Introduction

In recent years, attention has been given to gain a better understanding of food texture perception (Renard et al., 2006; Van Vliet, 2002; Wilkinson et al., 2001).

Studies of food texture are encouraged with the aspiration to create foods that satisfy the consumer needs in terms of acceptability and quality. Previous studies primarily focus on macroscopically homogeneous foods due to the ability to control and establish specific texture properties. However, many foods that are highly liked have a macroscopically heterogeneous structure (e.g. cream filled biscuits, yoghurt with fruit pieces). These composite foods consist of different components with different mechanical properties. The presence of different mechanical properties in foods provides an intra-oral sensory variety that is linked to the qualitative and quantitative continuous changes of perceived texture (Hyde & Witherly, 1993). Such variation of mechanical properties within a food is associated to texture contrast perception, i.e. perception of heterogeneity, and it is proposed that this can boost sensory responses during mastication due to the experience of complex sensory stimulation (Szczesniak & Kahn, 1984). Lévy et al. (2006) suggested that consumer exposure to foods with multiple types of stimuli should lead to an increase in long-term liking. It was proposed that variations in texture and tastants can be used to provide a discontinuous stimulation and thus reduce adaptation of specific sensory perceptions (Emorine et al., 2014, 2015; Funami et al., 2016; Mosca et al., 2010, 2012). Texture contrast perception can be achieved by combining food elements with different mechanical or physicochemical properties within one food. A systematic understanding of how the mechanical and physicochemical properties contribute to the perception of texture contrast as heterogeneity is lacking, particularly of the relation between mechanical contrast and sensory perception of heterogeneous foods. Mechanical contrast might be primarily responsible for the perception of texture contrast, but a direct quantification of the relation between mechanical contrast and sensory perception is missing.

Recently, Devezeaux de Lavergne et al. (2015) investigated the role of mechanical contrast on oral processing behaviour and dynamic texture perception of bi-layer gels. It was shown that mechanical contrast influences sensory perception and oral processing behaviour. Dynamic texture perception of bi-layer gels resembled an average of the dynamic texture perception of the two individual gel layers. Hutchings et al. (2011, 2012) demonstrated that mechanical properties of the matrix (i.e. gelatine gels and chocolate) affect oral breakdown of foods with embedded peanuts. Similarly, other studies showed that bolus properties were directly affected by combining different components varying in mechanical properties in a food (Laguna & Sarkar, 2016; Larsen et al., 2015, 2016; Tang et al., 2017, 2016). The oral breakdown was influenced by the degree of "texture complexity". Gels with higher texture complexity resulted in the formation of smaller and more gel particles in comparison to gels with lower texture complexity. Such an increase in texture complexity decreased food intake while keeping the oral residence time constant (Tang et al., 2016). While these results show that mechanical contrast within a single bite influences perception, oral processing behaviour, and food intake, it is unclear how differences in mechanical and physicochemical properties of food components impact detection of perceived texture contrast as heterogeneity.

The aim of this study was to investigate the influence of mechanical and physicochemical properties of semi-solid model foods on the detection of perceived texture contrast. Model gels were used to systematically vary mechanical contrast and physicochemical properties in bi-layer gels.

We hypothesize that the ability to discriminate texture contrast depends not only on the initial, static, mechanical properties of the different components, such as fracture stress (σ_F) and strain (ε_F), but also on dynamic properties such as syneresis and melting behaviour during oral processing. Gels were made with different gelling agents to vary mechanical contrast and physicochemical properties. To test our hypothesis, two sensory studies were performed in which the minimum perceivable difference and the temporal evolution of heterogeneity were quantified. Results were linked to the instrumentally quantified mechanical and physicochemical properties of the gels.

2.2 Materials and Methods

2.2.1 Ingredients

Ferwo agar 700 (Caldic Ingredients B.V., Oudewater, NL), κ-carrageenan (GENUGEL® carrageenan type CHP-2, CP Kelco, Levallois-Perret, France) and pigskin gelatine (Bloom 240-260, Rousselot B.V., Gent, Belgium) were used as gelling agents. Potassium chloride was provided by Merck (Darmstadt, Germany). Titanium dioxide (TiO_2, E171) was purchased from Pomona Aroma B.V. (Hedel, NL). Food-grade red colourant (Bharco Foods, NL) and sunflower oil were purchased at a local retailer. Demineralized water was used for all solutions. All materials were food grade and were used without further purification.

Table 2.1. Composition of gel layers. All concentrations are given in weight percentage (% w/w). Fracture stress denotes target fracture stress.

Gel name	Composition	Fracture stress [kPa]								
		20	25	30	40	60	80	90	95	100
A	Agar	0.81	0.94	1.06	1.31	1.81	2.31	2.56	2.68	2.80
	TiO_2	0.20	0.20	0.20	0.30	0.30	0.40	0.40	0.40	0.40
	Red Colourant	0.08	0.08	0.08	0.07	0.06	0.06	0.06	0.06	0.06
	Water	98.91	98.78	98.66	98.32	97.83	97.23	96.98	96.86	96.74
K	κ-carrageenan	0.90	0.98	1.05	1.20	1.51	1.81	1.96	2.04	2.12
	TiO_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Red Colourant	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
	KCl solution	98.93	98.85	98.78	98.63	98.32	98.02	97.87	97.79	97.71
G	Gelatine	4.03	4.54	5.05	6.07	8.11	10.15	11.17	11.68	12.19
	TiO_2	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
	Red Colourant	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
	Water	95.3	94.79	94.28	93.26	91.22	89.18	88.16	87.65	87.14

2.2.2 Preparation of gel layers

Table 2.1 shows the composition of all gel layers prepared with agar (A), κ-carrageenan (K) or gelatine (G). In **Table 2.1**, fracture stress denotes target fracture stress for all gel layers. Colourants were added to obtain gels with equal visual appearance. Slightly different methods were used to prepare gels depending on the gelling agent. Solutions were first prepared by adding colourants and gelling agents to demineralized water. Agar solutions were stirred for 30 min to allow hydration. After hydration, agar solutions were heated in a water bath at 95°C for 45 min under continuous stirring. For κ-carrageenan solutions, κ-carrageenan was dispersed in a 0.075% wt KCl solution and stirred for 30 min to allow hydration. κ-carrageenan solutions were heated in a water bath at 90°C for 30 min. Gelatine solutions were stirred for 30 min and subsequently heated in a water bath at 60°C for 20 min.

Cylindrical gels were obtained by pouring warm biopolymer solutions into plastic tubes (Omnifix 65 mL syringes, B. Braun) with 26 mm internal diameter, which were lightly coated with sunflower oil. Solutions were kept in the fridge at 4°C for 15-18 hours to gel. After gelation, gels were removed from the tubes and cut with a custom-made cutting frame. All gels were used within 48 hours after preparation.

2.2.3 Preparation of mono-layer and bi-layer gels and study design

2.2.3.1 Preparation of mono-layer gels without mechanical contrast

2

Nine mono-layer, homogeneous gels without mechanical contrast were prepared for each type of gelling agent (agar, κ-carrageenan, gelatine). The homogeneous gels had a dimension of 26 mm diameter x 10 mm height. These gels varied in target fracture stress from 20 to 100 kPa and were used to determine the perceived hardness of homogeneous gels without mechanical contrast as a function of fracture stress.

2.2.3.2 Preparation of bi-layer gels with and without mechanical contrast

Bi-layer gels were prepared by combining two gel layers, each having a dimension of 26 mm diameter x 5 mm height, as shown in **Figure 2.1A**. Gel layers were placed on top of each other by hand. A thin layer of gelatine solution (10% wt) was brushed between the layers to glue them together without significantly influencing the composite fracture properties. The bi-layer gels were always composed of two gel layers prepared from the same gelling agent. Gel layers with different fracture stress were combined to obtain bi-layer gels with mechanical contrast with a difference in fracture stress ($\Delta\sigma_F$) ranging from 0 to 80 kPa. $\Delta\sigma_F$ =0 kPa refers to homogeneous, bi-layer gels. For each gelling agent, a series of soft (σ_F =20 kPa) and hard (σ_F =100 kPa) bi-layer gels were prepared. **Table 2.2** and **Figure 2.1** show the combination of layers in bi-layer gels for the two series; the soft series in which the top layer is always a soft gel (σ_F =20 kPa) combined with a harder, bottom layer, and the hard series in which the top layer is always a hard gel (σ_F =100 kPa) combined with a softer, bottom layer. Samples are coded with the gelling agent type (A, K, G for agar, K-carrageenan and gelatine, respectively) and target fracture stress of the two layers, i.e. 20|100, denotes a bi-layer gel with a top gel layer with σ_F =20 kPa and a bottom gel layer with σ_F =100 kPa.

Table 2.2. Layer combinations for soft and hard series of bi-layer gels.

Soft series			Hard series		
Fracture stress σ_F-Top layer [kPa]	Fracture stress σ_F - Bottom layer [kPa]	Difference fracture stress between layers $\Delta\sigma_F$ [kPa]	Fracture stress σ_F -Top layer [kPa]	Fracture stress σ_F -Bottom layer [kPa]	Difference fracture stress between layers $\Delta\sigma_F$ [kPa]
20	20	0	100	100	0
20	25	5	100	95	5
20	30	10	100	90	10
20	40	20	100	80	20
20	60	40	100	60	40
20	100	80	100	20	80

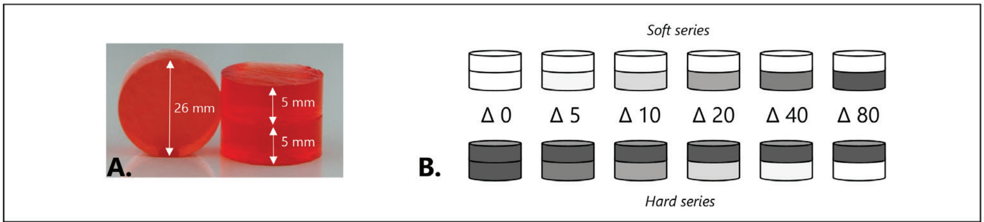


Figure 2.1. A. Picture and dimensions of bi-layer food gels (κ-carrageenan gel as example). B. Overview of heterogeneous bi-layer gels used for soft and hard series. Δ denotes the difference in fracture stress between layers ($\Delta\sigma_F$). In each series, the top layer is the same throughout the series (20 kPa for soft and 100 kPa for hard series). The darker the colour of the gel layer, the higher the σ_F.

2.2.4 Characterization of mechanical and physicochemical gel properties

2.2.4.1 Uniaxial compression test of mono-layer gels

Mechanical properties of the mono-layer gels were characterized by uniaxial compression tests with a Texture Analyzer (TA.XT plus, Stable Micro Systems-SMS). A probe of 150 mm diameter, coupled with a load cell of 50 kg, was used. Homogeneous monolayer gels were cut into cylindrical pieces of 26 mm diameter and 20 mm height. A thin layer of paraffin oil was applied on top of the sample, while a piece of rough paper was placed underneath the sample to prevent sliding. The compression test was performed at room temperature (20 ± 1°C) with a crosshead velocity of 1 mm/s up to a compression strain of 80%. The mean value for fracture stress, fracture strain and Young's modulus were calculated from measurements of at least 12 replicates. The strain is expressed as true or Hencky's strain (ε_H), which was calculated as previously described by Peleg (1987).

2.2.4.2 Penetration test of bi-layer gels

2

To characterize the mechanical properties of the bi-layer gels, a penetration test with a wedge probe (35 mm height, 10 mm width, tip angle of 8.2°) was performed. Penetration tests were executed with a Texture Analyser (TA.XT plus, Stable Micro Systems-SMS) at a speed of 1 mm/s to a maximum strain of 80%. Cylindrical pieces of bi-layer gels were used with 26 mm diameter and 20 mm height. **Figure 2.2** shows a typical outcome of a penetration test of a bi-layer gel. For bi-layer gels, two peaks were obtained. The first peak is related to the fracture of the top layer, whereas the second peak is linked to the fracture of the bottom layer. From the force-distance curves, the fracture force of the top layer ($F_{F\ 1st\ peak}$) and the fracture force of the bottom layer ($F_{F\ 2nd\ peak}$) were determined for each bi-layer gel.

The fracture properties of the top layer can influence the fracture properties of the bottom layer, since energy can be transferred from the top to the bottom layer during penetration of the top layer with the wedge. We estimated this effect by calculating the difference in fracture force between the bottom layer of a homogeneous bi-layer gel ($F_{F\ 2nd\ peak\ homo}$) and the bottom layer of a heterogeneous bi-layer gel ($F_{F\ 2nd\ peak\ hetero}$) and normalizing the difference by the fracture force of the bottom layer of the homogeneous bi-layer gel ($F_{F\ 2nd\ peak\ homo}$). The normalized difference in fracture force ($\Delta F_{F\ normalized}$) of the 2nd peak (bottom layer) was calculated as:

$$\Delta F_{F\ normalized} = \left| (F_{F\ 2nd\ peak\ homo} - F_{F\ 2nd\ peak\ hetero}) / F_{F\ 2nd\ peak\ homo} \right| \qquad (1)$$

where $F_{F\ 2nd\ peak\ hetero}$ denotes the fracture force of the 2nd peak of the bi-layer heterogeneous gel and $F_{F\ 2nd\ peak\ homo}$ denotes the fracture force of the 2nd peak of the corresponding homogeneous bi-layer gel. We suggest that the normalized difference in fracture force ($\Delta F_{F\ normalized}$) represents an estimation of mechanical contrast during the first bite since it takes into account the energy transfer in a bi-layer gel during fracture. We hypothesize that $\Delta F_{F\ normalized}$ correlates better with perceived texture contrast than $\Delta\sigma_F$. For this reason, the penetration tests of all bi-layer gels were performed with the same layer orientation as in the sensory ranking test. In the soft series of bi-layer gels, the soft layer (σ_F =20 kPa) was always placed on top, while for the hard series, the hard layer (σ_F =100 kPa) was always placed on top.

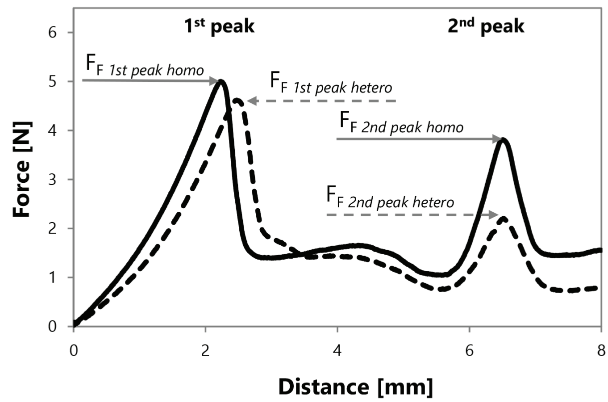


Figure 2.2. Example of force-distance curves of bi-layer gels obtained from wedge penetration tests. Continuous line represents the κ 100|100 sample, whereas dashed line denotes the κ 100|60 sample.

2.2.4.3 Serum release under mechanical compression

Serum release under uniaxial compression was determined as described by van den Berg et al. (2007). Homogeneous mono-layer gel specimens (26 mm diameter x 10 mm height) were compressed at a constant deformation speed of 1 mm/s up to 90% strain using a Texture Analyzer. For these measurements, no paraffin oil was used to lubricate the compression plate. Absorbing paper was placed underneath the sample in order to collect the exuded serum. The amount of exuded serum, M_s, was calculated as:

$$M_s = M_{wp} - M_{dp} \qquad (2)$$

where M_{wp} denotes the mass of wet paper after gel compression and M_{dp} denotes the mass of the dry paper before gel compression. The serum release (SR) was calculated as:

$$SR = M_s / M_g \qquad (3)$$

where M_s denotes the mass of the exuded serum and M_g the mass of the gel before compression. The measurements were performed at least in triplicate and averaged.

2.2.4.4 Melting behaviour

Gels layers were placed on top of a steel plate heated to 37°C to simulate in-mouth temperature. Gels had a diameter of 26 mm (contact surface area with heated steel plate was 531 mm^2) and a height of 10 mm. The heated plate was tilted at an angle of 2° to allow the liquefied, molten gel to flow down. The weight percentage of molten gel (w/w) relative to the initial weight of the semi-solid gel was quantified at given time points (10, 20, 40, 80 s). The time needed to completely melt the gels was also quantified. Only gelatine gels were measured since neither agar nor κ-carrageenan gels showed melting behaviour under the experimental conditions. Gelatine gels of three concentrations were used (samples 20, 60, 100) and measurements were performed at least in quadruplicates.

2

2.2.5 Sensory evaluation of mono-layer and bi-layer gels

2.2.5.1 Subjects

Thirty-three subjects (21 female/12 male, age: 21-32 yrs) participated in the ranking tests. Participants were selected based on self-reported nationality (European), age (18-35 yrs), BMI (18.5-25 kg/m^2) and having no dental implants or missing teeth (except wisdom teeth). Participants gave written informed consent and were reimbursed for participation. Subjects had not participated previously in sensory studies and were naïve with respect to the experimental conditions and purpose of the study.

Table 2.3. Sensory descriptors and their definitions.

Sensory attribute	Definition
Hardness	Force required to bite through the sample which is placed between teeth.
Heterogeneity	Perceivable contrast of texture during mastication, i.e. one sample contains both soft and hard parts.

2.2.5.2 Ranking method

Sensory tests were performed in meeting rooms equipped with desk dividers at Wageningen University. Data were collected on paper during four test sessions of 30 min. To allow participants to become familiar with the gels, the sensory method and the definition of sensory attributes one familiarization session of 30 min was carried out. The sensory descriptors used are presented in **Table 2.3**. During the familiarization session, subjects were asked to complete a preliminary test to evaluate their ability to perform a discrimination test of model gels. In particular, two triangle tests were completed: in the first triangle test participants had to identify the heterogeneous sample (20|100) among two other homogeneous samples (20|20; 100|100); in the second triangle test subjects were asked to identify the homogeneous sample (100|100) among two heterogeneous samples (20|100). Gels used during the familiarization session were K-20|20, K-100|100 and K-20|100. These bi-layer gels were selected as they represent the largest mechanical contrast (largest $\Delta\sigma_F$). Participants who did not discriminate the samples were excluded from the study. As a measure for perceived texture contrast, we asked subjects to rank the samples in order of increasing perceived heterogeneity. This attribute was clear to all participants after the familiarization procedure. To inform the participants, an explanation brochure was available during the sessions.

During the first three test sessions, participants evaluated the series of bi-layer gels. During the fourth session, participants assessed homogeneous mono-layer gels. All sessions were completed by each participant within one month. The different samples were evaluated using a ranking method (Kim & O'Mahony, 1997; O'Mahony et al., 1980). Subjects were presented with a series of six or nine gels. For bi-layer gels (first three sessions), participants were asked to rank the samples in order of increasing heterogeneity. For mono-layer gels (fourth session), participants were asked to rank the samples in order of increasing hardness. In both ranking tests, ties were allowed. The presentation order of samples was fully randomized within each series (Williams Latin square design). Participants were free to change the location of the samples on the ranking scale during the evaluation and allowed to re-taste previous samples as often as they wanted. For this reason, three portions of each sample were provided. Subjects orally processed the samples according to a defined chewing protocol. The sample was brought in the mouth with a fork and spoon. The position of the gel layers relative to the mouth was controlled. The soft layer for the soft series and the hard layer for the hard series was always the top layer. The model food was placed between the front teeth and bitten in half with the front teeth. Then, subjects were instructed to continue chewing freely until swallowing. Subjects were allowed to spit out the sample at the swallowing point.

2.2.5.3 Time-intensity profiling

Ten participants (7 female/3 male, age: 21-26 yrs) joined the time-intensity profiling in which perceived heterogeneity intensity of the bi-layer gels was evaluated over time. Participants were recruited from subjects who participated in the ranking tests. Subjects attended one test session of approximately 90 min. After a short familiarization with the time-intensity method and the samples, participants were asked to perform a preliminary time-intensity test to evaluate their understanding of the methodology. For the time intensity profiling, two bi-layer homogeneous samples (20|20; 100|100) and a heterogeneous sample (20|100) were used for each of the gelling agents (A, K, G). Subjects rated the perception of heterogeneity intensity continuously during mastication until swallowing using a 100-point scale, anchored "Not heterogeneous" at scale value 0 and "Very heterogeneous" at scale value 100. Participants moved the cursor on a horizontal rating-bar on the screen while chewing. From the time-intensity profiling the maximum perceived intensity, time to maximum intensity, total area under the curve (AUC) and heterogeneity intensity at specific time points (1, 5, 10, 15, 20, 25, 30 s) were obtained. AUC was used as an estimate of total heterogeneity intensity. Gels were served in duplicate in randomized order.

2.2.6 Data analysis

The results of mono-layer gels obtained from the uniaxial compression tests were analysed by ANOVA with a significant value of $p<0.05$ and Tukey's HSD test as post-hoc comparison (SPSS Software Statistic 23, SPSS Inc., Chicago, USA). The data obtained from the ranking test were analysed using R language (version 3.2.3). The Pairwise Multiple Comparison of Mean Ranks Package (PMCMR) was used to perform a Friedman test on the data obtained for each series and the Wilcoxon Signed Rank test was executed as a post-hoc comparison with Bonferroni adjustment.

Data from the ranking test were converted into binomial correct/wrong answers. This conversion was realized by assigning a score of 1 to samples that were ranked separately from the homogeneous sample. On the contrary, a score of 0 was assigned in the case that participants did not discriminate between homogeneous and heterogeneous samples (tied ranks). Therefore, a positive score indicates that samples with mechanical contrast were perceived different with respect to heterogeneity from the homogeneous samples. The cumulative percentages of correct positive answers were calculated and plotted against the mechanical contrast of the samples. For the time intensity ratings, EyeQuestion software (V3.8.13, Logic 8, The Netherlands) was used. The maximum perceived intensity, the time to maximum intensity, the area under the obtained curves and the heterogeneity intensity at specific time points (1, 5, 10, 15, 20, 25, 30 s) were analysed by ANOVA in SPSS.

2.3 Results and discussion

2.3.1 Mechanical properties of gels

2.3.1.1 Homogeneous mono-layer gels

The target and measured fracture stress, fracture strain and Young's modulus of all homogeneous mono-layer gels are presented in **Table 2.4**. It can be seen that the measured fracture stress is close to the target fracture stress for all gels and varies by a factor of up to 5x for each gelling agent. Three main gel types can be distinguished based on fracture strain: brittle agar gels with a low fracture strain ranging from 0.41 to 0.46; κ-carrageenan gels with a medium fracture strain ranging from 0.60 to 0.77; and elastic gelatine gels with a high fracture strain ranging from 0.99 to 1.39. The fracture strain increased slightly by a factor of up to 1.4x with increasing concentration of gelling agent for all gelling agents. The increase of Young's modulus with increasing concentration of gelling agent depends on the type of gel and is higher for agar gels and lower for gelatine gels.

2.3.1.2 Heterogeneous bi-layer gels

A penetration test with a wedge probe was performed to characterize the fracture behaviour of bi-layer gels with mechanical contrast. Differences were found between the soft series (soft, top layer with harder, bottom gel layer) and the hard series (hard, top layer with softer, bottom gel layer). In both series, the fracture force of the top layer (1st peak) was fairly constant and only minimally influenced by the mechanical properties of the bottom layer (data not shown).

Table 2.4. Mechanical properties of homogeneous mono-layer gels. Different superscript letters indicate significant differences between means at p<0.05.

Gel	Fracture stress [kPa]			Fracture strain [-]		Young's modulus [kPa]	
	Target	Measured	SD	Measured	SD	Measured	SD
Agar	20	19.7 ^{A}	± 1.2	0.41 ^{A}	± 0.02	11.3 ^{A}	± 1.7
	25	24.7 ^{B}	± 1.0	0.42 ^{AB}	± 0.02	14.2 ^{A}	± 3.3
	30	30.6 ^{C}	± 1.0	0.45 ^{BC}	± 0.02	18.7 ^{A}	± 2.7
	40	39.8 ^{D}	± 2.0	0.47 ^{CD}	± 0.02	24.7 ^{A}	± 6.0
	60	62.1 ^{E}	± 2.7	0.47 ^{D}	± 0.02	48.3 ^{B}	± 8.0
	80	79.6 ^{F}	± 3.5	0.47 ^{CD}	± 0.03	67.1 ^{C}	± 20.5
	90	89.4 ^{G}	± 3.8	0.48 ^{D}	± 0.03	77.3 ^{C}	± 23.9
	95	95.8 ^{H}	± 2.3	0.48 ^{D}	± 0.03	96.8 ^{D}	± 18.2
	100	102.1 ^{I}	± 3.2	0.46 ^{CD}	± 0.01	125.8 ^{E}	± 12.0
κ-carrageenan	20	20.8 ^{A}	± 2.4	0.60 ^{A}	± 0.03	8.7 ^{A}	± 1.0
	25	25.7 ^{B}	± 2.5	0.63 ^{A}	± 0.03	10.7 ^{AB}	± 1.5
	30	30.9 ^{C}	± 4.0	0.63 ^{A}	± 0.04	14.5 ^{B}	± 1.4
	40	43.4 ^{D}	± 5.3	0.63 ^{A}	± 0.05	22.3 ^{C}	± 3.8
	60	58.1 ^{E}	± 5.5	0.68 ^{B}	± 0.04	30.2 ^{D}	± 9.4
	80	82.7 ^{F}	± 3.6	0.73 ^{C}	± 0.04	48.0 ^{E}	± 9.6
	90	89.8 ^{G}	± 4.7	0.75 ^{C}	± 0.04	58.5 ^{F}	± 4.4
	95	95.6 ^{H}	± 3.7	0.76 ^{C}	± 0.05	66.0 ^{G}	± 5.7
	100	101.8 ^{I}	± 3.3	0.77 ^{C}	± 0.05	70.4 ^{G}	± 6.3
Gelatine	20	20.5 ^{A}	± 2.5	0.99 ^{A}	± 0.08	8.0 ^{A}	± 1.6
	25	25.2 ^{B}	± 1.3	1.00 ^{A}	± 0.05	10.3 ^{A}	± 2.1
	30	31.3 ^{C}	± 2.7	1.06 ^{AB}	± 0.09	11.7 ^{A}	± 2.0
	40	40.9 ^{D}	± 2.7	1.12 ^{BC}	± 0.08	18.5 ^{B}	± 4.3
	60	60.7 ^{E}	± 3.5	1.20 ^{CD}	± 0.09	24.0 ^{C}	± 3.2
	80	78.8 ^{F}	± 3.3	1.25 ^{DE}	± 0.07	33.3 ^{D}	± 5.2
	90	89.9 ^{G}	± 2.2	1.31 ^{EF}	± 0.12	35.0 ^{DE}	± 8.5
	95	95.6 ^{H}	± 1.6	1.40 ^{F}	± 0.15	39.0 ^{EF}	± 4.9
	100	103.4 ^{I}	± 3.7	1.39 ^{F}	± 0.12	40.7 ^{F}	± 4.3

Figure 2.3 shows the normalized difference in fracture force of the 2nd peak ($\Delta F_{F\ normalized}$) as a function of mechanical contrast $\Delta\sigma_F$ of all gels. We hypothesize that with increasing $\Delta F_{F\ normalized}$ the detectability of perceived texture contrast increases. Agar gels displayed larger values of $\Delta F_{F\ normalized}$, followed by κ-carrageenan gels and gelatine gels at any given $\Delta\sigma_F$. For the soft series, the normalized difference in fracture force is mostly related to the mechanical properties of the bottom layer and, in particular, to its brittleness and elasticity. For more elastic gels, the fracture

properties of the second peak are most affected and therefore smaller $\Delta F_{F\ normalized}$ values are found.

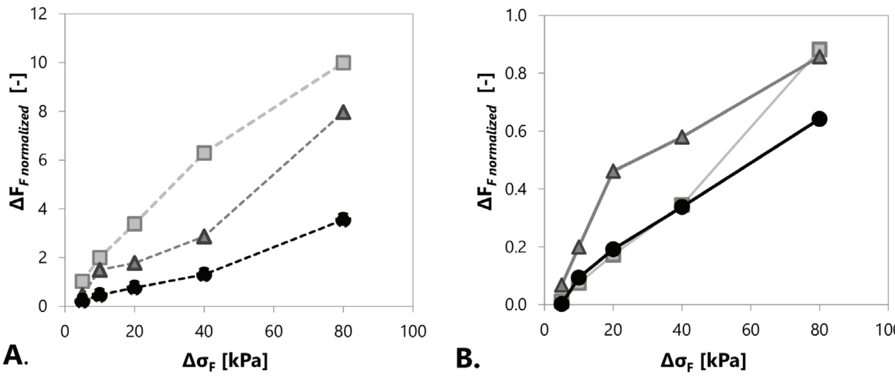


Figure 2.3. $\Delta F_{F\ normalized}$ (determined by penetration wedge tests of bi-layer gels) as a function of mechanical contrast (difference in fracture stress of separate, individual layers, $\Delta\sigma_F$, determined by uniaxial compression tests on mono-layer gels). Soft series are presented in figure 2.3A (dashed lines), hard series in figure 2.3B (solid lines). Agar gels are represented by (■); κ-carrageenan gels by (▲); gelatine gels by (●).

Figure 2.3B presents $\Delta F_{F\ normalized}$ as a function of $\Delta\sigma_F$ for the hard series. The $\Delta F_{F\ normalized}$ for agar and gelatine gels displayed similar values up to $\Delta\sigma_F$ =40 kPa, whereas for κ-carrageenan gels $\Delta F_{F\ normalized}$ is larger. For larger differences in the mechanical contrast of the separate layers ($\Delta\sigma_F$ =80 kPa), gelatine bi-layer gels present lower values for $\Delta F_{F\ normalized}$ compared to agar and κ-carrageenan heterogeneous bi-layer gels. In this case, we speculate that the perceived heterogeneity may therefore be smaller for the gelatine gels. Overall, it can be seen that the measured difference in fracture force, $\Delta F_{F\ normalized}$, for the hard series is much smaller than for the soft series. The compression of the top, hard layer has a large influence on the fracture of the bottom, soft layer. During compression of the top, hard layer, energy is transferred from the top to the bottom layer, and fracture of the soft, bottom layer is already initiated before the first layer is completely fractured. Therefore, the bottom layer fractures after application of a smaller force than the fracture force that would be needed to fracture the individual, separate gel layer. We can conclude that for the hard series, the fracture behaviour of the bi-layer gels depends mostly on the relative difference in fracture stress between layers, and much less on brittleness/elasticity as noticed in the soft series.

To summarize, fracture properties of the layers and their position (top/bottom) affect the fracture behaviour of heterogeneous bi-layer gels. We suggest that this effect might be relevant for the detection of texture contrast at first bite.

2.3.2 Physicochemical properties of gels

2.3.2.1 Serum release under mechanical compression

To investigate the effect of physicochemical properties of gels on the detection of texture contrast, gelling agents that form gels with different degrees of syneresis were used. We hypothesize that the amount of serum release under compression influences the detectability of perceived texture contrast. Agar gels displayed the highest serum release (5.0-11.5%), followed by κ-carrageenan (3.0-4.5%) and gelatine gels (0.1-3.0%) (data not shown). Differences in serum release under compression between the gels can be explained by differences in porosity and microstructure (Urbonaite et al., 2016; van den Berg et al., 2007; van Vliet et al., 2009). For example, the lowest degree of syneresis was found for gelatine, which can easily be explained by the very fine-stranded network. With increasing concentration of gelling agent, so with increasing fracture stress, the serum release decreased for all gels (data not shown). This can be explained by the higher water holding capacity of the stronger networks in which the higher number of junction zones retain more serum.

2.3.2.2 Melting behaviour

Gelatine gels were melted by placing them on a heated, tilted plate (37°C). The fraction of molten, liquefied gelatine gel was quantified over time (**Figure 2.4A**) and the time required to completely melt the gelatine gels was determined (**Figure 2.4B**). As expected, the melting rate of gelatine gels depends on gelatine concentration. The higher the gelatine concentration (the larger the fracture stress), the slower the melting process. From **Figure 2.4A** it can be observed that the gel with the lowest gelatine concentration (grey squares; 4.03% w/w; σ_F =20 kPa) reached 20% of molten state after 20 s, and approx. 80% of molten state after 80 s. Contrary, the gel representing the highest concentration of gelatine (black circles; 12.19% w/w; σ_F =100 kPa) melted about 5% and 40% after the same time intervals. As displayed in **Figure 2.4B**, the time needed to completely melt the gels ranged from 87 to 212 s depending on the gelatine concentration.

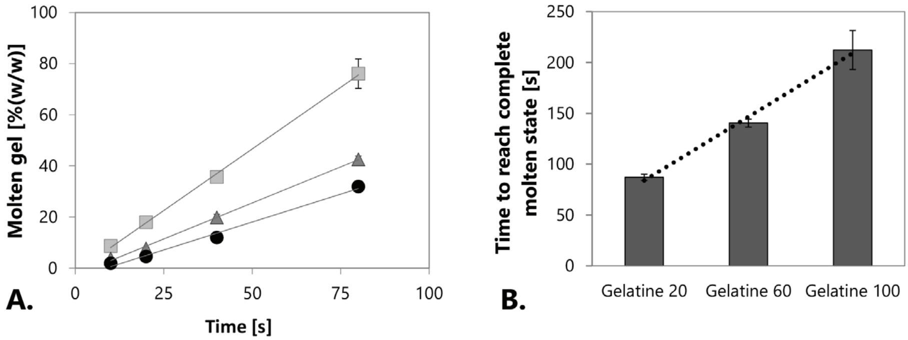


Figure 2.4. A. Percentage of molten gel (% w/w) as a function of time (s) at 37°C for gels with a gelatine concentration of 4.03% w/w (σ_F =20 kPa; ■), 8.11% w/w (σ_F =60 kPa; ▲) and 12.19% w/w (σ_F =100 kPa; ●). B. Time required to melt gelatine gels completely (37°C) for gels varying in fracture stress (σ_F =20 kPa, σ_F =60 kPa and σ_F =100 kPa). Bars represent mono-layer gels of 26 mm diameter and 10 mm height. Error bars indicate the standard deviation to the mean.

These results show that gelatine gels only partly melt in the first few seconds under the experimental conditions, and needed a relatively long time to completely melt. In addition to the gel properties, the surface area of the gel that is in contact with the heated environment is another important parameter affecting melting behaviour. During mastication, gelatine gels break down into smaller fragments which increases the total surface area. The increased surface area leads to a proportionally higher heat transfer from the environment (oral cavity) to the gels and consequently to shorter melting times under in-mouth conditions. Although the breakdown during consumption will decrease the melting time, it is unlikely that gelatine gels are completely molten within the time frame of mastication (< 30 s). The partial melting of the surface might provide extra oral lubrication and impact heterogeneity perception. The perception of texture contrast as a heterogeneity might be reduced (melting of gel matrix in mouth and disappearance of mechanical contrast) or enhanced (mechanical contrast increases by partly liquefied and partly semi-solid gel) as a result of this process.

2.3.3 Ranking tests

2.3.3.1 Perception of hardness in homogeneous mono-layer gels

The homogeneous, mono-layer gels were ranked in order of increasing perceived hardness. The average ranks and levels of significance are reported in **Table 2.5**. In general, 6 or 7 ranks were significantly different within each series of 9 samples offered. A difference of 10 kPa was required to observe significant differences in sensory hardness for soft, brittle agar gels (A20 and A30). For soft, elastic gelatine gels, a smaller difference of 5 kPa was sufficient to discriminate significantly sensory hardness of gels (G20 and G25). These results suggest that the ability to perceive differences in gel hardness depends on gel type. The sensitivity to perceive differences in gel hardness seems to be higher for elastic gelatine gels and lower for brittle agar gels.

For harder gels (90-100), the discriminability of gels according to the perceived hardness is similar among the three gelling agents. Subjects could not clearly differentiate between samples 95 and 100, and samples 90 and 95 for all three gelling agents. For κ-carrageenan gels, the discrimination ability was relatively high since sample κ 80 could be discriminated from the other hard gels of the series (κ 90, 95, 100). For the gelatine and agar gels, a larger difference in fracture stress was needed (A60 and G60) to perceive a difference in hardness. The outcome indicates that for hard gels, brittleness (fracture strain) does not considerably influence the sensitivity to discrimination perceived hardness of homogeneous gels.

Table 2.5. Average ranks for perceived hardness for agar, κ-carrageenan and gelatine homogeneous gels varying in fracture stress. Different superscript letters (within columns) indicate significant differences between gels ($p<0.05$).

	Average ranks sensory hardness								
	Fracture stress [kPa]								
	20	25	30	40	60	80	90	95	100
Agar	1.36 ± 0.52 ^{a}	1.97 ± 0.51 ^{a}	2.85 ± 0.54 ^{b}	3.89 ± 0.39 ^{c}	5.27 ± 0.70 ^{d}	6.74 ± 1.05 ^{e}	7.26 ± 0.97 ^{ef}	7.71 ± 0.92 ^{ef}	7.94 ± 0.88 ^{f}
κ-carrageenan	1.47 ± 0.60 ^{a}	2.05 ± 0.64 ^{ab}	2.68 ± 0.75 ^{b}	3.92 ± 0.47 ^{c}	5.03 ± 0.59 ^{d}	6.39 ± 0.61 ^{e}	7.47 ± 0.89 ^{f}	7.74 ± 0.66 ^{f}	8.24 ± 0.72 ^{f}
Gelatine	1.47 ± 0.64 ^{a}	2.24 ± 0.71 ^{b}	2.86 ± 0.72 ^{bc}	3.56 ± 0.84 ^{c}	5.09 ± 0.72 ^{d}	6.44 ± 0.77 ^{e}	7.30 ± 0.97 ^{ef}	7.86 ± 0.86 ^{fg}	8.17 ± 0.85 ^{g}

2.3.3.2 Perception of heterogeneity in bi-layer gels

Ranking tests were used to gain information on the minimum degree of mechanical contrast required to perceive texture contrast as a heterogeneity. Two series were evaluated: a soft series with a homogeneous sample "20|20" as a reference, and a hard series with the homogeneous "100|100" sample as a reference. The differences in fracture stress between the two layers ($\Delta\sigma_F$) were the same for both series. An overview of the ranking scores and related significant differences ($p<0.05$) is presented in **Table 2.6**.

2

It can be seen that for softer gels (soft series), it is easier to perceive texture contrast than for harder gels (hard series), i.e. heterogeneity is perceived at smaller $\Delta\sigma_F$. This was expected based on the observations of the hardness perception of homogeneous gels. However, it can be seen that it is difficult to extract a specific value for the required minimum difference in mechanical contrast for each of the gel types. A conversion to binomial (right/wrong answers) was performed to permit a direct evaluation of the different gel types.

Table 2.6. Average rank scores for perceived texture contrast (perceived heterogeneity) of bi-layer gels. Different superscript letters (within a column) indicate significant differences between samples (p < 0.05). Different shades of grey highlight significant differences relative to the homogeneous samples. Dark grey colour indicates gels that are not significantly different from the homogeneous gels. Light grey colour indicates gels that are not significantly different from each other but significantly different from the homogeneous gels.

	20|20	20|25	20|30	20|40	20|60	20|100
Agar	1.44 ± 0.37 ^{a}	2.23 ± 0.83 ^{b}	2.55 ± 0.69 ^{b}	3.86 ± 0.55 ^{c}	5.09 ±0.42 ^{d}	5.83 ±0.30 ^{e}
κ-carrageenan	1.92 ± 0.64 ^{a}	2.17 ± 0.67 ^{a}	2.65 ± 0.99 ^{ab}	3.42 ± 0.84 ^{b}	4.94 ± 0.60 ^{c}	5.89 ± 0.24 ^{d}
Gelatine	1.97 ± 0.60 ^{a}	2.27 ± 0.78 ^{a}	2.47 ± 0.53 ^{a}	3.41 ± 0.99 ^{b}	5.02 ± 0.32 ^{c}	5.86 ± 0.40 ^{d}
	100|100	100|95	100|90	100|80	100|60	100|20
Agar	2.23 ± 0.89 ^{a}	2.64 ± 0.91 ^{a}	2.64 ± 0.86 ^{a}	3.08 ± 0.98 ^{a}	4.64 ± 0.72 ^{b}	5.79 ± 0.64 ^{c}
κ-carrageenan	1.95 ± 0.60 ^{a}	2.36 ± 0.89 ^{ab}	2.94 ± 0.92 ^{b}	3.14 ± 1.07 ^{b}	4.68 ± 0.72 ^{c}	5.92 ± 0.22 ^{d}
Gelatine	2.05 ± 0.71 ^{a}	2.45 ± 0.70 ^{ab}	2.56 ± 0.81 ^{ab}	3.20 ± 0.92 ^{b}	4.88 ± 0.47 ^{c}	5.86 ± 0.55 ^{d}

Figure 2.5 shows the results of the conversion in which the cumulative percentages of correct answers are plotted against the differences in fracture stress between layers ($\Delta\sigma_F$). From the conjunctions of the different data points of each series, it was possible to gain psychometric functions that resemble psychometric functions normally obtained by the method of Constant Stimuli (Lawless & Heymann, 2010). The corresponding mechanical contrast required to achieve 50% of correct responses was considered as a minimum mechanical contrast needed to perceive texture contrast (i.e. threshold of texture contrast). The results obtained from this analysis are similar to the results summarized in **Table 2.6**, but allow for a more convenient and intuitive interpretation of perceived texture contrast thresholds.

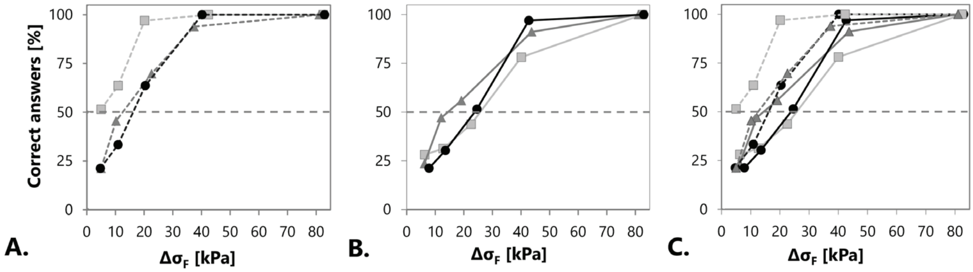


Figure 2.5. Perception of texture heterogeneity: cumulative frequency of correct answers as a function of difference in fracture stress between layers $\Delta\sigma_F$: A. Soft series (dotted lines); B. Hard series (solid lines); C. Soft and Hard series combined. Agar gels are represented by squares (■); κ-carrageenan gels by triangles (▲); gelatine gels by circles (●).

For the soft series (**Figure 2.5A**), smaller differences in mechanical contrast were sufficient for agar gels ($\Delta\sigma_F$ =5 kPa) to be perceived as heterogeneous (so displaying texture contrast) than for κ-carrageenan gels ($\Delta\sigma_F$ =12 kPa) and gelatine gels ($\Delta\sigma_F$ =16 kPa). The results suggest that in soft gels, the detection of mechanical contrast depends on the type of gelling agent. We speculate that the detection of mechanical contrast as perceived texture contrast is partly influenced by the brittleness (fracture strain) of the gels. As already observed in **Figure 2.3**, the fracture properties of the different gels have an influence on the measured mechanical contrast (with wedge test) in the composite gels. We hypothesised that this may affect the perception of heterogeneity. As seen in **Figure 2.3A**, the difference in mechanical contrast, measured as $\Delta F_{F\ normalized}$, was the largest for the agar gels and the smallest for the gelatine gels. This suggests that the expected perceivable texture contrast in agar gels is larger and therefore the heterogeneity of agar gels was perceived more easily than in κ-carrageenan and gelatine gels. This is consistent with the results presented in **Figure 2.5**. The gels with the largest measured mechanical contrast (agar gels) were perceived as heterogeneous for a smaller difference in mechanical contrast, $\Delta\sigma_F$. The elastic gelatine gels with the lowest values in **Figure 2.3A**, required a larger difference in the mechanical contrast of the separate layers to be perceived as heterogeneous. These results indicate that the detection of mechanical contrast is indeed related to the brittleness of the gels.

The outcomes for the hard series highlight that larger mechanical contrasts are required to lead to texture contrast perception compared to the soft series (**Figure 2.5C**). Texture contrast was detected in κ-carrageenan gels when mechanical contrast was $\Delta\sigma_F$ =14 kPa, whereas agar and gelatine gels required mechanical contrasts of $\Delta\sigma_F$ =26 and $\Delta\sigma_F$ =24 kPa, respectively. This may be explained by the results from the wedge test (**Figure 2.3B**), in which the speculated perceivable texture contrast for the carrageenan gels in this regime was larger, and therefore the heterogeneity in texture contrast of such carrageenan gels may be detected more easily compared to the agar and gelatine bi-layer gels. However, the differences are very small and therefore no clear trend can be observed.

2.3.4 Temporal heterogeneity perception

The perception of texture contrast over time was characterized using time-intensity profiling. It was hypothesized that physicochemical properties, especially melting, affect the perception of texture contrast over time. The average ratings for the perceived heterogeneity over time of three bi-layer heterogeneous gels "20|100" made from agar, gelatine and κ-carrageenan are shown in **Figure 2.6**. The perception of heterogeneity is a rather fast process for the three gels with mechanical contrast. Subjects perceived texture contrast already after 1 s as shown by the steep incline of the time-intensity profiles. The perception of texture contrast starts to decrease after 10 s for all gels and approaches zero intensity after 30 s. The area under the curves (AUC) as a quantification of the degree of perceived heterogeneity intensity was 960 (±308) for κ-carrageenan, 1043 (±395) for agar and 1390 (±338) for gelatine gels. The AUC for gelatine gels was significantly higher than the AUC of both agar and κ-carrageenan gels, which indicates that the highest heterogeneity perception over time was perceived for gelatine gels. The mean maximum heterogeneity intensity was found to be 71.2 (±26.8) after 7 s for agar gels, 76.0 (±15.7) after 5 s for κ-carrageenan gels and 81.3 (±11.1) after 7 s for gelatine gels. The maximum heterogeneity intensity and time to maximum intensity did not significantly differ between the three gels. The intensity of perceived heterogeneity at given time points (1, 5, 10, 15, 20, 25, 30 s) can be seen in **Figure 2.6**. Gelatine gels were perceived as significantly more heterogeneous between 10 and 20 s compared to agar and κ-carrageenan gels.

These results indicate that heterogeneity is perceived longer for gelatine gels in early stages of mastication compared to agar and κ-carrageenan gels with similar differences in fracture stress. No significant differences in perceived heterogeneity were noticed among the three model gels at later stages of mastication (25-30 s). Therefore, texture contrast perception is a rather fast sensory process. It is plausible that detection of texture contrast is dominated by texture perception during the first bites. In this mastication stage, the mechanical properties are most relevant for texture perception.

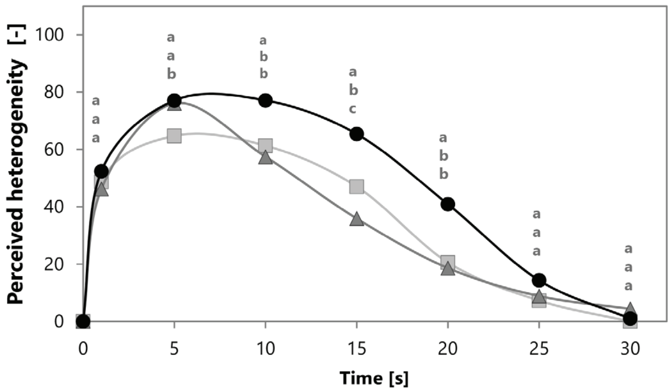


Figure 2.6. Perceived heterogeneity intensity over time for the heterogeneous samples (20|100). Agar gels are represented by squares (■); κ-carrageenan gels by triangles (▲); gelatine gels by circles (●). Different superscript letters indicate a significant difference at given points in time where the upper letter refers to gelatine gels, middle letter to κ-carrageenan and lower letter to agar gels.

Gelatine gels were perceived as heterogeneous for the longest time. A possible explanation for the increased perceived heterogeneity can be given by considering the time frame of the melting process. The melting process is fast at the surface of the gelatine gels but rather slow for the bulk. In the oral cavity, the gelatine gels are partly liquefied at the surface, which leads to an even larger difference in mechanical properties between the liquefied and semi-solid bulk gel resulting in higher intensity of perceived heterogeneity. Also, the breakdown of the gels during chewing may affect perceived heterogeneity. As the gelatine gels are highly elastic, the gels do not break easily and the particles stay rather large (Mosca et al., 2015; Devezeaux de Lavergne et al., 2015). The larger size of the gel particles might increase the detection ability above smaller particles, and therefore a higher chance of perceived heterogeneity over time could be caused. The melting profile may also be influenced by changes in the gelatine network, as the interactions in the gelatine network weaken at body temperature. The softening of the gel network could have an effect on texture perception especially at later stages of mastication. Such an effect may be more pronounced for soft gelatine gels. These changes may increase the differences in mechanical contrast and might enhance the perception of texture contrast.

Besides melting, we hypothesized that other physicochemical properties, such as syneresis, might be involved in the perception of texture contrast. Specifically, we expected that the release of water might change the slipperiness of the samples and change the mechanical properties. For more slippery samples, the contact between the gel and the tongue and the palate in the mouth would decrease. This would lead to a lower degree of perceived heterogeneity. However, the relatively low amount of water released during compression for all gels (between 1-12%) suggests that in this study serum release did not considerably contribute to the perception of texture contrast. In addition, the differences in serum release between layers varying in fracture stress within each model system were relatively small. This is further confirmed by the outcomes of the time-intensity experiments since no differences were recorded between the temporal perceptions (AUC) of gels with the relative highest serum release (agar and κ-carrageenan gels). Although these results indicate that serum release is not an important factor, we do not generally exclude that the release of serum might have an influence on detectability of mechanical contrast in other conditions, especially when tastants are present.

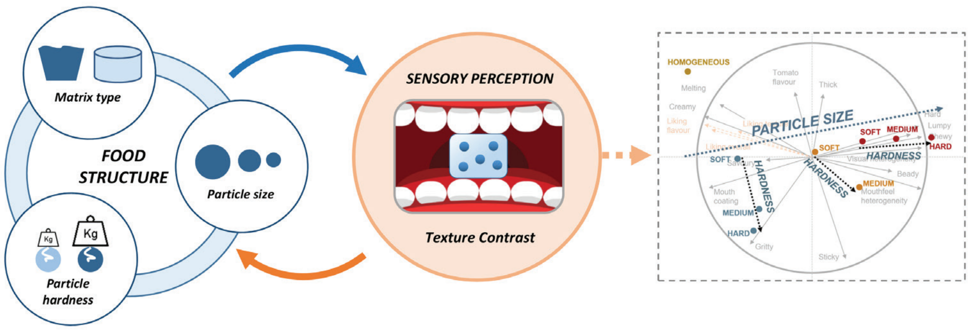
2.4 Conclusions

The aim of this study was to investigate the influence of mechanical and physicochemical properties of semi-solid gels on the detection and temporal perception of texture contrast. Variations in mechanical contrast of heterogeneous bi-layer gels modified the minimum perceivable difference of texture contrast. Texture contrast perception thresholds changed as a function of fracture stress and strain for a series of soft and a series of hard gels. In soft gels, a difference of $\Delta\sigma_F$ =5 kPa was required for brittle agar gels to be perceived as heterogeneous, while for elastic gelatine gels the required difference increased to $\Delta\sigma_F$ =16 kPa. In harder bi-layer gels, the sensitivity to perceive texture contrast decreased and differences up to $\Delta\sigma_F$ =26 kPa were required to discriminate heterogeneous from homogeneous gels. Melting of gelatine gels was found to contribute to texture contrast perception, and detectability was mainly related to the mechanical properties and the fracture behaviour of the heterogeneous gels. The perception of texture contrast over time was found to be significantly higher for gelatine gels probably due to a combination of a high degree of elasticity and partial melting of the gels in mouth.

Chapter 3

NOT ONLY PARTICLE SIZE MATTERS

EFFECT OF MECHANICAL CONTRAST ON SENSORY PERCEPTION OF HETEROGENEOUS LIQUID AND SEMI-SOLID FOODS



This chapter is based on:

Santagiuliana, M., Christaki, M., Piqueras-Fiszman, B., Scholten, E., Stieger, M., Effect of mechanical contrast on sensory perception of heterogeneous liquid and semi-solid foods. *Food Hydrocolloids* 83, 2018, p. 202-212.

Abstract

This study investigated the influence of size and fracture stress (σ_F) of dispersed particles embedded in liquid and semi-solid model food matrices on sensory perception and hedonic response. K-carrageenan particles varying in size (0.8, 2.4, 4.2 mm) and fracture stress (σ_F: 25, 100, 250 kPa) were added (15% w/w) to liquid starch-based model soups and semi-solid protein-based model gels. Sensory profiles were quantified by untrained panellists (n=54) using the Rate-All-That-Apply (RATA) method. Particle size mainly affected the type of sensory descriptors selected by the subjects, whereas fracture stress of particles determined mainly the perceived intensity of selected descriptors. Soups and gels with small particles (0.8 mm) were mainly perceived as gritty, whereas soups and gels with medium-sized particles (2.4 mm) were mainly perceived as beady. Increasing particle size to 4.2 mm caused lumpy and heterogeneous sensations in soups and gels. With variations of particle fracture stress, the perceived intensity of the selected attributes increased or decreased significantly for all particle sizes. Mouthfeel heterogeneity and chewiness increased significantly when increasing the fracture stress from 20 to 100 or 250 kPa. Mechanical contrast did not enhance liking of model soups and gels probably because κ-carrageenan particles were perceived as artificial and provided texture contrast without flavour contrast. We conclude that size and fracture stress of dispersed particles embedded in liquid and semi-solid model food matrices affect differently sensory perception with particle size determining type of sensory descriptors selected and particle fracture stress determining intensity of selected sensory attributes.

3.1 Introduction

Many commercially available foods contain particles embedded in a food matrix varying in size, hardness, and nature. Examples of such particles are fruit pieces in yoghurt, vegetable pieces and noodles in soups, and nuts or chocolate pieces in biscuits and ice cream. These composite foods with dispersed particles display complex texture profiles and are often associated with positive hedonic responses (Szczesniak & Kahn, 1984). Despite the high consumer appreciation and industrial relevance of such foods, the food properties that contribute to texture perception and positive hedonic responses are poorly understood.

The effects of size and number of particles embedded in foods on sensory perception have been mainly investigated in liquid and semi-solid foods with particle sizes ranging from 0.4 to 240 μm (e.g. Engelen et al., 2005; Liu et al., 2016; Tyle, 1993). These studies investigated the specific effect of particle size, concentration, shape, and hardness on the sensory perception of composite dispersed foods. To summarize, they highlight complex interrelations between these variables and sensory perception, although no comprehensive understanding of such correlations is currently present. Other studies demonstrated the specific effect of addition of solid particles (calcium carbonate, alumina, rye bran) on several sensory attributes, such as creamy, gritty, rough, dry, and powdery (e.g. Kilcast & Clegg, 2002; Krzeminski et al., 2013; Petersson et al., 2013). The results showed that addition of particles can trigger very diverse perceptions. Depending on factors related to both the dispersed particles and the continuous matrix, perceptions like creaminess or grittiness can be obtained, and this depends on whether or not the consumers are able to detect the particles. Particles with irregular shapes and sharp edges display higher oral detectability compared to regularly shaped particles with soft edges. Besides shape, also hardness and size of particles affect detectability and sensory perception. The presence of small (typically 25 to 150 μm) and hard particles often leads to undesired perceptions such as grittiness and graininess in products such as ice-creams and yoghurts (Imai et al.,1998; Modler et al.,1989; Sainani et al., 2004). On the other hand, when smooth and soft particles are added to foods, negative effects on perception were prevented (Chojnicka-Paszun et al., 2014; Scholten, 2016). The presence of soft particles in liquid foods has recently been investigated by Appelqvist and co-workers (2015). Carrot particles (size <400 μm) were incorporated in a viscous matrix, which did not lead to grainy perception due to the soft structure of the carrot particles and their related inability to deform the oral mucosa. Therefore, the addition of smooth and soft particles might be used as a strategy to change the texture of composite foods, while maintaining or enhancing positive sensory perceptions such as creaminess or smoothness.

In addition to the properties of particles, also the consistency of the matrix in which the particles are dispersed affects the sensory detectability of the particles and overall sensory perception of heterogeneous foods. Heterogeneities are commonly easier perceived in liquids than in solid matrices (Liu et al., 2016). Hutchings et al. (2011, 2012) demonstrated that the mechanical properties of the matrix affect oral processing behaviour and breakdown properties of solid composite foods (chocolates and gelatine gels with embedded peanuts). Laguna & Sarkar (2016) demonstrated that the level of heterogeneities introduced into a gel matrix by addition of gel beads can be used to influence oral processing behaviour and sensory perception. A prolongation of oral transition time was positively related to an increase in the degree of heterogeneity in terms of particle size (185, 1210, 2380 μm) and particle hardness.

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Besides affecting mechanical properties and oral processing behaviour, the presence of particles also affects dynamic sensory perception and satiation. Tang et al. (2017) demonstrated that sensory perception was largely affected by the level and type of embedded macroscopic heterogeneities (millimetre scale) in heterogeneous model foods. The addition of particles (various seeds) and embedded layers varying in mechanical properties largely influenced temporal sensory perception. Textural complexity of these heterogeneous foods impacted satiation and decreased total food intake (Larsen et al., 2016). The authors suggested that additional sensory stimulation evoked by addition of particles could contribute to the satiation response, while keeping oral processing time constant.

Although several studies have focussed on sensory perception of foods with added particles in the micron range, limited knowledge is available about the sensory perception of foods with added, dispersed particles on a millimetre length scale, although this length scale (mm) is known to contribute to texture perception. The presence of different components of larger length scales could lead to the perception of texture contrast. This latter perception is a sensory property that seems to be triggered by the presence of mechanical contrast between the different elements of composite foods. Texture contrast might be used to provide intra-oral variations that could help to prevent adaptation of the sensorial stimulus during mastication and in the long term (Dember & Earl, 1957; Lévy et al., 2006). We hypothesize that the boosted sensorial stimulus might also contribute to enhanced liking.

The aim of this study was to investigate the combined effects of particle size (millimetre length scale), particle hardness (fracture stress), and matrix type of dispersed model foods (semi-solid, chewable and liquid, spoonable matrix) on sensory perception and liking.

3.2 Materials and Methods

3.2.1 Ingredients

K-carrageenan (GENUGEL® carrageenan type CHP-2, CP Kelco, Levallois-Perret, France) and pigskin gelatine (Bloom 240-260, Rousselot B.V., Gent, Belgium) were used. Potassium chloride was obtained from Merck (Darmstadt, Germany). Spray dried skimmed milk powder (0% fat) was purchased from LacPatric Dairies (Artigarvan Strabane, Ireland). Rennet Maxiren® XDS in liquid form (DSM, The Netherlands) and soy lecithin (Cargill, Belgium) were used. Skimmed fresh milk (0% fat), cornstarch flour, vanilla aroma, tomato drink bouillon powder (Knorr® drinkbouillon tomaat), liquid sweetener (RIO® Zoetstof) and sunflower oil were purchased in a local retailer. All ingredients were food grade and samples for sensory evaluation were prepared under food-safe conditions.

3.2.2 Sample preparation

3.2.2.1 Particle preparation

Particles varying in size and hardness (fracture stress) were prepared to obtain heterogeneous foods with controlled mechanical contrast. K-carrageenan was used as gelling agent and its concentration was adjusted to engineer fracture stress (see **Table 3.1**). K-carrageenan was dispersed into 0.075% w/w KCl solution. The solution was subsequently stirred for 30 min to permit hydration of the gelling agent and then heated in a water bath at 90°C for 30 min.

To obtain κ-carrageenan particles differing in size two methods were used: emulsification and extrusion. The emulsification method allowed the creation of particles with a diameter smaller than 1.5 mm, while the extrusion method was used to create particles with a diameter larger than 2 mm (**Figure 3.1**).

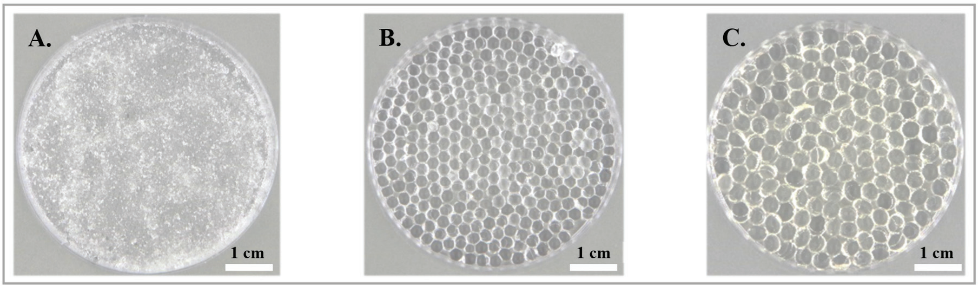

Figure 3.1. K-carrageenan particles varying in sizes: A. Small (0.8 mm); B. Medium (2.4 mm); C. Large (4.2 mm).

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Emulsification method

For the emulsification method, a water in oil emulsion (w/o) was prepared in Schott bottles (500 ml). The aqueous phase, which consisted of a hot κ-carrageenan solution, was added into heated sunflower oil (90°C) at a volume fraction of 40%. No emulsifiers were used. The solution was cooled down to room temperature within one hour under continuous stirring to allow gelation of the κ-carrageenan and small, spherical gel particles (diameter <1.5 mm) were obtained.

Extrusion method

The hot κ-carrageenan solution was extruded from a syringe (Omnifix 65 mL syringes, B. Braun) into cold sunflower oil (5-10°C). The syringe was coupled to a Texture Analyzer (TA.XT plus, Stable Micro Systems-SMS) to control the rate of the extrusion process, which was set at 0.2 mm/s. The mixture was kept under gentle stirring to avoid clustering of particles. Two particle sizes could be obtained by changing the syringe orifice dimension. A needle of 0.8 mm diameter was employed to produce particles of about 2.5 mm in diameter, whereas the original orifice of the syringe (diameter of approximately 2.5 mm with no needle attached) was used to prepare larger particles of approximately 4 mm in diameter. Medium-sized hard particles could not be produced with this set-up due to the high viscosity of 4% κ-carrageenan solution and the resulting blockage of the needle.

3.2.2.2 Particle collection

The spherical gel particles obtained from the emulsification and extrusion methods were collected using sieves with different mesh sizes (Retsch, Germany): 0.7 and 1.4 mm sieves were used as lower and upper limits to collect small particles (S-); 1.4 and 2.8 mm sieves were used for medium particles (M-); 2.8 and 5 mm sieves were used for large particles (L-). This step also narrowed the particle size distribution. Oil was further removed by washing the particles on the sieve with a 0.075% w/w KCl solution containing 0.05% w/w lecithin and subsequently rinsing twice with pure 0.075% w/w KCl solution. The excess washing solution was removed with the help of absorbing paper.

Macroscopic gels with the same κ-carrageenan concentration were prepared to determine the fracture stress of the gels. These gels were obtained by pouring a hot κ-carrageenan solution into 65 mL syringes previously greased with sunflower oil. The gels were kept overnight at 4°C and were cut into cylinders of 26 mm diameter and 20 mm height.

3

3.2.3 Matrix preparation

Two matrices were prepared, a liquid and semi-solid matrix, to mimic two commercially available foods, namely tomato soups and dairy desserts. **Figure 3.2** shows pictures of the model foods without particles (**Figure 3.2A** and **3.2C**) and with added particles (**Figure 3.2B** and **3.2D**).

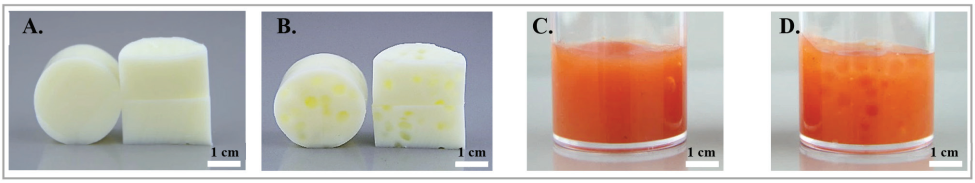

Figure 3.2. A. Homogeneous, semi-solid model food gel without particles; B. Heterogeneous, semi-solid model food gel with 15% w/w κ-carrageenan particles embedded; C. Homogeneous, liquid model soup without particles; D. Heterogeneous, liquid model soup with 15% w/w κ-carrageenan particles embedded.

3.2.3.1 Liquid matrix

A 4% cornstarch solution (w/w) was used as liquid matrix. Starch was added to tap water and the suspension was stirred for 10 min. The suspension was heated in a water bath at 95°C for 30 min to allow gelatinization of the starch. Commercially available tomato broth powder was added to the matrix and the obtained model soup was cooled down. The model soup was sieved to remove possible lumps and herbs. The model soups were served at room temperature (20°C).

3.2.3.2 Semi-solid matrix

A protein-based model gel was prepared as semi-solid matrix. Spray dried skimmed milk powder (10% w/w) was dissolved in water and gelatine (4% w/w) was added to the solution. The solution was stirred for 30 min to allow hydration and subsequently heated at 60°C for 20 min to dissolve the gelatine. Vanilla aroma (0.02% w/w) and liquid sweetener (1% w/w) were added. The solution was then cooled down to 42°C and rennet (0.02% w/w) incorporated while stirring. The enzyme concentration was selected to allow matrix gelation within 5 min. The solution was immediately poured into plastic tubes (Omnifix 65 mL syringes, B. Braun) of 26 mm internal diameter coated with a thin layer of sunflower oil to obtain cylindrical gels. These were stored at 4°C for 15-18 hours and were cut with custom-made cutting frames to 26 mm diameter and 15 mm. The serving temperature was 20°C.

3.2.3.3 Particle incorporation into the matrices

Particles varying in size and fracture stress were incorporated into the liquid and semi-solid matrices at a constant percentage of 15% (w/w). In the liquid matrix, particles were added by mixing the particles immediately before the sensory tests (max 1 hour). In the semi-solid matrix, particles were added at the moment of rennet addition, so when the matrix was still in a liquid state (at 42°C). The protein solution containing the particles was placed in a closed syringe, which was slowly rotated on a wheel (end over end) during gelation to ensure that the particles were homogeneously distributed in the gel. Air bubbles were carefully removed before rotation. After the gelation process was completed, so within 5 min, the semi-solid gels were stored at 4°C for 15-18 hours to allow complete setting of gelatine.

3.2.4 Study design

Nine samples of each matrix (liquid and semi-solid) were investigated including two homogeneous reference samples (without added particles). The study design and sample codes for the two matrices are shown in **Table 3.1**. The first letter in the sample code denotes the size of the added particles. The second letter denotes the fracture stress of the added particles. Samples containing small, medium, and large particles were denoted as S(-), M(-), and L(-) respectively, whereas samples containing soft, medium, and hard particles were denoted as (-)S, (-)M, and (-)H. Homogeneous samples without added particles were indicated as C (Control).

Table 3.1. Sample codes for homogeneous and heterogeneous model soups and gels with composition and preparation method for particles with different target fracture stress (σ_F) and target particle size.

Sample name	Target particle size	Target particles fracture stress (σ_F)	K-C (% w/w)	Preparation method	K-C (% w/w)	Preparation method
C	-	-	-	-	-	
SS	Small	(< 1.5mm)	Soft	(25 kPa)	1	Emulsification
SM	Small	(< 1.5mm)	Medium	(100 kPa)	2	
SH	Small	(< 1.5mm)	Hard	(250 kPa)	4	
MS	Medium	(2.5mm)	Soft	(25 kPa)	1	Extrusion
MM	Medium	(2.5mm)	Medium	(100 kPa)	2	
LS	Large	(4mm)	Soft	(25 kPa)	1	Extrusion
LM	Large	(4mm)	Medium	(100 kPa)	2	
LH	Large	(4mm)	Hard	(250 kPa)	4	

3.2.5 Sample characterization

3.2.5.1 Particle size determination

Two methods were used to characterize particle size. For small particles, dynamic light scattering was used to establish the volume-to-surface ($D_{4,3}$) diameter (Malvern MasterSizer X, Malvern, Instruments Ltd., Malvern, UK). For medium and large particles a digital calliper was employed to establish the mean diameter. The average diameter and standard deviation were calculated based on 50 measurements.

3.2.5.2 Viscosity measurements

Flow curves of the liquid matrix without added particles were determined using a Physica MCR 501 Rheometer (Anton Paar GmbH) at 20°C at shear rates ranging from 1 to 1000 s^{-1} in a total time interval of 2.50 min with a concentric cylinder geometry (beaker diameter 18.08 mm; cylinder diameter 16.66 mm; length 24.94 mm). A waiting time of 5 min was used to obtain equilibrium before the measurements were performed. The obtained flow curves were fitted with a power law model:

$\eta = k\,\dot{y}^{(n-1)}$ (1)

where k is the flow consistency (η_{1s-1}), $\dot{y}$ is the shear rate and n is the flow behaviour index. Measurements were performed in duplicates. All samples displayed a standard deviation lower than 15%.

3.2.5.3 Uniaxial compression tests

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Uniaxial compression tests were performed with a Texture Analyzer (TA.XT plus, Stable Micro Systems-SMS) to characterize the mechanical properties of the semi-solid protein gel matrices and κ-carrageenan macroscopic gels. A probe of 150 mm diameter was coupled with a load cell of 50 kg. Top and bottom plates were lubricated with a thin layer of paraffin oil. Specimens were cut into cylindrical pieces (26 mm diameter and 20 mm height) and compression tests performed at room temperature (20 ± 1°C) after an equilibration time of 1 hour. A crosshead velocity of 1 mm/s up to a compression strain of 80% was applied. From the force-distance curves, young's modulus, true fracture stress, and true fracture strain were calculated according to the method described by Peleg (1987) from the measurements of at least three replicates.

3.2.5.4 Puncture tests

Puncture tests were performed with semi-solid model gels to quantify the level of heterogeneity as a function of size and fracture stress of added particles. Puncture tests were carried out with a needle probe (max. 1.96 mm diameter; 35 mm height) using a Texture Analyser coupled with a 500 g load cell (TA.XT plus, Stable Micro Systems-SMS). A speed of 1 mm/s and a maximum penetration of 80% were selected. **Figure 3.3** shows a typical outcome of the puncture tests for a homogeneous and heterogeneous semi-solid gel. For homogeneous gels, the force-distance puncture curves increased linearly, whereas for heterogeneous gels with embedded particles the force-distance curves were characterized by several peaks. These peaks are a result of differences in mechanical properties between the added particles and the semi-solid gel matrix.

The heterogeneity was quantified by calculating the positive (+) and negative (-) areas under the puncture test curve in comparison to the homogeneous sample without added particles (black line).

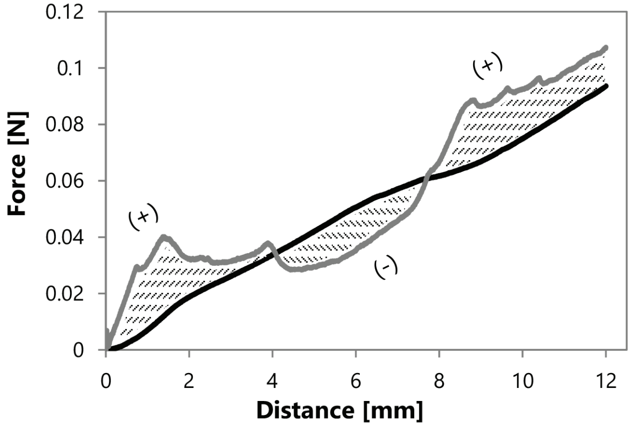

Figure 3.3. Example of force-distance curves of homogeneous gel without added particles (gel C, black line) and heterogeneous gel with added particles (gel LM, grey line) obtained from puncture tests. Dashed areas characterize positive and negative differences between homogeneous and heterogeneous gels.

All the areas above the black line were added up to obtain the positive $AUC_{positive}$, and all the areas below the black line were added up to obtain the negative $AUC_{negative}$ for each sample. The total area under the curve (AUC_{total}) was obtained as the sum of the absolute values $AUC_{positive}$ and $AUC_{negative}$. This AUC_{total} was considered a measure of the degree of heterogeneity for semi-solid gels with added particles (**Figure 3.3**) and can be considered a complementary strategy to the one described by Tang et al. (2017). This approach focuses on possible hardening and softening effects related to the addition of particles since in composite foods the mechanical properties of one component can influence the fracture properties of another component during penetration (**Chapter 2**). Five specimens were measured for each sample, and five puncture tests were performed for each sample.

3.2.6 Sensory evaluation

3.2.6.1 Subjects

Fifty-four participants (n=54, 35 female, age: 21-31 years) were recruited for the study. Subjects were selected based on a screening questionnaire according to self-reported criteria such as origin (born and living in European Union), age (18-35 years), BMI (18.5-25 kg/m^2) and having no dental implants or missing teeth (except wisdom teeth). A consent form was signed by all participants. Subjects received a reimbursement for their participation and were naïve concerning the experimental conditions and purposes.

3.2.6.2 Sensory sessions

The sensory tests were conducted in meeting facilities (Wageningen University) during one familiarization session of 30 min and one test session of 90 min. The test session was divided in two blocks with a break of 15 min between blocks. In each block, one set of 9 samples of model soups or model gels was served and evaluated. The test room was equipped with desk dividers for a maximum of 10 participants per session. Subjects were asked to fill in a paper questionnaire. One short familiarization session was carried out to allow participants to become familiar with the sensory method. An explanation brochure for the different descriptors and their definitions was provided during the test session. A sequential monadic presentation was used for all the samples, which were presented in random order within each participant group (Williams Latin square design) and across participant groups. Subjects were instructed to cleanse their mouth with water and have a break of at least 2 min between evaluations of each sample. A portion of 40 g of model soup (around 3 tablespoons) and 3 bite-size pieces of model gels (26 mm diameter and 15 mm height) were provided for each sample. Participants completed the familiarization session and test session within two weeks.

3.2.6.3 Hedonic characterization and Rate-all-that-apply (RATA)

Participants first evaluated liking of the products using a hedonic 9-point scale ranging rom “Dislike it extremely” (1) to “Like it extremely” (9). Three hedonic evaluations were performed: overall liking, texture liking, and flavour liking.

Table 3.2. List of descriptors and definitions used in the RATA test for model soups and model gels. Check marks indicate that the term was used for the specific product type.

Attribute			**Definition**
	Soup	**Gel**	
Appearance			
Visual heterogeneity	✓	✓	Observation of different elements in the sample.
Texture			
Beadiness	✓	✓	Perception of medium-small particles in the mouth (e.g. dimension of mustard seeds).
Chewiness	✓	✓	The amount of work required to masticate the sample into a state ready for swallowing.
Cohesiveness		✓	The extent to which the sample holds together during chewing (sample holds in one mass together or product remains as a whole).
Creaminess	✓	✓	Sensation of a thick, smooth and velvety texture in the mouth.
Crumbliness		✓	Extent to which sample crumbles or breaks into different smaller pieces during mastication.
Elasticity		✓	The degree to which the sample returns to its original shape after being compressed between the teeth.
Grittiness	✓	✓	Perception of small particles in the mouth (e.g. dimension of sand).
Hardness	✓	✓	Force required to compress and/or break the sample (or its components) between the teeth.
Lumpiness	✓	✓	Perception of large particles in the mouth (e.g. tapioca pudding).
Melting	✓	✓	Degree to which the sample (or its components) melts during mastication.
Mouth-coating	✓	✓	Sensation of a layer covering the mouth (film sensation inside the mouth).
Mouthfeel heterogeneity	✓	✓	Sensory perception of different elements in the mouth during consumption (i.e. one sample contains soft and hard parts).
Stickiness	✓	✓	Degree to which the sample (or its components) sticks to your tongue, palate and teeth.
Thickness	✓		Force required to deform the sample and the perceived resistance to flow.
Flavour			
Dairy/milky flavour		✓	The perception of milk or dairy product flavour.
Savoury	✓		Perception of salt, broth-like, spices and herbs.
Sweet		✓	The perception of sugar taste.
Tomato flavour	✓		Perception of tomato flavour.
Vanilla flavour		✓	The perception of vanilla flavour.

After the hedonic evaluations, subjects were asked to evaluate the samples using a Rate-all-that-apply (RATA) method with 9-box scales as previously described by Meyners et al. (2016b) and Oppermann et al. (2017). The lists of attributes differed between soups and gels and were generated upon discussion of researchers and consumers during feasibility tests (data not shown). In particular, 14 descriptors were provided for the soups and 17 for the gels. The complete list of sensory terms, as well as their definitions, are reported in **Table 3.2**. The list of attributes was presented to the subjects, who were asked to indicate whether the specific descriptors were applicable to the assessed sample ("Yes" or "No" choice). Once an attribute was selected as applicable to the sample ("Yes" choice), then subjects had to rate the perceived intensity of the selected attribute on a 9 point-scale where "1" corresponded to low intensity and "9" to high intensity. An explanation was provided on the meaning of applicability of the different attributes. It was clarified that a non-selection of an attribute was equivalent to a non-perception of the sensory stimulus. The order in the questionnaire of the sensory attributes was randomized within each block of attribute category (appearance, texture, and flavour) for each participant.

3.2.7 Data Analysis

Both RATA frequency and RATA intensity were analysed as previously described by Meyners et al. (2016). The RATA frequencies were based on frequency of selection of the different sensory terms, whereas RATA intensities were obtained considering the outcomes as 10-points scales. A 0 score was assigned to a specific descriptor when a "No" (not applicable) was selected. The step-wise data were treated with parametric methods (Meyners et al., 2016; Oppermann et al., 2017). For this reason, a two-way ANOVA was performed to investigate the differences for all sensory descriptors within each product type (model soups and model gels). Sample was set as fixed factor, whereas panellist as random factor. Tukey's HSD test at 95% confidence level was used for post-hoc comparison when significant differences were found. PCAs (Principal Components Analysis) were performed to identify possible correlations between samples and sensory attributes. The RATA frequencies were determined by converting the data into binary responses (applicable as 1; not applicable as 0). The differences in selection were analysed by Cochran's Q test for all the sensory attributes within each product type. R language (version 3.2.3) was used to perform all statistical tests. RVAideMemoire package was employed for the Cochran's Q test, while the panelipse function of SensoMineR was used to create confidence ellipses in the PCA.

3.3 Results and Discussion

3.3.1 Sample characterization

3.3.1.1 Particle sizes

The particle sizes of all κ-carrageenan particles are presented in **Table 3.3**. Small particles had an average diameter (D) of 0.79 mm, medium particles of 2.44 mm and large particles of 4.21 mm. For small and large particles, an increase in polysaccharide concentration let to marginally larger particle sizes but the increase in size was within the error margin.

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Table 3.3. Averaged particle size with standard deviation of all κ-carrageenan particles.

	Small			Medium		Large		
K-C (% w/w)	1	2	4	1	2	1	2	4
D [mm]	0.77 ± 0.06	0.80 ± 0.04	0.81 ± 0.14	2.44 ± 0.19	2.44 ± 0.19	4.11 ± 0.40	4.13 ± 0.23	4.37 ±0.23
Average D [mm]	0.79			2.44		4.21		

3.3.1.2 Viscosity of liquid matrix

The model soup displayed a consistency, k = 7 Pa.s and had a power law index, n = 0.38. Such values are comparable to those of commercially available products: creamy chicken soup (k = 2 Pa.s, n= 0.43); full-fat yoghurt (k = 3 Pa.s, n= 0.56); free-fat yoghurt (k = 6 Pa.s, n= 0.42); custard (k = 15 Pa.s, n= 0.40); mayonnaise (k = 76 Pa.s, n= 0.25).

3.3.1.3 Mechanical properties of semi-solid gels

The mechanical properties of the macroscopic κ-carrageenan gels and the gel matrix (C) are shown in **Table 3.4**. For κ-carrageenan gels, fracture stress significantly increased in a non-linear fashion with increasing polysaccharide concentration. This demonstrates that the increment of network strength tends to level off at higher κ-carrageenan concentrations. An increase in fracture stress with increasing κ-carrageenan concentration was associated with a significant increase in fracture strain. The dairy model gel (C) showed a fracture stress and Young's modulus comparable to the 1% κ-carrageenan gel (soft), whereas fracture strain of the model gel matrix was significantly higher than for the 1% κ-carrageenan gel. As the fracture stress of the soft particles and the matrix gels are similar, we expect those gels to present a low degree of heterogeneity.

Table 3.4. Mechanical properties of macroscopic κ-carrageenan gels and homogeneous model dairy gel (C). Different superscript letters indicate significant differences between samples ($p<0.05$).

Gel	κ-carrageenan concentration [%w/w]	True Fracture stress [kPa]	True Fracture strain [-]	Young's Modulus [kPa]
κ-carrageenan				
soft	1%	25.8 ± 1.8 ^{B}	0.64 ± 0.03 ^{A}	8.7 ± 0.5 ^{A}
medium	2%	96.7 ± 1.4 ^{C}	0.78 ± 0.03 ^{A}	45.6 ± 1.9 ^{B}
hard	4%	253.1 ± 2.4 ^{D}	1.04 ± 0.03 ^{B}	301.8 ± 1.3 ^{C}
Model gel matrix (C)		21.1 ± 0.5 ^{A}	1.32 ± 0.05 ^{C}	10.3 ± 1.1 ^{A}

3.3.1.3 Degree of heterogeneity

To quantify the level of mechanical heterogeneity of model gels with added particles, puncture tests were executed. **Figure 3.4** summarises the outcome of this test. We suggest that AUC_{total} ($AUC_{positive}$ + $AUC_{negative}$) provides an estimate of the degree of heterogeneity of composite model food gels. Both fracture stress and size of embedded particles influenced AUC_{total} as a consequence of variations in $AUC_{positive}$ and $AUC_{negative}$. Gel LH containing large and hard particles displayed the highest AUC_{total} (0.58 N*mm) suggesting it is the most heterogeneous gel, whereas gel SM containing small particles of medium hardness showed the lowest AUC_{total} (0.06 N*mm) suggesting it is the least heterogeneous gel. All other gels (LM, LS, MM, MS, SH and SS) displayed comparable AUC_{total} ranging from 0.12 to 0.20 N*mm and therefore, the degree of heterogeneity of those gels was considered comparable and larger than the heterogeneity of SM and smaller than LH.

For a more detailed differentiation of the heterogeneity of gels, $AUC_{positive}$ and $AUC_{negative}$ are considered separately. The higher the fracture stress within the same particle size category (small, medium or large), the higher $AUC_{positive}$.

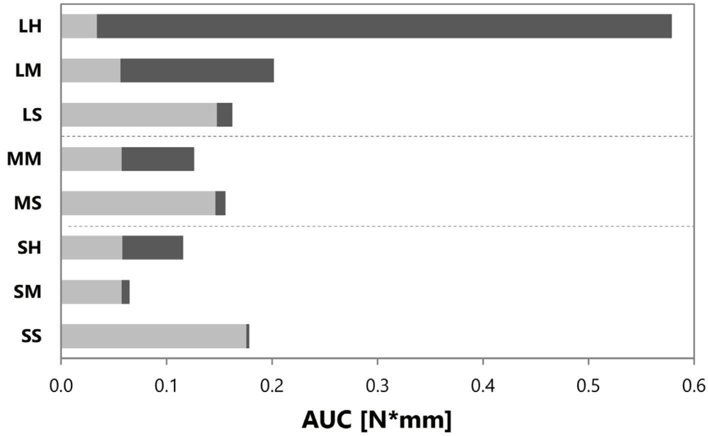

Figure 3.4. The total area under the curve ($AUC_{total} = AUC_{negative} + AUC_{positive}$) between heterogeneous gels with added particles and homogeneous gel without added particles obtained by puncture tests. Negative areas under the curve $AUC_{negative}$ are shown in light grey, and positive areas under the curve $AUC_{positive}$ in dark grey. All samples displayed a standard error lower than 20%. The first letter in the sample code denotes size of added particles (Small, Medium, Large), the second letter denotes fracture stress of added particles (Soft, Medium, Hard).

This indicates that the addition of harder particles to the gel matrix leads to an overall larger puncture work (hardening) in comparison to the homogeneous sample. Such behaviour was also noticed by Tang and co-workers (2017), who characterized the complexity in texture of heterogeneous model gels. In their study, it was observed that the puncture penetration profile was characterized by several distinct peaks when harder components were present in the matrix. In addition to this effect, our results suggest that the size of the embedded particles influences the hardening effect. Particle size had a larger effect on $AUC_{positive}$ than particle hardness. For instance, gel LH displayed values for $AUC_{positive}$ approx. 9 times larger than gel SH. We cannot exclude that this difference might also be related to the limited sensitivity of the puncture tests to detect small heterogeneities in a continuous matrix. We expect that sensory detectability of mechanical contrast as perceived heterogeneity is higher for gels with higher values of $AUC_{positive}$ since harder particles are easier to perceive compared to soft particles.

With decreasing fracture stress of embedded particles, so with increasing softness of added particles, $AUC_{negative}$ increased for all three particle sizes. This indicates that soft particles led to a softening of the heterogeneous gel compared to the homogeneous gel, even though the particles themselves were slightly harder than the matrix. The higher values of $AUC_{negative}$ might be caused by specific composite fracture behaviour of the model gels. During deformation, energy transfer from the matrix to the embedded particles may change the mechanical properties of the embedded components, resulting in a decrease in the required puncture work.

3.3.2 Sensory evaluation

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3.3.2.1 Frequency of selection

The percentages of descriptors selection of the RATA test (**Table 3.5** and **3.6**) were examined with Cochran's test. From this test, it was found that 9 of 14 descriptors were significantly different for the soups (highlighted in bold). For the model gels, 10 out of 17 descriptors were found to be significantly different.

Large variations were observed for all descriptors related to heterogeneity (i.e. visual heterogeneity, mouthfeel heterogeneity, hard, chewy). Samples containing particles presented higher frequencies of selection of such attributes and, in general, higher percentages of selections were obtained for samples with increasing particles size. The effect of fracture stress was most obvious by the changes in the descriptor hard, which increased with the particle fracture stress for all particle sizes in both liquid and semi-solid samples. The selection of size-related descriptors of the added particles (gritty, beady, and lumpy) differed considerably among samples. In model soups, gritty was selected when small particles were incorporated into the matrix (72-94%). Beady was mainly associated with medium-sized particles (81-83%), and lumpy with large particles (72-89%). The data of the solid matrix followed comparable trends. Samples containing small particles scored higher percentages in grittiness (63-89%), samples with medium particles were mainly associated with beady (69-83%) and samples with large particles had a higher lumpy perception (44-74%).

For both matrices, the combined effect of particle size and fracture stress led to a change in the frequency of selection of the descriptor creamy. The selection frequency of creaminess was enhanced by the presence of larger and harder particles, whereas it was not considerably influenced by small and soft particles. For some descriptors, the selection was dependent on the type of the matrix and this was partly related to the visual recognition of embedded particles. Small-sized particles were more visible in the semi-solid model gels than in the liquid model soups (visual heterogeneity), even though the mouthfeel perception of heterogeneity was comparable between both matrices. The descriptor chewy was affected considerably as a function of particle size in the case of the model soups, whereas for model gels, no clear distinction was presented between the different particle sizes. Considering the significant differences highlighted by the Cochran's test (**Table 3.5** and **3.6**), no effect of the addition of particles was found on melting, mouth-coating, sticky, savoury and tomato flavour for model soups. For model gels, crumbly, elastic, sticky, dairy milky flavour, sweet, and vanilla perception were also not significantly affected by the presence of particles. In general, upon the incorporation of particles into a chewable matrix, a decrease in the selection of the descriptors cohesive and elastic can be seen in comparison with the model gels without particles. Such findings might be explained by the results obtained in the puncture tests. In fact, all samples with embedded particles displayed a heterogeneous structure, as exemplified by the values for AUC_{total} (**Figure 3.4**). Both $AUC_{positive}$ and $AUC_{negative}$ represent a discontinuity of the matrix network due to the presence of heterogeneities. These structural heterogeneities could have weakened the overall structure of the matrix during large deformation (i.e. mastication), which may lead to the perception of an overall less cohesive and elastic gel.

3.3.2.2 Intensity of descriptors

The samples were also compared based on the scored intensities of the selected descriptors. The significant differences and the averaged values of RATA intensity are represented in **Table 3.7** and **3.8**. For soups, the number of significantly different descriptors (**Table 3.7**) was found to be 10 out of 14 when RATA intensities are considered. For the model gels (**Table 3.8**), 14 out of 17 descriptors were found to be significantly different considering RATA intensities.

The treatment of the RATA data as intensities provides different information than the frequency of selection analysis. When the p-values of specific attributes in model soups are compared between intensity (ANOVAs) and frequency (Cochran's tests) outcomes (**Table 3.5** and **3.7**), it can be seen that melting and savoury become significantly different for RATA intensities compared to RATA frequencies, whereas thick becomes not significantly different, although it was significantly different for RATA frequencies. In model gels (**Table 3.6** and **3.8**), chewy, crumbliness, elasticity, and vanilla aroma become significantly different with RATA intensities, while these were not significant for the frequencies of selection.

Table 3.5. Frequency of selection of RATA descriptors for model soups. Values are given in percentage (%). The first letter in the sample code denotes size of the added particles (Small, Medium, Large), the second letter denotes fracture stress of the added particles (Soft, Medium, Hard). Significant p-values are highlighted in bold.

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Model soups	Visual heterogeneity (A)	Beady (T)	Chewy (T)	Creamy (T)	Gritty (T)	Hard (T)	Lumpy (T)
p-value	**<0.001**	**<0.001**	**<0.001**	**0.002**	**<0.001**	**<0.001**	**<0.001**
C	13	4	7	87	22	87	54
SS	48	11	11	81	72	2	2
SM	50	33	22	72	80	6	6
SH	44	15	13	76	94	9	7
MS	98	83	67	67	13	9	7
MM	98	81	69	59	11	26	39
LS	98	54	63	67	9	39	41
LM	98	50	85	65	9	30	72
LH	94	41	87	56	7	52	78

Model soups	Melting (T)	Mouth-coating (T)	Mouthfeel heterogeneity (T)	Sticky (T)	Thick (T)	Savoury (F)	Tomato flavour (F)
p-value	0.853	0.440	**<0.001**	0.647	**0.033**	0.659	0.401
C	22	19	19	24	83	98	98
SS	54	76	67	30	80	96	98
SM	54	74	87	31	72	94	100
SH	50	72	94	33	76	96	96
MS	48	72	98	33	72	98	100
MM	52	72	98	35	74	100	100
LS	48	65	98	33	81	96	98
LM	52	72	98	30	85	96	100
LH	50	69	98	28	85	98	98

Based on the results of **Table 3.7** and **3.8**, the model soup and gels can be divided into three groups based on visual heterogeneity: homogeneous samples, samples containing small particles and samples containing medium-large particles. As observed with the RATA frequency, the particle size mainly determined the selection of the descriptor visual heterogeneity. The visual heterogeneity intensity increased when the particles increased in size from small to medium, but no significant difference was seen between the medium and large particles.

Table 3.6. Frequency of selection of RATA descriptors for model gels. Values are given in percentage (%). The first letter in the sample code denotes size of the added particles (Small, Medium, Large), the second letter denotes fracture stress of the added particles (Soft, Medium, Hard). Significant p-values are highlighted in bold.

Model gels	Visual hetero-geneity (A)	Beady (T)	Chewy (T)	Cohesive (T)	Creamy (T)	Crumbly (T)	Elastic (T)	Gritty (T)	Hard (T)
p-value	**<0.001**	**<0.001**	**0.056**	**0.040**	**<0.001**	0.333	0.172	**<0.001**	**0.001**
C	4	4	96	72	4	59	78	2	72
SS	83	13	91	54	57	69	67	63	59
SM	89	19	83	59	59	63	65	85	65
SH	80	22	87	56	59	65	65	89	65
MS	98	69	89	65	54	57	63	13	70
MM	96	83	93	61	46	70	70	11	80
LS	100	65	93	69	41	67	70	6	69
LM	100	56	87	59	44	67	74	4	81
LH	98	50	94	61	37	67	69	6	89

Model gels	Lumpy (T)	Melting (T)	Mouth-coating (T)	Mouthfeel hetero-geneity (T)	Sticky (T)	Dairy Milky flavour (F)	Sweet (F)	Vanilla flavour (F)
p-value	**<0.001**	**0.032**	**0.021**	**<0.001**	**0.736**	0.9445	0.383	0.321
C	31	72	2	6	6	89	89	89
SS	11	44	35	67	31	87	93	81
SM	7	61	35	89	30	85	87	74
SH	4	63	43	91	35	85	93	80
MS	4	50	48	89	33	87	93	87
MM	28	46	35	94	26	89	96	81
LS	30	37	33	91	30	89	91	80
LM	44	48	31	98	30	83	94	85
LH	69	44	37	98	28	87	93	81

The particle size was also seen to be related to the descriptors gritty, beady, and lumpy. Once attributes were selected (so considered clearly applicable for the vast majority of consumers), the RATA intensities were mainly influenced by the fracture stress of the particles. For instance, when small particles were added with increasing fracture stress from soft to hard (SS to SH), the RATA intensity of grittiness perception doubled for both matrices. For larger particles (LS to LH), the descriptor gritty was not dependent on the fracture stress of the particles in either of the matrices. Contrary, the descriptors beady and lumpy were affected in a different manner. In the case of beady, a significant difference in the model gels was found for medium-sized particles varying from soft (MS) to medium hardness (MM), whereas no differences were found in soups for the same particle size. For lumpy, an increase in particle fracture stress from soft (LS) to medium/hard (LM, LH) for large particles led to significantly higher perceived lumpiness intensities for both the liquid samples as the semi-solid gels.

The incorporation of particles into the liquid and semi-solid samples also affected the intensity scores of the descriptor creamy. In model soups, the addition of soft and small (SS) particles did not significantly affect creaminess, even though these heterogeneities were clearly perceivable since mouthfeel heterogeneity was four times higher than in the homogeneous soup (C). Creaminess decreased with an increase in the particles size and particle fracture stress, and the largest decrease in creaminess was recorded for the large and hard (LH) particles. For the semi-solid gels, the addition of particles had a smaller influence on the intensity scores for creaminess. Only for large and hard particles (MM, LM, and LH), the decrease in creaminess becomes significant. These results suggest that smooth and creamy sensations are not influenced by the incorporation of sufficiently small and soft particles. On the contrary, these attributes are significantly affected by the presence of large variations in mechanical contrast and particle size.

The effect of particle size and fracture stress was also obvious in the intensity scores for the descriptor chewy and hard. Soft particles showed similar scores as the reference sample without particles, but for an increase in particle size and hardness, the intensity scores decreased. Hard and large particles (LH) showed the highest intensity scores for chewy and hard for both liquids and semi-solid gels. For the model gels, these results are in line with what was observed with the puncture test.

Table 3.7. P-values and mean sensory scores on a 9-point scale for model soups with embedded particles. Different superscript letters indicate significant differences between the samples ($p<0.05$). The first letter in the sample code denotes size of the added particles (Small, Medium, Large), the second letter denotes fracture stress of the added particles (Soft, Medium, Hard).

Model soups	Visual hetero-geneity (A)	Beady (T)	Chewy (T)	Creamy (T)	Gritty (T)	Hard (T)	Lumpy (T)	Melting (T)	Mouth-coating (T)	Mouthfeel heterogeneity (T)	Sticky (T)	Thick (T)	Savoury (F)	Tomato flavour (F)
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.036	0.084	<0.001	0.220	0.220	0.012	0.167
C	0.37^{A}	0.11^{A}	0.19^{A}	4.13^{A}	0.43^{A}	0.13^{A}	0.11^{A}	2.69^{A}	3.00^{A}	0.54^{A}	0.56^{A}	3.04^{A}	5.54^{A}	5.57^{A}
SS	1.41^{B}	0.41^{AB}	0.22^{A}	3.37^{AB}	2.76^{B}	0.09^{A}	0.11^{A}	2.30^{AB}	2.89^{A}	2.09^{B}	0.81^{A}	2.87^{A}	4.83^{AB}	5.15^{A}
SM	1.54^{B}	1.72^{BC}	0.54^{A}	2.67^{BC}	4.07^{C}	0.20^{A}	0.26^{A}	2.15^{AB}	3.00^{A}	3.94^{C}	1.00^{A}	2.76^{A}	5.22^{AB}	5.11^{A}
SH	1.35^{B}	0.59^{AB}	0.37^{A}	2.85^{BC}	5.94^{D}	0.20^{A}	0.19^{A}	2.02^{AB}	3.00^{A}	4.80^{CD}	1.13^{A}	2.83^{A}	5.37^{AB}	5.15^{A}
MS	5.63^{C}	4.69^{E}	1.61^{B}	2.43^{CD}	0.37^{A}	0.48^{A}	2.00^{B}	2.24^{AB}	2.87^{A}	5.74^{DE}	0.85^{A}	2.85^{A}	5.37^{AB}	5.20^{A}
MM	6.30^{CD}	5.20^{E}	2.30^{B}	2.11^{CD}	0.46^{A}	1.19^{BC}	2.31^{B}	2.02^{AB}	2.69^{A}	6.78^{EF}	1.02^{A}	2.39^{A}	5.35^{AB}	5.41^{A}
LS	5.94^{CD}	3.11^{D}	2.00^{B}	2.37^{CD}	0.35^{A}	0.76^{AB}	4.31^{C}	2.00^{AB}	2.52^{A}	6.24^{FG}	0.91^{A}	2.85^{A}	4.78^{B}	5.48^{A}
LM	6.59^{D}	3.06^{CD}	3.24^{C}	2.11^{CD}	0.22^{A}	1.59^{C}	5.30^{CD}	2.09^{AB}	2.41^{A}	7.20^{FG}	1.00^{A}	3.02^{A}	4.94^{AB}	5.39^{A}
LH	6.50^{CD}	2.44^{CD}	4.33^{D}	1.81^{D}	0.19^{A}	3.19^{D}	6.20^{D}	1.70^{B}	2.54^{A}	7.50^{G}	0.80^{A}	3.20^{A}	5.15^{AB}	5.00^{A}

Table 3.8. P-values and mean sensory scores on a 9-point scale for model gels with embedded particles. Different superscript letters indicate a significant difference between the samples ($p<0.05$). The first letter in the sample code denotes size of the added particles (Small, Medium, Large), the second letter denotes fracture stress of the added particles (Soft, Medium, Hard).

Model gels	Visual hetero-geneity (A)	Beady (T)	Chewy (T)	Cohesive (T)	Creamy (T)	Crumbly (T)	Elastic (T)	Gritty (T)	Hard (T)	Lumpy (T)	Melting (T)	Mouth-coating (T)	Mouthfeel heterogeneity (T)	Sticky (T)	Dairy Milky flavour (F)	Sweet (F)	Vanilla flavour (F)
p-value	<0.001	<0.001	<0.001	0.022	0.019	0.005	<0.001	<0.001	<0.001	<0.001	0.017	0.02	<0.001	0.464	0.49	0.097	0.046
C	0.28^{A}	0.20^{A}	3.26^{ABC}	2.89^{A}	2.04^{A}	1.96^{A}	3.19^{A}	0.07^{A}	1.93^{AB}	0.46^{ABC}	1.69^{ABC}	1.39^{AB}	0.30^{A}	0.74^{A}	3.78^{A}	4.22^{A}	4.06^{A}
SS	3.06^{B}	0.37^{A}	2.61^{A}	1.70^{B}	2.11^{A}	2.28^{AB}	2.50^{AB}	2.48^{B}	1.52^{A}	0.41^{AB}	2.20^{A}	1.19^{AB}	1.94^{B}	0.57^{A}	3.52^{A}	3.76^{A}	3.20^{ABC}
SM	3.31^{B}	0.87^{A}	2.67^{A}	1.65^{B}	1.74^{AB}	2.57^{AB}	2.39^{AB}	4.22^{C}	1.65^{A}	0.06^{A}	2.15^{AB}	1.43^{AB}	4.06^{C}	0.94^{A}	3.46^{A}	3.81^{A}	2.98^{BC}
SH	2.89^{B}	1.02^{AB}	2.61^{A}	1.57^{B}	1.69^{AB}	2.54^{AB}	2.00^{B}	5.15^{C}	1.57^{A}	0.22^{AB}	1.67^{ABC}	1.67^{A}	4.48^{CD}	0.98^{A}	3.85^{A}	3.81^{A}	2.63^{C}
MS	5.17^{C}	2.98^{C}	3.22^{ABC}	2.17^{AB}	1.54^{AB}	2.35^{AB}	2.56^{AB}	0.56^{A}	1.87^{A}	1.20^{BCD}	1.50^{ABC}	1.15^{AB}	3.89^{C}	0.72^{A}	3.54^{A}	4.07^{A}	3.52^{AB}
MM	6.06^{CD}	4.65^{D}	3.54^{CD}	2.13^{AB}	1.33^{B}	3.06^{B}	2.76^{AB}	0.48^{A}	2.67^{C}	1.54^{CD}	1.26^{C}	1.04^{AB}	5.80^{E}	0.93^{A}	3.46^{A}	3.94^{A}	3.37^{ABC}
LS	5.63^{CD}	2.61^{C}	3.13^{AB}	2.17^{AB}	1.57^{AB}	2.63^{AB}	2.74AB	0.24^{A}	1.81^{A}	2.15^{D}	1.43BC	1.09^{AB}	4.30^{C}	0.98^{A}	3.65^{A}	3.50^{A}	2.94^{BC}
LM	6.09^{CD}	2.30^{BC}	4.02^{D}	2.04^{B}	1.17^{B}	2.89^{B}	3.20^{A}	0.19^{A}	2.61^{BC}	3.93^{E}	1.20^{C}	1.26^{AB}	5.46^{DE}	0.67^{A}	3.30^{A}	3.30^{A}	3.31^{ABC}
LH	6.28^{D}	3.09^{C}	4.96^{E}	2.30^{AB}	1.13^{B}	2.94^{B}	2.87^{A}	0.24^{A}	4.04^{D}	4.59^{E}	1.30^{C}	0.93^{B}	7.13^{F}	0.76^{A}	3.37^{A}	3.37^{A}	3.06^{BC}

For gels containing medium and large particles, positive correlations between $AUC_{positive}$ and intensity level of perceived hardness (R^2=0.915) and chewiness (R^2=0.834) were found. For gels containing small particles, $AUC_{positive}$ poorly correlated with chewiness (R^2=0.123) and hardness (R^2=0.475). On the other hand, for the latter gels, $AUC_{positive}$ was found to be better correlated to the perceived grittiness (R^2=0.962).

3.3.2.3 Liking

Table 3.9 reports the average values of liking for the model soups and gels. In general, particle addition leads to a decrease in liking of model soups and gels.

In soups, only the incorporation of small and soft particles did not significantly influence liking. When the particle size (i.e. medium and large size) or the fracture stress increased (100 and 250 kPa σ_F), liking decreased. In terms of overall liking, the least liked model soup was the one containing large hard (LH) particles, followed by soups with LM, MM and SH particles. This indicates that the presence of large and hard particles (high heterogeneity) significantly decreased palatability of the model soups. This might be the result of a combined effect of decreased appreciation of both texture and flavour. Also for these descriptors, the large and hard particles (LH) were least liked. In general, the intensity of liking texture and liking flavour decreased for an increase in the particle size or fracture stress.

Table 3.9. Averaged liking scores ± standard deviation on a 9-point scale of model soups and gels. Different superscript letters indicate significant differences between means at p<0.05.

Product	Soup			Gel		
	Overall liking	Texture liking	Flavour liking	Overall liking	Texture liking	Flavour liking
C	6.1 ±1.5 ^{A}	6.0 ±1.8 ^{A}	6.3 ±1.4 ^{AB}	5.9 ±1.6 ^{A}	5.8 ±1.8 ^{A}	6.0 ±1.7^{A}
SS	5.7 ±1.7 ^{AB}	5.4 ±1.8 ^{AB}	6.1 ±1.4 ^{ABC}	5.1 ±1.7 ^{AB}	5.1 ±1.6 ^{AB}	5.1 ±1.7 ^{BCD}
SM	5.2 ±1.7 ^{BC}	4.6 ±1.9 ^{BC}	6.1 ±1.3 ^{ABC}	4.8 ±1.8 ^{BC}	4.6 ±1.9 ^{AB}	4.9 ±1.8 ^{CD}
SH	4.9 ±1.8 ^{C}	4.5 ±2.0 ^{CD}	5.7 ±1.8 ^{BC}	4.3 ±1.9 ^{CD}	4.1 ±2.2 ^{C}	4.8 ±1.7 ^{D}
MS	5.2 ±1.9 ^{BC}	4.6 ±2.0 ^{CD}	6.3 ±1.5 ^{A}	5.4 ±1.3 ^{AB}	4.9 ±1.6 ^{ABC}	5.8 ±1.4 ^{AB}
MM	4.8 ±1.9 ^{C}	3.9 ±2.0 ^{CDE}	5.8 ±1.5 ^{ABC}	4.8 ±1.7 ^{BC}	4.3 ±2.0 ^{AB}	5.4 ±1.6 ^{ABCD}
LS	5.1 ±2.0 ^{BC}	4.5 ±2.1 ^{CD}	6.0 ±1.5 ^{ABC}	5.2 ±1.5 ^{AB}	4.8 ±1.8 ^{AB}	5.6 ±1.5 ^{ABC}
LM	4.5 ±2.1 ^{C}	3.7 ±2.1^{DE}	5.6 ±1.8 ^{C}	4.9 ±2.0 ^{BC}	4.4 ±2.1 ^{AB}	5.4 ±1.7 ^{ABCD}
LH	3.8 ±1.9 ^{D}	3.1 ±1.8 ^{E}	5.5 ±1.6 ^{C}	3.6 ±1.8 ^{D}	3.0 ±2.0 ^{D}	4.8 ±1.4 ^{D}

For texture liking, only soups with small and soft particles were not perceived significantly different than the homogeneous samples. Flavour liking was affected less, as in this case, only soups with large and harder particles (LM and LH) were significantly different than the homogeneous soup.

For model gels, all the samples containing soft particles were overall liked as much as the homogeneous sample independent of particle size. However, when the particles had a larger fracture stress, a large decrease in palatability was obtained for all particle sizes. The lowest scores were found for samples containing the particles with the highest fracture stress (SH and LH), presenting the largest mechanical contrast.

We hypothesized that mechanical contrast within a single bite leads to enhanced palatability of complex foods due to prevention of adaptation of the sensorial stimulus. In this study, the incorporation of structural heterogeneities changed the sensory profile of model soups and gels, although the intra-oral variation did not enhance liking, but maintained or decreased palatability. Three possible reasons can be considered to explain these indicative hedonic findings. The first reason is that our initial hypothesis was false. Texture contrast might not be related to an enhanced palatability of foods, although the contrary has been suggested (Hyde & Witherly, 1993). The second reason is related to the combined effect of particle visibility and appearance, and consumer familiarity and expectations. Participants were allowed to see the heterogeneous appearance of the products, and no attempts were done to mask visual recognisability of particles. The presence of transparent spherical particles could have induced subjects to perceive the heterogeneous texture as a product defect. Similarly, the added particles might have evoked novel and unexpected sensations, since such particles (κ-carrageenan model gels without added flavour) are not commonly found in commercial products. The hedonic response was probably biased by the nature of embedded particles (gel-like) and their appearance (transparent). The third reason is that no aroma or tastants were added to the particles. This means that the particles required chewing effort without delivering flavour or taste. The negative effect on food palatability in this study design may be related to the combined effect of unexpected changes in the texture and flavour differences. These results suggest that mere mechanical contrast is not sufficient to enhance food appreciation of model soups and gels, but a combination of changes in the texture and flavour variations might be required to boost food liking.

3.3.2.3 Multivariate analysis combining sensory and hedonic data

Finally, PCA was used to investigate the relative relationship between different sensory descriptors in model soups and gels (**Figure 3.5A** and **3.5B**, respectively). When considering the PCA of the model soups (**Figure 3.5A**), PC1 and PC2 described a total of 73.25% of the variance between products. For the model gels, PC1 and PC2 account for 76.41% of the variance between samples.

For both matrices, a big cluster of descriptors was associated with heterogeneity perception related to the addition of particles. Lumpy, beady, chewy, hard, visual, and mouthfeel heterogeneity were highly correlated with each other and associated with the addition of medium and large particles (M- and L-). Incorporation of small particles of medium and high fracture stress (SM and SH) led to more gritty perception, whereas samples containing small and soft particles were closer to creamy and melting sensations. In case of model soups, liking pointed in the direction of creamy and melting sensations, and the homogeneous products were better liked. For the model gels, liking overall and liking texture pointed towards sweet sensations, whereas liking of flavour was associated with vanilla flavour. Creamy sensations played a minor role, even though the descriptor was located in the same quadrant of the graph as liked sensations. Cohesiveness and, in particular, elasticity were inversely correlated to grittiness.

Overall, the addition of particles moved the scores further away from the direction of liking, similar as found for the model soups. However, in the model gels, a chewable matrix, a decrease in the discriminability between medium- and large-sized particles was noticed. Confidence ellipses of gels containing medium-sized particles overlapped with gels containing large particles. The higher correlation of beady and lumpy (size-related attributes) in the model gels compared to the model soups indicates that subjects found it more difficult to perceive medium and large particles embedded in the semi-solid matrix compared to the liquid matrix. This suggests that the addition of particles in soups has a larger impact on the sensory profile compared to the addition of particles to a solid matrix. A semi-solid matrix has a larger ability to mask the perception of embedded particles. As a consequence, larger differences in particle sizes are required to trigger different sensory responses.

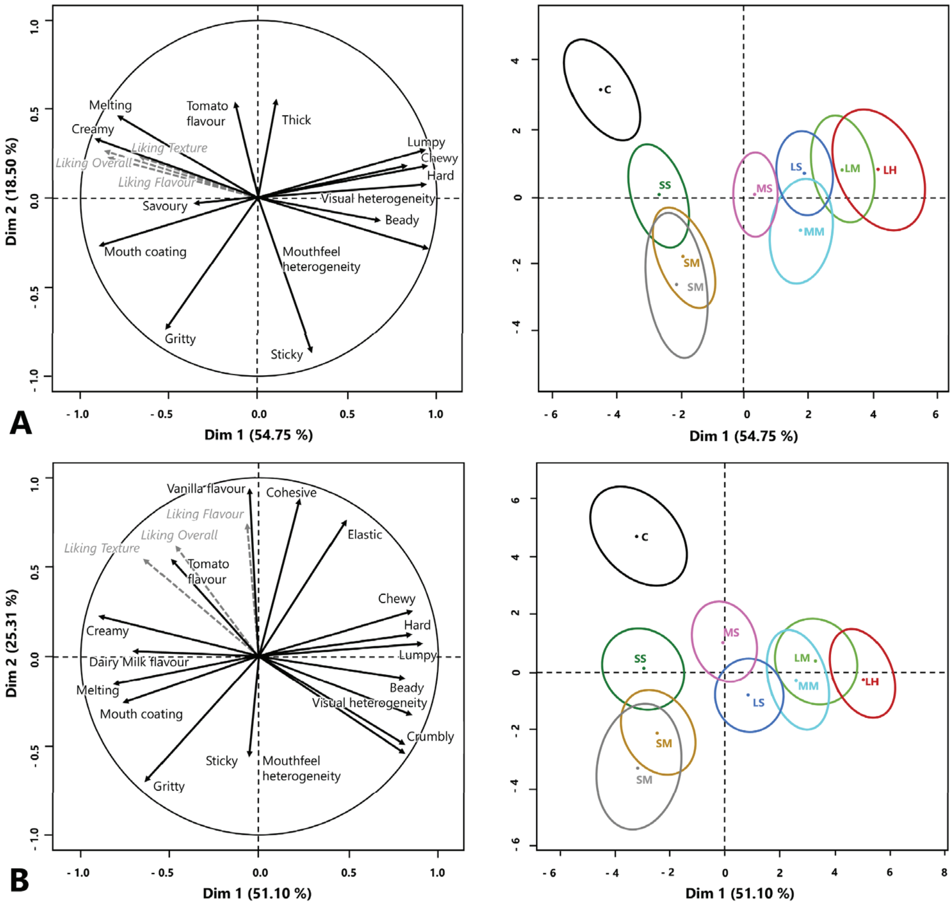


Figure 3.5. Principal Component Analysis on RATA intensity data for model soups (A) and model gels (B). Loading plots are presented on the left, whereas product maps including 95% confidence ellipses are located on the right. Liking scores are plotted as supplementary variables.

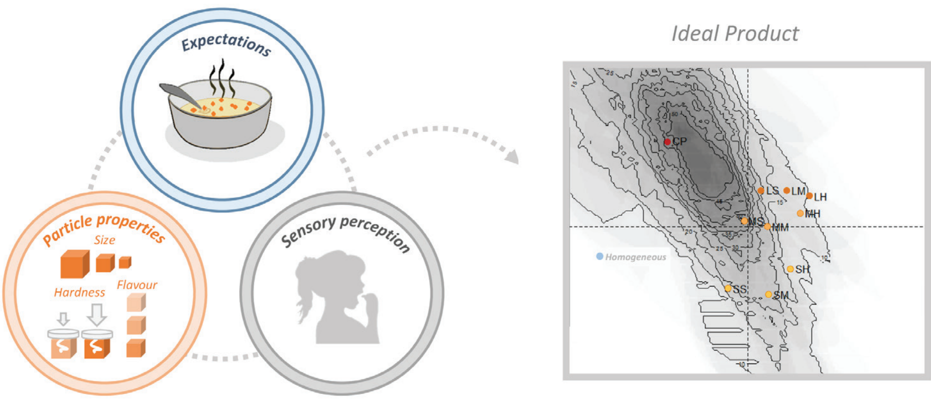
3.4 Conclusions

This study aimed to investigate the effect of size and mechanical properties of dispersed particles on sensory perception and hedonic response in model soups and model gels. Gel particles of three different sizes (0.79, 2.44 and 4.21 mm) and three levels of fracture stress (25, 100 and 250 kPa) were used to control heterogeneity. Particle shape, concentration, and nature of particles were kept constant. Sensory perception and liking of model soups and gels were found to be influenced by both the size and the fracture stress of the added particles. The type of descriptors selected was mainly affected by the particle size, whereas the intensity of the selected descriptors was determined by the fracture stress of the particles. In general, the addition of small and hard particles led to gritty sensations, whereas the addition of larger particles triggered more heterogeneity-related perception such as chewy, lumpy, and beady. The incorporation of mechanical contrast by adding κ-carrageenan model gels particles without flavour did not lead to an improvement of liking. We conclude that the sensory perception of heterogeneous foods can be changed by varying the size and the mechanical properties (fracture stress) of the embedded components. However, in our experimental design κ-carrageenan particles were probably perceived as an undesired artificial heterogeneity and their addition as mechanical contrast without flavour contrast did not positively contribute to liking. Further studies are required to better understand how particle flavour and consumer expectations contribute to appreciation of complex foods.

Chapter 4

AS GOOD AS EXPECTED?

HOW CONSUMER EXPECTATIONS AND ADDITION OF VEGETABLE PIECES TO SOUPS INFLUENCE SENSORY PERCEPTION AND LIKING



This chapter is based on:

Santagiuliana, M., van den Hoek, I.A.F., Stieger, M., Scholten, E., Piqueras-Fiszman, B., As good as expected? How consumer expectations and addition of vegetable pieces to soups influence sensory perception and liking. *Food & Function* 10, 2019, p. 665-680.

Abstract

This study investigated the effect of mechanical contrast and particle flavour concentration of carrot particles added to soups on expected and perceived sensations and liking. The properties of a chicken soup were varied by addition of real carrots, model carrots and model chicken particles differing in size, fracture stress, and/or carrot flavour concentration. The four aims of the study were: (1) To study the effect of mechanical contrast on expected and perceived sensations; (2) To investigate the role of particle carrot flavour concentration on perceived sensations and liking; (3) To study the effect of dis/confirmation of expected by perceived sensations on liking; (4) To investigate the consumer's preferences and ideal profile of soups. Expected sensory properties were affected by particle size: the larger the particles, the higher the expected intensities for hardness, chewiness, and crunchiness of soups. Perceived sensory properties were significantly influenced by size and fracture stress of carrot particles. Increasing flavour concentration in model carrot particles added to soups marginally influenced liking suggesting that flavour concentration in particles added to soups has a limited effect on liking. When model carrot particles were added to soups, expected sensory properties were confirmed by perceived sensory properties, and consequently liking did not change considerably. The congruency and familiar appearance of the model carrot pieces probably contributed to the confirmation of expectations. When model chicken pieces were added to soups, expected sensory properties were disconfirmed by perceived sensory properties leading to a significant decrease in liking. Soups containing medium-sized, soft carrot particles were the closest to the consumer's ideal product profile. To summarize, consumer expectations and physicochemical properties of chicken and carrot particles added to chicken soup contributed to perception and liking of soups. We conclude that the sensory product profile of common products such as soups can be optimised by addition of congruent and familiar particles that match consumer' expectations.

4

4.1 Introduction

The presence of contrasting mechanical properties in heterogeneous foods, such as soups with vegetable pieces, can lead to the perception of texture contrast. Texture contrast can provide intra-oral variation in perception, which could help to prevent adaptation to a sensorial stimulus. It has been suggested that texture contrast contributes to the high palatability of many composite foods (Santagiuliana et al., 2018; Szczesniak & Kahn, 1984).

Several studies have shown that the presence of components with contrasting mechanical properties within a food influences sensory perception and oral processing behaviour (Devezeaux de Lavergne et al., 2015; van Eck et al., 2019; van Eck et al., 2018). **Chapter 3** demonstrated that both size and fracture stress of gel particles added to liquid and semi-solid model foods influenced sensory perception. Using Rate-All-That-Apply (RATA), the researchers demonstrated that the size of added particles mainly determined the selection of applicable sensory attributes, whereas particle hardness (fracture stress, σ_F) determined perceived intensities of applicable attributes. Generally, small and hard particles determined gritty sensations, whereas larger particles triggered perceptions such as chewy, lumpy, and beady.

Laguna and Sarkar (2016) showed that size and hardness of gel beads embedded into model gels influenced oral processing behaviour. An increase in size and hardness of beads present in a gel matrix prolonged oral transit time, and changed the sensory profile towards less cohesive and softer compared to the profile of homogeneous gels. In model gels with embedded layers and seeds, it was shown that the level of structure breakdown was affected during oral mastication. Smaller and more broken-down particles were obtained with gels with higher texture complexity (Larsen et al., 2015, 2016; Tang et al., 2017). In addition, matrix characteristics have also been shown to affect oral processing behaviour of composite foods. When peanuts were embedded into different food matrices, mechanical properties of the matrix (gelatine gels and chocolate) altered breakdown of the embedded peanuts during mastication (Hutchings et al., 2011, 2012).

As a result of the presence of different components in foods, the spatial distribution of flavour compounds can also differ, affecting perception. A heterogeneous distribution of sucrose or salt led to an increase in sweetness or saltiness intensity, which might be accompanied by an increase in liking (Emorine et al., 2013, 2014, 2015; Mosca et al., 2010, 2012, 2015). Such effects are not limited to tastants, as a heterogeneous distribution of apple aroma in model gels also resulted in a higher perceived flavour intensity (Nakao et al., 2013). These boosted intensities in heterogeneous foods have been suggested to be related to a pulsatile stimulation that prevents adaptation of the receptor cells and might help to enhance the consumers' hedonic response.

Food palatability is not only related to food characteristics, but also to consumer expectations and related product ideals (Burgess, 2016; Tan et al., 2017; Tarancón et al., 2014; Tuorila et al., 1998; Wei et al., 2012; Worch, et al., 2014, 2013). Several studies demonstrated that expectations and matching of consumer's ideal product characteristics also determine consumer satisfaction (Burgess, 2016; Cardello, 1994; Cardello & Sawyer, 1992; Hurling & Shepherd, 2003; Piqueras-Fiszman & Spence, 2015; Worch et al., 2013, 2014). Consumer expectations are of primary importance in establishing food palatability since confirmation or disconfirmation of expectations can determine the acceptance or rejection of foods. Based on visual appearance, orthonasal olfactory cues, and descriptive information, consumers establish expectations that can largely influence sensory perception and liking (Ares et al., 2010; Cardello & Sawyer, 1992; Carrillo et al., 2012; Deliza & Macfie, 1996; Deliza et al., 1996). Front-of-pack health labels (e.g. now reduced in salt, healthy choices-tick logo) have been shown to significantly affect expectations and palatability in the case of chicken soups (Liem et al., 2012). Sensory and hedonic expectations of biscuits served with different nutritional claims ('low saturated fat content') and claims about the fat source ('with olive oil') were shown to influence the hedonic responses and perception of product healthiness (Tarancón et al., 2014). Such expectation-driven evaluation processes are particularly relevant for familiar food products as consumers can use an internal, imagined product with ideal properties as a reference (Booth et al., 1987; Worch et al., 2013).

In heterogeneous foods such as soups with added particles, even when no front-of-pack information or health claims are present, the mere visual appearance of particles provides cues on expected sensations and liking. **Chapter 3** previously showed that the addition of model gel particles to model soups and gels led to decrease in liking probably because particles were perceived as undesired, artificial heterogeneities that did not match consumer's expectations. These model gel particles did not contain any flavour nor resembled commercially available products. It was suggested that incorporation of mere mechanical contrast is not sufficient to enhance palatability of foods, but a combination of mechanical and flavour contrast might be necessary to enhance liking.

To summarize, while several studies have focused on the effect of food structural components with diverse mechanical properties and flavour distribution on oral processing behaviour and sensory perception, little is known about how these food modifications affect expected, perceived and ideal sensory properties of foods. Since the addition of particles provides specific visual cues which influence the expected sensory properties, these expectations might be confirmed or disconfirmed once the food is tasted. This (dis)confirmation might result in a profile that might move toward or away from the consumer's product ideal.

The overall aim of this study was to determine the effect of mechanical contrast and flavour concentration of carrot particles added to soups on expected and perceived sensations and liking. Real carrot, model carrot and model chicken particles differing in size, fracture stress, and/or carrot flavour concentration were added to chicken soups. To address the overall aim, the following aims were investigated: (1) To study the effect of mechanical contrast on expected and perceived sensations; (2) To investigate the role of particle carrot flavour concentration on perceived sensations and liking; (3) To study the effect of confirmation/disconfirmation of expected by perceived sensations on liking; (4) To investigate the consumer's preferences and ideal profile of soups. We hypothesize that the incorporation of particles with a familiar appearance that matches the consumer's expectations leads to an enhanced product palatability and that particle flavour intensity positively influences consumer hedonic response of heterogeneous foods.

4.2 Materials and Methods

4.2.1 Materials

Carrots were purchased from a local supermarket. Creamy chicken soup powders composed of "taste base mix" and "binding and garnishing mix" were provided by Unilever (Rotterdam, The Netherlands). Agar was purchased from Caldic Ingredients B.V. (Rotterdam, The Netherlands) and titanium dioxide from Pomona Aroma B.V. (Hedel, The Netherlands). Orange food colourant (Annatto WS 2.5%, E-160b) was kindly provided by Holland Ingredients (Meppel, The Netherlands). Matze crackers (Hollandia® Matzes B.V.) without salt and commercial creamy chicken soup were purchased from a local supermarket. All ingredients were food grade and samples for the sensory study were prepared under food safe conditions.

4

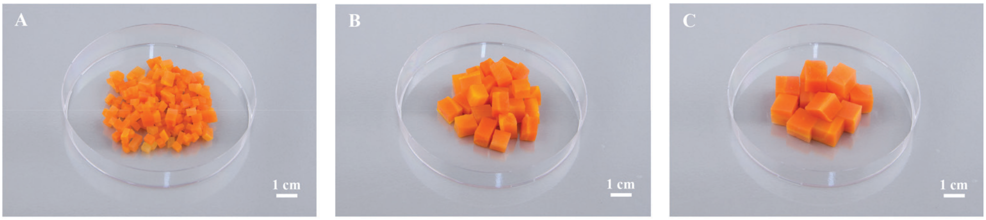


Figure 4.1. Real carrot particles varying in size: A. Small-sized cubes (3x3x3 mm); B. Medium-sized cubes (7x7x7 mm); C. Large-sized cubes (10x10x10 mm).

4.2.2 Sample preparation

4.2.2.1 Real carrot particles preparation

Real carrot cubes varying in size and fracture stress were prepared to investigate the effect of mechanical contrast caused by addition of familiar vegetable particles to soups on expected and perceived sensations (first objective). Carrots were peeled, washed, and cut into pieces of 20x20x60 mm. The resulting regularly shaped carrots were then vacuum sealed in plastic bags. Different heating conditions (sous vide) were applied to vary mechanical properties (fracture stress) of carrots: 95°C for 120 min, 90°C for 60 min or 85°C for 45 min to obtain soft, medium and hard carrot particles, respectively. This cooking method (sous vide) allowed to obtain rather similar flavour profiles for all carrots independent of the heating conditions. Afterwards, carrots were cooled down by placing them in an ice bath for 1h. Carrots were cut into cubes of 3x3x3, 7x7x7, and 10x10x10 mm using a mandolin (Michel BRAS, Laguiole, France) obtaining small, medium, and large particles, respectively (**Figure 4.1**). Carrot particles were stored at 4°C and used within 4 days after production for the determination of the mechanical properties or for sensory evaluation.

4.2.2.2 Model carrot particle preparation

Model carrot particles (carrot-flavoured agar gels, **Figure 4.2A**) were prepared to investigate the effect of addition of particles varying in carrot flavour concentration on perceived sensations and liking (second objective). To adjust the flavour intensity, carrot juice was first extracted from carrots with a juicer (Philips HR 1861, Eindhoven, The Netherlands). The juice was boiled in an open pan to approx. 66% (w/w) of its initial weight. Gels obtained from this juice were tasted by the researchers and consumers during feasibility tests (data not shown) and the flavour of the gelled juice was found to be closest to the flavour of real carrots. The concentration of this juice is referred to as 100% in the remainder of the paper. The resulting concentrated carrot juice was sieved (mesh size 63 µm) and stored at -20°C. Carrot model gels were prepared by combining concentrated carrot juice and water in different ratios to vary the flavour concentration from 0 to 100% (**Table 4.1**). Agar, TiO_2 and annatto were added to the mixtures to modify the colour of the gels. The two food colourants were added in such an amount to ensure an equal appearance of the gels and a good resemblance with the colour of real carrots.

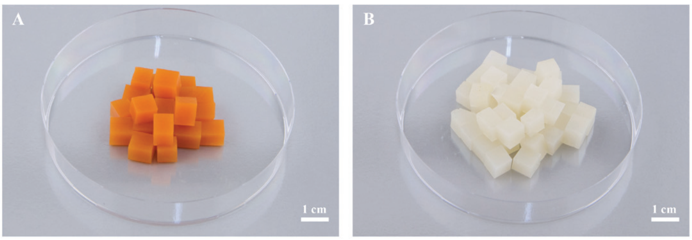


Figure 4.2. Model gel particles. A. Carrot gel particles (7x7x7 mm) B. Chicken soup-based gel particles (7x7x7 mm).

As described in **Table 4.1**, agar concentration determined fracture stress (σ_F: 40 or 100 kPa). The solutions were placed in a water bath at 95°C under continuous stirring for 45 min, and then poured in 30 ml syringes (Terumo, Leuven, Belgium). Samples were then cooled down by placing them on ice for 1 h. The carrot-flavoured gels were cut into cubes of 7x7x7 mm using a mandolin and stored at 4°C for a maximum of 4 days.

Table 4.1. Composition of model carrot gel particles and chicken soup-based gel particles varying in fracture stress and flavour intensity. The first letter in the sample code denotes the fracture stress (Soft, Medium), the numbers denote the flavour intensity of the carrot (0, 33, 66, 100 as zero, low, medium, high respectively) or the flavour of chicken soup (C).

Sample		Carrot juice (% w/w of aqueous phase)	Water (% w/w of aqueous phase)	Agar (% w/w)	TiO_2 (% w/w)	Annatto (% w/w)	Taste Base mix (% w/w)
Model carrot gels	S|0	5.0	95.0	1.42	0.04	0.3	-
	S|33	33.3	66.7	1.38	0.06	0.3	-
	S|66	66.6	33.4	1.41	0.07	0.3	-
	S|100	100.0	0.0	1.32	0.08	0.3	-
	M|0	5.0	95.0	3.05	0.04	0.3	-
	M|33	33.3	66.7	2.91	0.06	0.3	-
	M|66	66.6	33.4	2.99	0.07	0.3	-
	M|100	100.0	0.0	2.83	0.08	0.3	-
Chicken soup-based gels	S|C	-	100.0	1.66	0.05	-	1.36
	M|C	-	100.0	3.24	0.05	-	1.36

4.2.2.3 Chicken soup based gels preparation

Gels with the same flavour as the creamy chicken soup were made to prepare a soup that had mechanical but no flavour contrast. These particles were presented to the consumers as "chicken pieces" considering the chicken flavour profile. These model chicken particles as well as the real and model carrot particles were used to investigate the effect of confirmation/disconfirmation of expected sensations by perceived sensations on liking (third objective). Taste base mix powder, water, agar and TiO_2 were mixed in different ratios (**Table 4.1**) to obtain gels with different fracture stress (σ_F: 40 or 100 kPa). Gels were obtained by placing the samples in a water bath at 95°C under continuous stirring. After 45 min, the solutions were poured in 30 ml syringes (Terumo, Leuven, Belgium) and placed on ice for 1 h to cool down. The chicken soup-based gels were cut into cubes with a side length of 7 mm using a mandolin (Michel BRAS, Laguiole, France) (**Figure 4.2B**) and were stored at 4°C for a maximum of 4 days.

4.2.2.4 Commercial product particles

Particles (carrots, shallots, celery, and chicken pieces) present in commercially available creamy chicken soup were collected by sieving the soup and the particles were stored at 4°C. These particles differed in type, size, mechanical properties, and flavour, and were added to the same soup base. Considering the different types of particles, researchers ensured a homogeneous distribution of particles in soups through visual inspection during weighing of the product for each sample. The sample containing these particles will be referred to as "commercial product" (CP).

4.2.2.5 Soup preparation

Creamy chicken soup was used as a liquid matrix, to which different particles were added. The soup was prepared by dissolving taste base mix (1.37% w/w) and binding and garnishing mix (4.47% w/w) in water (94.16% w/w). The mixture was boiled for 3 min and thereafter the soup was placed on ice for 1 h to cool down. The soup was sieved and stored at 4°C. Before sensory assessment, the soup was re-heated in a water bath to 65°C. Just before serving, approx. 34 g heated soup was added to the serving cups already containing particles (15% w/w), which were previously left to equilibrate at 20°C for 1 h.

4.2.3 Study design

A total of 21 samples were investigated in the sensory study as shown in **Table 4.2**. A homogeneous product (O) without particles was used as a control sample, whereas the recombined commercial soup (CP) was included to compare the experimentally prepared samples with a product that is currently available on the market. The codes for all samples are reported in **Table 4.2**. The first letter of the sample code denotes particle size (Small, S-; Medium, M-; Large, L-), the second letter denotes fracture stress (Soft, -S; Medium, -M; Hard, -H), the third number or letter denotes carrot flavour concentration (Zero, |0; Low, |33; Medium, |66; High, |100) or the flavour of chicken soup (|C).

4.2.4 Sample characterization

4.2.4.1 Viscosity measurements

Rheological properties of the homogeneous soup without particles were determined using a Physica MCR 501 Rheometer (Anton Paar GmbH 501) at shear rates ranging from 1-1000 and 1000-1 s^{-1} in a time period of 2.50 min. The rheometer was operated in rotational mode with a C-CC17/T200/Ti cup (diameter of 18.08 mm) and a CC17/Ti cylinder (diameter 16.66 mm and length of 24.94 mm). A resting period of 2 min was used to obtain equilibrium before the soup sample was measured in triplicate at both 20°C and 65°C. The flow curves obtained from the measurement were fitted to the power law model

$$\eta = k\,\dot{y}^{(n-1)} \qquad (1)$$

where η is the viscosity (Pa.s), *k* is the flow consistency (Pa.s), $\dot{y}$ s the shear rate (s^{-1}) and n is the flow behaviour index (-). At 20°C, the creamy chicken soup presented a consistency *k* of 1.92±0.21 Pa.s and a flow behaviour index n of 0.430±0.001. At 65°C, the soup had a significantly lower consistency *k* of 1.13 ±0.19 Pa.s and a significantly higher flow behaviour index n of 0.46±0.02 than at 20°C ($p>0.05$). Such n-values are comparable to other commercially available spoonable products (**Chapter 3**).

4.2.4.2 Uniaxial compression test of macroscopic model carrot gels and real carrots

Uniaxial compression tests with a Texture Analyser (TA.XT plus, Stable Micro Systems-SMS) were performed to determine the mechanical properties of the real and model carrot particles and chicken soup-based gel particles. A probe with a diameter of 100 mm was coupled with a load cell of 50 kg. The crosshead velocity was set at 1.0 mm/s with a compression strain of 50%. Real carrot particles of 20x20x15 mm were used for this experiment and each sample was measured at least 12 times. The model carrot gels and chicken soup-based gels had a diameter of 23 mm and a height of 15 mm and at least six replicates were measured. Average true fracture stress and true fracture strain were calculated from the measurements. The uniaxial compression tests were performed at room temperature (20 ± 1°C).

4.2.4.3 Penetration test

Penetration tests were performed with a Texture Analyser (TA.XT plus, Stable Micro Systems-SMS) equipped with a 5 kg load cell. Medium sized (7x7x7 mm) real carrot particles (σ_F: 40, 100, 300 kPa) and model carrot particles (σ_F: 40, 100 kPa, only --|100 samples) were prepared and each sample type was measured six times. A custom-made wedge probe (35 mm height, 10 mm width, tip angle of 8.2°, 0.8 mm flat edge) was used and the materials were fractured with a speed of 1.0 mm/s to a maximum strain of 90% at room temperature. The force (N) was plotted against the distance (mm) and the area under the curve (AUC), the maximum peak force and the number of peaks were determined with Texture Exponent 32 (version 4.0.13.0).

Table 4.2. Samples codes for the soup samples.

Sample code		Particle size (mm)		Target fracture stress (σ_F)		Flavour concentration	
References	O	-	-	-	-	-	-
	CP	-	-	-	-	-	-
Real carrot particles	SS	Small	3x3x3	Soft	40 kPa	-	-
	SM	Small	3x3x3	Medium	100 kPa	-	-
	SH	Small	3x3x3	Hard	300 kPa	-	-
	MS	Medium	7x7x7	Soft	40 kPa	-	-
	MM	Medium	7x7x7	Medium	100 kPa	-	-
	MH	Medium	7x7x7	Hard	300 kPa	-	-
	LS	Large	10x10x10	Soft	40 kPa	-	-
	LM	Large	10x10x10	Medium	100 kPa	-	-
	LH	Large	10x10x10	Hard	300 kPa	-	-
Model carrot particles	MS|0	Medium	7x7x7	Soft	40 kPa	Zero	0%
	MS|33	Medium	7x7x7	Soft	40 kPa	Low	33.3%
	MS|66	Medium	7x7x7	Soft	40 kPa	Medium	66.6%
	MS|100	Medium	7x7x7	Soft	40 kPa	High	100%
	MM|0	Medium	7x7x7	Medium	100 kPa	Zero	0%
	MM|33	Medium	7x7x7	Medium	100 kPa	Low	33.3%
	MM|66	Medium	7x7x7	Medium	100 kPa	Medium	66.6%
	MM|100	Medium	7x7x7	Medium	100 kPa	High	100%
Chicken soup-based gel particles	MS|C	Medium	7x7x7	Soft	40 kPa	Chicken soup	-
	MM|C	Medium	7x7x7	Medium	100 kPa	Chicken soup	-

4.2.5 Sensory evaluation

4.2.5.1 Subjects

Seventy untrained consumers (n=70, 52 female/18 male, age: 18-31 yrs) were recruited for the study. Participants were selected based on self-reported criteria of nationality (European), age (between 18-35 years), and BMI (18.5-25 kg/m^2). Subjects were excluded in case of allergies, smoking habit, missing teeth (except wisdom teeth) or dental implants. They were requested to refrain from eating 1 h before the session. During the participant selection, participants were asked to rate their familiarity with chicken soup on a scale from 1 to 6 (1= unfamiliar; 6= very familiar) and their consumption habit for chicken soups (once a week, once a month, every 3 months, never). The latter parameter was used as extra selection criteria and only consumers who consumed chicken soup at least every 3 months were included in the study. Most panel members (51%) consumed chicken soup at least once every week, 40% at least once every month and only 9% of consumers fulfilled the minimum level required to join the study (at least every 3 months). A familiarization session was held, in which an explanation was provided on how to perform the sensory evaluation. Participants were naïve with respect to the experimental conditions and purpose of this study. All participants signed a consent form and received compensation for their participation.

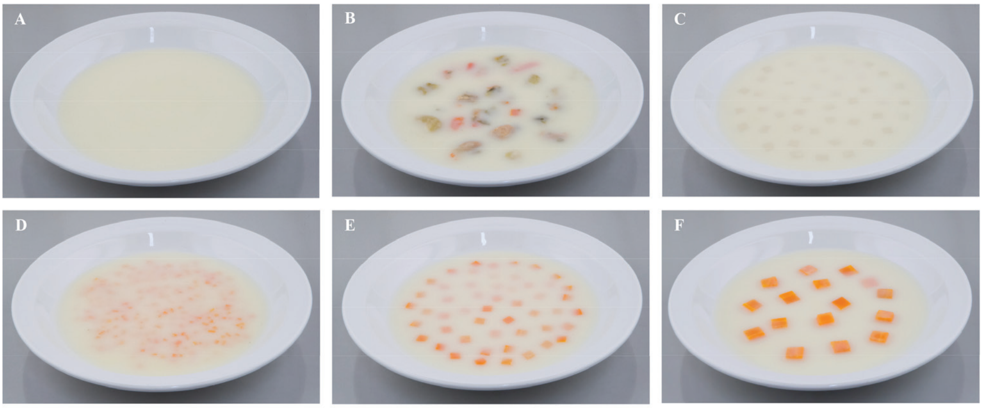


Figure 4.3. Pictures of the soup samples and their descriptions provided during the expected condition of the sensory study. A. Homogeneous creamy chicken soup; B. Creamy chicken soup with carrots, shallots, celery and chicken pieces; C. Creamy chicken soup with chicken pieces; D. Creamy chicken soup with small-sized carrot pieces; E. Creamy chicken soup with medium-sized carrot pieces; F. Creamy chicken soup with large-sized carrot pieces.

4.2.5.2 Sensory sessions

Evaluation of expected sensations

A two-step method (Expected-Perceived) was used to investigate expected and perceived sensations. During the first step, participants were provided with pictures of six soups (**Figure 4.3**, printed 1:1 scale) in combination with an objective and neutral descriptions of the soups. The descriptions are outlined in the caption of **Figure 4.3**. During this test session of approximately one hour, subjects viewed the pictures and were asked to evaluate the soups based on their expectations using a nine-point scale ranging from 'not' to 'very'. Participants first had to indicate expected hedonic responses on overall liking, flavour liking, and texture liking. Thereafter, participants were asked to rate expected intensity of 17 sensory attributes (**Appendix 4.1**). Attributes and their definitions were tested in a feasibility test (n=20), in which consumers reported that even the more technical attributes (e.g. chewiness) were understandable as also reported in other studies investigating food texture perception with consumers (Ares et al., 2010; Oppermann et al., 2017; van Eck et al., 2018). The pictures were presented in a monadic sequence and the order was counterbalanced.

Evaluation of perceived sensations and Ideal Profile Method

The second series of sessions started one week after and consisted of three test sessions distributed over three weeks. During each test session of approx. one hour, participants were given 7 out of 21 samples in a counterbalanced sequential monadic fashion (**Table 4.2**). Soups were provided with a written description as reported in the caption of **Figure 4.3**. Participants were asked to taste and evaluate the soups using the Ideal Profile Method and the nine-point scale of the expected condition (Worch et al., 2014, 2013). Participants first rated perceived hedonic responses and then perceived and ideal intensity of the provided sensory attributes on nine-point scales (**Appendix 4.1**). For this condition, subjects were asked to evaluate the samples visual particle size and visual thickness based on visual cues and product description. The other sensory attributes were evaluated after product consumption. When evaluating soups, subjects were instructed to make sure that both particles and soup were on the spoon. A waiting time of at least 1.5 min was set between the evaluation of the different samples and participants were instructed to rinse their mouth with water and eat some cracker. A brochure with definitions of all descriptors of all attributes was provided in all the test sessions.

4.2.6 Data analysis

All the data obtained instrumentally was analysed by Analysis of Variance (ANOVA) with the measured instrumental value as dependent variable. To address the first and second objectives, ANOVAs were performed on sample subsets with the data obtained from the perceived condition. Samples containing real carrots were tested considering the factors panellist, particle size, particle fracture stress and the interaction between particle size and particle fracture stress. Samples containing model carrots were tested considering panellist, particle flavour concentration, particle fracture stress and the interaction between particle flavour concentration and particle fracture stress as factors. The data obtained from the expected sensation, the perceived sensation and hedonic response were analysed separately by ANOVA with sample as fixed factor and panellist as random factor to allow a comparison between all products. When effects were significant, post-hoc pairwise comparisons were conducted with Tukey's HSD test ($p<0.05$). As this study aimed to compare all the different soups containing particles in relation to the reference samples (O, CP) and across samples subsets (real and model carrot particles), only the product/ sample effect will be used to discuss the comparisons between specific samples throughout the manuscript. To address the third objective, individual paired t-tests were performed for expectation and perceived sensation for the samples with the same description (**Figure 4.3**) to identify whether expectations were confirmed or disconfirmed. The samples containing model carrot particles from the evaluation of the perceived sensation were also analysed with Principal Component Analysis (PCA) to determine possible correlations between the samples and the investigated attributes. To address the fourth objective, Ideal Profile Method (IPM) was used to obtain an ideal product mapping that combines perceived and ideal intensities of the attributes for the different products. RStudio (version 3.4.0) with the use of the packages Factominer, SensomineR, Factoextra and RVAideMemoire was used for data analysis.

4.3 Results and Discussion

4.3.1 Mechanical properties

4.3.1.1 Carrot gels and real carrots

Real carrot particles had a true fracture stress of 39.8 ±6.3, 102.1 ±32.2 and 300.5 ±47.7 kPa (mean ± SD) for the soft, medium, and hard samples, respectively, which is close to the target values (σ_F: 40, 100, 300 kPa). Similarly, model carrot particles and chicken soup-based particles displayed true fracture stresses (soft σ_F: 38.5-43.9 kPa, SD: 0.4-1.3; medium σ_F: 97.8-110.7 kPa, SD: 0.7-3.1) that were comparable to the target values. No significant differences were found between true stress and strain values within the same targets. The true fracture strain of chicken soup-based particles and model carrot particles ranged from 0.39 to 0.45, whereas the true fracture strain of real carrot particles ranged from 0.27 to 0.41. This shows that model carrot agar gels were slightly less brittle than real carrots.

4.3.1.2 Penetration test

Penetration tests were performed on medium-sized (7x7x7 mm; M-) real carrot particles and model carrot particles and chicken soup-based particles to roughly simulate the action of the incisors during mastication. No significant differences in AUC were found between soft and medium (σ_F: 40, 100 kPa) model carrot particles (MS|100 and MM|100, 0.91 and 2.71 N.mm respectively) and real carrot particles (MS and MM, 6.52 and 10.76 N.mm respectively). Only real, hard carrot particles (σ_F: 300 kPa; MH, 42.61 N.mm) displayed a significantly higher AUC than all other samples. For the maximum peak force, real, hard carrot particles (σ_F: 300 kPa; MH, 11.28 N) displayed a significantly higher peak force than all other samples (0.51-1.79 N). Real carrot particles had a larger number of peaks (4.13-9.80) in the force-distance curves than the model carrot particles (1.29-2.14), probably due to their cellular and fibrous structure.

4.3.2 Products sensory evaluation

4.3.2.1 Effect of mechanical contrast on expected and perceived sensations

Expected sensations of soups containing mechanical contrast

To study the effect of mechanical contrast on expected sensations (first part of the first objective), the averaged expected scores obtained from the picture evaluation of samples containing real carrot particles and the reference samples (O and CP) were compared (**Table 4.3**). In the expected condition, participants assessed the samples based on visual cues and product description (**Figure 4.3**). As can be seen in **Table 4.3**, the expected scores for all attributes with the exception of mushroom flavour and sour were significantly different between soups. As an obvious consequence of particle absence, the homogeneous sample (O) presented the lowest values for particle-related attributes as visual and perceived particles size, crunchiness, hardness and carrot flavour. In general, the addition of particles led to an increase in the score of those attributes when particles could be observed in the sample picture or were mentioned in the picture description. For instance, the expected product hardness increased from 1.11 for homogeneous samples to 2.46-4.67 for heterogeneous samples. Similarly, the expected carrot flavour sensations increased from 1.16 for plain samples to 6.30-6.61 for samples containing carrot particles. At the same time, the addition of particles decreased the expected sensation of some matrix-related

Table 4.3. Mean expected intensity scores of different sensory descriptors per sample together with p-value (ANOVA).

	Visual particle size	Visual thickness	Chewiness	Creaminess	Crunchiness	Hardness	Mouth-coating	Mouthfeel heterogeneity	Perceived thickness
p-values	<0.001	<0.001	<0.001	0.013	<0.001	<0.001	0.003	<0.001	<0.001
O	0.01^{E}	4.20^{C}	1.17^{D}	6.23^{A}	1.06^{D}	1.11^{D}	5.54^{A}	1.73^{D}	4.27^{C}
RP	6.61^{A}	5.51^{A}	5.57^{A}	5.99^{AB}	3.40^{B}	4.46^{A}	5.46^{AB}	6.73^{A}	5.31^{A}
S-	2.11^{D}	4.44^{C}	2.93^{C}	5.64^{B}	2.44^{C}	2.46^{C}	4.93^{B}	4.80^{BC}	4.43^{BC}
M-	4.47^{B}	4.67^{BC}	3.96^{B}	5.76^{AB}	3.41^{B}	3.77^{B}	4.93^{B}	5.26B^{C}	4.57^{BC}
L-	6.57^{A}	5.20^{AB}	4.94^{A}	5.87^{AB}	4.30^{A}	4.67^{A}	5.11^{AB}	5.56^{B}	4.97^{AB}
M-|C	3.76^{C}	4.79^{BC}	4.04^{B}	6.03^{AB}	1.97^{C}	2.59^{C}	5.04^{AB}	4.61^{C}	4.60^{BC}

	Perceived particle size	Carrot flavour	Chicken flavour	Mushroom flavour	Salty	Savoury	Sour	Sweet
p-values	<0.001	<0.001	<0.001	0.874	<0.001	<0.001	0.062	<0.001
O	0.03^{E}	1.16^{C}	5.81^{B}	2.19	5.59^{A}	4.31^{C}	2.91	3.09^{BC}
RP	6.46^{A}	4.39^{B}	6.49^{A}	2.20	5.66^{A}	6.00^{A}	3.11	3.46^{B}
S-	2.13^{D}	6.30^{A}	4.91^{C}	2.06	5.01^{B}	4.51^{BC}	2.81	4.03^{A}
M-	4.39^{B}	6.20^{A}	5.16^{C}	2.10	4.97^{B}	4.59^{BC}	2.93	3.99^{A}
L-	6.70^{A}	6.61^{A}	4.89^{C}	2.19	4.89^{B}	4.61^{BC}	2.93	4.37^{A}
M-|C	3.63^{C}	1.23^{C}	6.74^{A}	2.11	5.67^{A}	4.96^{B}	2.71	2.93^{C}

attributes. Mouth-coating decreased for samples containing real small and medium carrot pieces, and chicken flavour decreased for all samples with added carrots.

An increase in the carrot particle size together with the description of increasing particle size led to a significantly higher expectation of particle size, visual thickness, chewiness, crunchiness and hardness of the soups. Particle size did not influence the expectations with respect to creaminess, mouth-coating, thickness, saltiness, savouriness, sweetness, carrot and chicken flavours. We acknowledge that such results might have been influenced by the provided descriptions which specified the particle size (caption of **Figure 4.3**). However, the descriptions of particle size together with the provided visual cues influenced the other expected sensations significantly (e.g. crunchiness, hardness and carrot flavour). Consequently, these results suggest that the visual cues together with product descriptions can significantly influence the expectations of particle-related attributes in heterogeneous soups. Such effect seems to be limited to attributes related to the particles and not to matrix related attributes. The commercial product (CP) showed the highest scores in expected intensities for mouthfeel heterogeneity, savouriness, particle size and chicken flavour. This was probably a result of the large variance of visible and described savoury particles (i.e. chicken pieces, shallots, herbs) present in the product. We conclude that the expected sensory profile of heterogeneous products based on visual and descriptive information can be influenced by the type and size of added particles and their descriptions.

Perceived sensations of soups containing mechanical contrast

The effect of mechanical contrast on perceived sensations (second part of the first objective) was studied by comparing the mean intensity scores obtained during the perceived condition of soups containing real carrot particles (SS to LH) and the reference soups (O and CP). P-values per sample considering the product effect are summarized in **Table 4.5** (texture attributes) and **Table 4.6** (flavour attributes). The specific influences of the investigated variables (i.e. panellist, particle size and hardness) on perceived sensations for samples containing real carrots are reported in **Table 4.4**.

Table 4.4. F-values obtained for the variables during the sensory perception of the samples containing real carrot particles (panellist, size, fracture stress and the interaction between size and fracture stress) and the variables during the sensory perception of the samples containing carrot model particles (panellist, flavour, fracture stress and the interaction between flavour and fracture stress). The superscript indicates significant differences between the samples (*=p<0.05, **=p<0.01, ***=p<0.001). The results are shown for the significant attributes and the hedonic responses.

Sample	Variables	Visual particle size	Chewiness	Crunchiness	Hardness	Mouthfeel heterogeneity	Particle size
Real carrot particles	Panellist	1.41*	3.54***	4.51***	4.37***	2.46***	1.60**
	Size	415***	38.2***	70.2***	78.2***	9.13***	374***
	Fracture stress	22.1***	110***	233***	221***	10.1***	25.0***
	Size: fracture stress	9.34***	0.949	0.789	1.32	0.291	11.6***
Model carrot particles	Panellist	3.84***	3.50***	2.81***	2.98***	3.99***	3.79***
	Flavour concentration	0.032	1.51	0.867	2.91*	0.141	0.122
	Fracture stress	1.44	95.9***	31.7***	89.3***	25.2***	2.97
	Flavour concentration: fracture stress	0.661	1.96	0.580	1.37	0.719	0.425

Sample	Variables	Carrot flavour	Sweet	Overall liking	Flavour liking	Texture liking
Real carrot particles	Panellist	2.94***	5.36***	2.97***	2.90***	1.73***
	Size	23.6***	0.649	5.16**	2.97*	3.36*
	Fracture stress	3.95*	0.509	5.62**	3.11*	4.58*
	Size: fracture stress	0.12	0.528	0.604	0.641	1.35
Model carrot particles	Panellist	2.48***	3.90***	3.63***	3.27***	3.02***
	Flavour concentration	18.5***	12.0***	3.88**	2.37	1.60
	Fracture stress	1.79	5.03*	0.072	1.97	6.09*
	Flavour concentration: fracture stress	0.053	0.318	0.491	0.914	0.065

From **Table 4.4**, it can be seen that variations in carrot size and hardness affected perceived sensations of several visual and textural attributes (visual particle size, chewiness, crunchiness, hardness, mouthfeel heterogeneity, particle size) significantly. The number of significantly different attributes increased when all products were compared (**Table 4.5**, product effect). For visual appearance and textural attributes (**Table 4.5**), 9 out of 10 descriptors significantly differed (p<0.05) between samples. Mouth-coating was the only attribute for which no significant differences between samples were found. From the post hoc test (**Table 4.5**), it can be seen that perceived sensations of visual thickness, creaminess, and perceived thickness differed significantly only between few pairs of products: SH and LS for visual thickness; O and SM for creaminess; MH/LM for perceived thickness. For all the other samples, these attributes were rated similarly. Since the liquid matrix was the same for all soups, these results indicate that the perceived sensations of these textural attributes were only slightly affected by addition of carrot particles varying in properties. On the contrary, particle-related descriptors (chewiness, crunchiness, hardness, mouthfeel heterogeneity) significantly differed only between more than two soups. These descriptors discriminated between up to 6 soups (i.e. chewiness discriminated 6 soups varying in particle hardness and particle type). This suggests that, as expected, the addition of particles varying in properties leads to differences in perceived sensations of particle-related attributes.

4

Perceived sensations of chewiness, crunchiness, hardness, and mouthfeel heterogeneity of the samples were influenced by particle size and fracture stress (**Tables 4.4** and **4.5**). An increase in particle size from small (S-) to large (L-) led to significantly higher perceived sensations of chewiness and hardness for samples containing particles with medium fracture stress (chewiness: SM 4.23, LM 5.14; hardness: SM 4.19, LM 5.21). An increase of fracture stress from 40 to 100 to 300 kPa (from -S to -H) led to significantly greater perceived intensities in several textural attributes (chewiness, crunchiness, hardness, and mouthfeel heterogeneity) for all particle sizes. For example, the perceived crunchiness in real carrots increased from 2.11-2.46 (SS to LS) for soft particles to 4.20-4.83 (SM to LM) for medium hard particles and it reached values of 5.69-6.33 for hard particles (SH to LH). Similarly, hardness perception also increased with fracture stress. These results are aligned with the results shown in **Chapter 3**. This study demonstrated that the perceived sensations of hardness and chewiness increased significantly when the particle fracture stress was increased from 20 to 100 or 250 kPa. The hardness perception of real particles was influenced by the size of the added particles, as small-sized particles (SM; 4.19) were perceived significantly less hard than large particles (LM; 5.21) with the same fracture stress. Such relations between particles size and hardness (firmness) were also observed in other studies on consumers preferences of drug delivery systems, in which women evaluated ovoid gels in their hands (Li et al., 2013; Zaveri et al., 2014).

Carrot flavour intensity of soups containing real carrots (**Table 4.4**) was influenced significantly by particle hardness and size, while sweetness was not influenced by these properties. The descriptors carrot flavour, chicken flavour, salty, savoury, and sweetness (**Table 4.6**) were found to be significantly different among all soups ($p<0.05$). The attributes showing no significant differences were mushroom flavour and sourness. The descriptors chicken flavour and savoury were found to be significantly higher only for the commercial product (CP) probably because it contained a range of different savoury ingredients such as shallots, celery, and chicken pieces in addition to carrots.

When real carrot particles were present in the soups, perceived sensations of carrot flavour were influenced by particle size. When particle size increased from small (S-) to large (L-), an increase in perceived carrot flavour was observed (**Table 4.6**). Fracture stress of particles did not affect carrot flavour perception, with the exception of soups containing small soft pieces (SS), which were perceived significantly less intense than small hard (SH) particles. We expected that carrot flavour perception would be affected by the total initial surface area of the particles. A larger total surface area would lead to more tastants and aroma compound release, resulting in a higher perceived intensity (Mosca et al., 2010, 2012; Sala & Stieger, 2013). As the particle concentration in this study was kept constant at 15% (w/w), the smaller particles had a larger initial surface area, and therefore expected to have the highest flavour intensity.

We observed that smaller particles did not lead to higher particle flavour perception, but instead, the large particles with the lowest initial surface area led to relatively higher carrot flavour perception. This indicates that the total initial surface area is not the main characteristic that determines particle flavour perception in heterogeneous foods. Carrot flavour perception may be better explained by taking into account differences in oral processing behaviour between small/soft (SS) and large/hard (LH) particles.

Table 4.5. Mean perceived intensity scores of different textural descriptors per sample together with p-value (ANOVA) obtained during the perceived condition. The superscript letters indicate significant differences between samples (p<0.05). The subscript sign indicates a positive (+) or negative (-) disconfirmation between perceived and expected intensities: - or + =p<0.05, -.-or ++ =p<0.01, - - -or +++ =p<0.001.

		Visual particle size	Visual thickness	Chewiness	Creaminess	Crunchiness	Hardness	Mouth-coating	Mouthfeel heterogeneity	Thickness	Particle size
p-values		<0.001	<0.001	<0.001	0.034	<0.001	<0.001	0.318	<0.001	0.002	<0.001
References	O	0.01^{G}	5.00^{AB}_{+}	1.10^{J}	5.96^{A}	1.01^{E}	1.01^{J}	4.93	1.74^{F}	4.61^{AB}	0.01^{F}
	CP	4.86^{BCD}_{---}	5.34^{AB}	4.20^{DE}_{---}	5.70^{AB}	1.93^{CD}_{---}	3.00^{EF}_{---}	5.27	6.13^{A}	4.96^{AB}	4.51^{BCD}_{---}
Real carrot particles	SS	1.74^{F}_{-}	4.86^{AB}	2.74^{FGHI}	5.24^{AB}	2.11^{CD}	2.34^{FGHI}	4.66	4.60^{DE}	4.46^{AB}	1.64^{E}_{--}
	SM	1.87^{F}	4.76^{AB}	4.23^{DE}_{+++}	5.04^{B}_{-}	4.20^{B}_{+++}	4.19^{D}_{+++}	4.27_{-}	5.24^{ABCD}	4.56^{AB}	1.77^{E}_{-}
	SH	1.67^{F}_{-}	4.70^{B}	5.11^{BC}_{+++}	5.23^{AB}	5.69^{A}_{+++}	5.76^{AB}_{+++}	4.73	5.86^{A}_{++}	5.01^{AB}	1.74^{E}_{-}
	MS	4.87^{BCD}	5.20^{AB}	3.20^{FG}_{-}	5.40^{AB}	2.24^{CD}_{---}	2.56^{EFGH}_{---}	4.86	4.67^{DE}	4.80^{AB}	4.81^{BC}_{++}
	MM	4.47^{B}_{++}	5.16^{AB}	4.90^{CD}_{+++}	5.37^{AB}	4.36^{B}_{++}	4.69^{CD}_{++}	4.79	5.27^{ABCD}	4.81^{AB}	5.16^{B}_{++}
	MH	5.01^{BC}_{+}	5.20^{AB}	5.99^{AB}_{+++}	5.19^{AB}_{-}	6.16^{A}_{+++}	6.21^{A}_{+++}	4.64	5.70^{AB}	5.14^{A}_{+}	5.17^{B}_{++}
	LS	7.44^{A}_{++}	5.60^{A}	3.41^{EF}_{---}	5.29^{AB}_{-}	2.46^{C}_{---}	3.03^{EF}_{---}	4.86	5.20^{ABCD}	5.10^{AB}	7.07^{A}
	LM	7.23^{A}_{+}	5.36^{AB}	5.14^{BC}	5.49^{AB}	4.83^{B}	5.21^{BC}	4.64	5.66^{ABC}	5.16^{A}	7.16^{A}
	LH	7.40^{A}_{++}	4.87^{AB}	6.13^{A}_{+++}	5.21^{AB}_{--}	6.33^{A}_{+++}	6.49^{A}_{+++}	4.81	5.93^{A}	5.07^{AB}	7.49^{A}_{+}
Model carrot particles	MS|0	4.31^{CDE}	5.07^{AB}	2.14^{I}_{---}	5.37^{AB}	1.63^{DE}_{---}	1.87^{HI}_{---}	4.91	4.10^{E}_{---}	4.67^{AB}	4.20^{CD}
	MS|33	4.20^{DE}	5.04^{AB}	2.23^{I}_{---}	5.40^{AB}	1.64^{DE}_{---}	1.97^{GHI}_{---}	4.76	4.10^{E}_{---}	4.60^{AB}	4.16^{CD}
	MS|66	4.14^{DE}	4.90^{AB}	2.29^{HI}_{---}	5.41^{AB}	1.57^{DE}_{---}	1.70^{IJ}_{---}	4.81	4.06^{E}_{---}	4.26^{B}	4.00^{D}
	MS|100	4.24^{DE}	5.13^{AB}	2.14^{I}_{---}	5.60^{AB}	1.54^{DE}_{---}	1.74^{IJ}_{---}	4.63	4.20^{E}_{---}	4.70^{AB}	4.13^{CD}
	MM|0	4.23^{DE}	4.97^{AB}	3.61^{EF}	5.31^{AB}	2.24^{CD}_{---}	2.94^{EF}_{-}	4.73	4.67^{DE}_{-}	4.80^{AB}	4.24^{CD}
	MM|33	4.34^{CDE}	5.04^{AB}	3.16^{FGH}_{-}	5.34^{AB}	2.00^{CD}_{---}	2.70^{EFG}_{---}	4.66	4.79^{BCDE}	4.76^{AB}	4.36^{CD}
	MM|66	4.47^{BCDE}	4.84^{AB}	3.17^{FG}_{--}	5.16^{AB}_{-}	2.17^{CD}_{---}	2.70^{EFG}_{---}	4.70	4.86^{BCDE}	4.61^{AB}	4.36^{CD}
	MM|100	4.36^{CDE}	5.01^{AB}	2.99^{FGHI}_{--}	5.31^{AB}	1.94^{CD}_{---}	2.37^{FGHI}_{---}	4.80	4.53^{DE}_{-}	4.53^{AB}	4.24^{CD}
Chicken soup-based particles	MS|C	3.83^{E}	4.69^{AB}	2.34^{GHI}_{---}	5.41^{AB}_{-}	1.63^{DE}	2.10^{GHI}_{-}	4.93	4.20^{E}	4.46^{AB}	3.76^{D}
	MM|C	4.00^{E}	4.99^{AB}	3.59^{EF}	5.31^{AB}_{-}	2.66^{C}_{++}	3.33^{E}_{++}	4.63	4.71^{CDE}	4.74^{AB}	4.01^{D}

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Table 4.6. Mean perceived intensity scores of different flavour descriptors per sample together with p-value (ANOVA) during perceived condition. The superscript letters indicate significant differences between samples (p<0.05). The subscript sign indicates a positive (+) or negative (-) disconfirmation between perceived and expected intensities: -or+=p<0.05, -.-or++=p<0.01, -.-.-or+++=p<0.001.

		Carrot flavour	Chicken flavour	Mushroom flavour	Salty	Savoury	Sour	Sweet
p-values		<0.001	<0.001	0.915	0.034	0.046	0.705	<0.001
References	O	1.23^{L}	4.21^{B}_{---}	3.03_{+}	5.14^{AB}	4.40^{B}	2.57	2.87^{G}
	CP	3.19^{K}_{---}	5.83^{A}_{-}	2.84	5.33^{A}	5.74^{A}	2.61	3.16^{DEFG}
Real carrot particles	SS	4.94^{GHIJ}_{---}	3.81^{B}_{---}	2.60	4.49^{B}_{-}	4.39^{B}	2.46	4.04^{ABCDE}
	SM	$5.77^{BCDEFGH}$	3.96^{B}_{--}	2.59	5.54^{AB}_{-}	4.53^{B}	2.31	$3.86^{ABCDEFG}$
	SH	6.04^{BCDEF}	3.86^{B}_{---}	2.50	4.49^{B}_{-}	4.37^{B}	2.40	3.94^{ABCDEF}
	MS	5.83^{BCDEFG}	3.81^{B}_{---}	2.37	4.81^{AB}	4.54^{B}	2.83	4.14^{ABCD}
	MM	6.34^{ABCD}	4.19^{B}_{--}	2.74	4.69^{AB}	4.56^{B}	2.44	4.07^{ABCDE}
	MH	6.27^{ABCDE}	3.97^{B}_{---}	2.57	4.83^{AB}	4.53^{B}	2.59	$3.81^{ABCDEFG}$
	LS	6.41^{ABC}	4.11^{B}_{-}	2.54	4.86^{AB}	4.57^{B}	2.64	4.11^{ABCD}
	LM	6.61^{AB}	4.07^{B}_{-}	2.77	4.91^{AB}	4.53^{B}	2.61	4.31^{ABC}
	LH	6.99^{A}	4.11^{B}_{-}	2.64	4.96^{AB}	4.59^{B}	2.63	4.09^{ABCD}
Model carrot particles	MS|0	4.20^{J}_{---}	4.00^{B}_{---}	2.56	4.93^{AB}	4.46^{B}	2.73	3.47^{BCDEF}
	MS|33	4.89^{HIJ}_{---}	4.07^{B}_{---}	2.63	4.81^{AB}	4.59^{B}	2.94	$3.60^{ABCDEFG}$
	MS|66	5.46^{DEFGHI}_{--}	3.96^{B}_{---}	2.54	4.76^{AB}	4.43^{B}	2.50	4.46^{AB}
	MS|100	5.59^{CDEFGH}_{-}	3.90^{B}_{---}	2.74_{+}	4.74^{AB}	4.31^{B}	2.61	4.63^{A}
	MM|0	4.07^{JK}_{---}	4.07^{B}_{---}	2.56	4.71^{AB}	4.30^{B}	2.77	3.27^{DEFG}_{-}
	MM|33	4.63^{IJ}_{---}	4.19^{B}_{--}	2.51	4.86^{AB}	4.26^{B}	2.73	3.41^{CDEFG}
	MM|66	5.31^{FGHI}_{--}	3.94^{B}_{---}	2.64	4.66^{AB}	4.41^{B}	2.71	4.06^{ABCDE}
	MM|100	5.34^{EFGHI}_{--}	3.93^{B}_{---}	2.57	4.70^{AB}	4.09^{B}_{-}	2.77	4.10^{ABCD}
Chicken soup-based particles	MS|C	1.24^{L}	4.40^{B}_{---}	2.83_{+}	5.07^{AB}_{-}	4.33^{B}_{-}	2.51	3.04^{EFG}
	MM|C	1.47^{L}	4.46^{B}_{---}	2.73	4.80^{AB}_{--}	4.33^{B}_{-}	2.67	3.00^{FG}

Large particles are expected to require more chewing cycles before swallowing and therefore they have a longer residence time in mouth. This might lead to higher flavour release and higher flavour perception. Oppositely, small soft carrot particles can be swallowed faster and possibly no or little chewing is required. This might lead to less flavour perception. Such hypothesis is supported by the findings of Kim et al. (2015) who found that small gel particles were chewed less than large gel particles. The lower chewing time of smaller gel particles resulted in fewer, larger fragments in their ready-to-swallow bolus, which leads to lower flavour intensity. These differences might also have been influenced by the variation in cooking times applied to prepare real carrots. However, considering soups containing large real carrots as examples, the different cooking times did not result in a significantly different perception of carrot flavour. We conclude that for heterogeneous soups with added particles, perceived flavour sensations depend on particle size and hardness (Lucas & Luke, 1983, 1984; Van Der Glas et al., 1987).

Saltiness was not significantly different between the homogeneous soup (O) and soups containing unsalted, real carrot particles or unsalted model carrot particles. Apparently, saltiness was dominated by the continuous liquid matrix and not by the dispersed particles. Even though the incorporation of unsalted particles (15% w/w) into a salty liquid matrix leads to a slight salt reduction (approx. 15%), saltiness did not decrease.

4.3.2.2 Role of particle carrot flavour concentration on perceived sensory properties and liking

To investigate the second study objective about the effect of addition of particles varying in flavour concentration on perceived sensations and liking, samples containing model carrot particles were compared (**Tables 4.4** and **4.6**). With increasing concentration of carrot flavour in model carrot particles perceived carrot flavour intensity increased (**Table 4.6**) as expected, even though a limited variation in perceived intensity between samples containing model carrots was observed (4.07-5.59). Samples containing model carrot particles without added carrot flavour (MS|0 and MM|0) were rated with an averaged perceived carrot flavour intensity of 4.20 and 4.07 respectively. These relatively high values for non-flavoured particles are probably an effect of the orange appearance of the model gels, as it is known that visual perception of colour influences flavour perception (Delwiche, 2004). The orange colour of the model particles was most likely associated with flavour of carrots and therefore carrot flavour was perceived even though it was not present. Carrot flavour concentration in model carrot particles influenced perceived sweetness (**Table 4.4** and **4.6**). Samples with soft model carrot particles with zero flavour concentration (MS|0) scored significantly lower in sweetness than samples with high flavour concentration (MS|100).

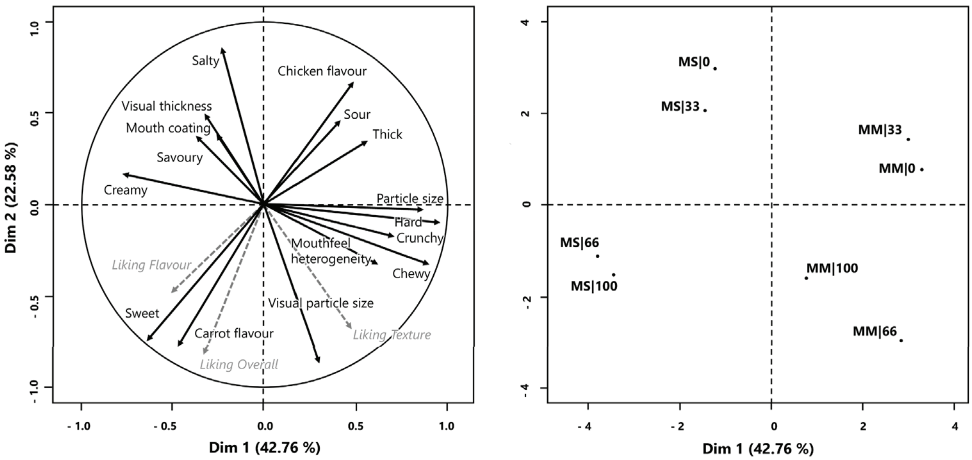


Figure 4.4. Principle Component Analysis on the data for the soup samples containing model carrot particles. The variables factor map is present on the left, whereas the individuals factor map is present on the right. Liking scores are plotted as supplementary variables.

This can be explained by the presence of sugars in carrots. For non-flavoured gels (MS|0), the absence of added sugars leads to a lower sweetness intensity. Furthermore, as no significant differences were observed in perceived sensations of chewiness, crunchiness, hardness, and mouthfeel heterogeneity between samples containing model carrot particles varying in flavour concentration, we conclude that changes in flavour particle concentration (--|0, --|33, --|66, --|100) do not influence texture perception of dispersed particles.

Figure 4.4 reports the PCA analysis for samples containing model carrot particles, which was performed to check the relation between product characteristics, perceived sensations and hedonic responses (second objective). In **Figure 4.4**, the first dimension

(42.76%) was explained by differences in fracture stress between the added particles. The attributes chewiness, crunchiness, hardness, and mouthfeel heterogeneity were highly correlated and associated with an increase in fracture stress (MS|- to MM|-). The second dimension (22.58%) describes the variation in flavour concentration of the added particles. The descriptors carrot flavour, sweetness and overall liking were associated with an increase in flavour concentration (M-|0 compared to M-|100). The flavour concentration of the model carrot particles influenced perceived sensations of carrot flavour, although the difference was found to be significant for overall liking only when the flavour concentration effect was considered for samples containing model carrot particles (**Table 4.4**). On the contrary, no significant differences in overall liking were found when soups containing particles varying in flavour concentration were compared to all the tested soups (**Table 4.6**). Considering that the overall liking revealed a limited variation between soups ranging from 5.00 to 5.63, we conclude that flavour concentration of dispersed particles seems to play a minor role in establishing the hedonic response of soups with added particles.

4.3.2.3 Effect of confirmation/disconfirmation of expected sensations by perceived sensations on liking

In both **Table 4.5** and **4.6**, the values for perceived intensity of both model and real particles were compared with the expected ones to investigate the effect of (dis)confirmation of expected sensations by perceived sensations on liking (third objective). Subscript signs indicate whether consumer expectations were positively (+; perceived value is higher than expected) or negatively (-; perceived value is lower than the expected) disconfirmed by perceived sensations. The absence of signs shows that expectations were confirmed, thus no differences between expected and perceived sensations were present.

As the evaluation of the visual particle size is based on visual clues, expected and perceived intensities should match. However, consumers' expectations were disconfirmed for small (S-) and large (L-) real carrot particles (**Table 4.5**). For soups containing small real carrot particles (S-), expectations of visual particle size were negatively disconfirmed (perceived value is lower than the expected) for two out of three samples and, therefore, participants expected larger particles based on the pictures. For the soup containing large real carrot particles (L-), the expected visual particle size was positively disconfirmed, suggesting that consumers expected smaller particles upon consumption. The commercial product (CP) was also negatively disconfirmed in terms of expectations of visual particle size as subjects expected larger particles from the pictures.

Particle size largely influenced consumer expectations for most textural attributes (**Table 4.5**). The expected sensations of chewiness, crunchiness, and hardness increased upon increasing particle size (S- to L-), which led to some disconfirmations of expectations for the soups containing real carrot particles. Considering such textural attributes, expectations for samples containing medium (small size SM and medium size MM) and hard particles (small size SH, medium MH, and large LH) were positively disconfirmed, whereas expectations for samples with soft medium- and large-sized (MS, LS) were negatively disconfirmed. We suggest that consumers might have based their expectations of these attributes on the estimated effort required for mastication of soups with these particles as a function of particle size. Therefore, small carrot particles (S-) might have been considered to require less effort during mastication and this would explain the relatively low expected intensities for the associated textural attributes leading to positive disconfirmation of expectations. Instead, larger particles were expected to require a higher oral manipulation (chewiness) and effort (hardness) leading to negative disconfirmation of expectations.

Most samples containing model carrot particles presented negative disconfirmation of expectations for the attributes chewiness, crunchiness, hardness, and mouthfeel heterogeneity. Soups containing medium-sized real carrot particles (M-) and model carrot particles (M-|-) differed in perceived sensations of chewiness, crunchiness, and hardness (**Table 4.5**). For these attributes, the presence of real carrot particles led to overall higher intensities than the respective model gel particles. The discrepancy in these perceived sensations between real carrot particles and model carrot particles can be related to the different microstructure of the two particles due to the cellular structure of real carrots. This is observed by the difference in the fracture properties. Upon penetration with a wedge, the real carrot particles were found to be mechanically harder (larger AUC and higher maximum peak force) than the model carrot particles, even though the fracture stresses measured by uniaxial compression are similar. The perceived sensations were found to be stronger related with the outcomes of this penetration test than with the results from the fracture stress measured by uniaxial compression (positive correlations between number of peaks and perceived chewiness (R^2=0.971), crunchiness (R^2=0.967), hardness (R^2=0.967), and mouthfeel heterogeneity (R^2=0.979). This difference in textural diversity and fracture characteristics between the model carrot particles and real carrot particles influenced the perceived sensations accordingly and led to a mismatch with the consumer' expected textural profile of carrots. This suggests that consumers are sensitive to variations in the expected texture profile of familiar products (i.e. carrots) even when these are dispersed in a liquid matrix.

For model carrot particles with 100% flavour concentration, expectations in terms of carrot flavour were negatively disconfirmed, which means consumers expected a higher carrot flavour than what they actually perceived (**Table 4.6**). On the contrary, expectations of carrot flavour for real carrot particles were confirmed, with the exception of samples containing small soft pieces (SS). For this sample, the expected intensity was higher than the actual one. This observation supports the idea that small soft carrot particles require low chewing and this results in a lower flavour perception. The expectation of the descriptor chicken flavour was negatively disconfirmed for all the samples. We can explain such negative disconfirmation considering the description "creamy chicken soup" that was provided for all soups. Specifically, this information could have created high expectations for chicken flavour and/or presence of chicken pieces, which was not perceived as expected.

No significant differences were found (**Table 4.7**) for overall liking between samples containing model carrot particles (M-|-) and real carrot particles (M-). On the other hand, chicken soup-based particles (MM|C) were rated significantly lower than the other samples in liking overall and texture. We relate their reduced palatability to a negative disconfirmation of expectations, especially of texture liking, chewiness and chicken flavour (**Table 4.5** and **4.6**). Since such particles were described as "chicken pieces", both appearance and texture of gels were perceived considerably different from actual chicken pieces. Therefore, the discrepancy between expected and actual perceived texture sensations for chicken soup based gel particles resulted in decreased hedonic scores compared to the carrot samples, even though their mechanical properties were comparable to those of model carrot particles. For model carrot particles (MS|100, MM|100), the appearance was satisfactorily close to the one of real carrots and did not result in a decrease in liking. We conclude that particle appearance and its match with consumer's expectation largely determine the palatability of heterogeneous soups (third objective). We conclude that relatively small differences between the expected and perceived sensory profile of soups with added carrot particles do not necessarily result in decreased liking (e.g. model carrot particles). When the discrepancy between the expected and perceived profile increases (i.e. chicken soup based gels), it leads to a negative contrast effect.

4.3.2.4 Consumer's preferences and ideal profile of soups

To achieve the fourth and final objective of the study, product likings of expected and perceived sensations for soups containing real carrot particles (SS to LH) and the reference samples (O and CP) were compared to the ideal product profile. The averaged values for overall liking, flavour liking, and texture liking in the expected and perceived conditions are reported in **Table 4.7**. The commercial product (CP) scored the highest average values for all forms of liking in both tested conditions. The other samples containing particles scored significantly lower expected likings than the commercial product. The plain sample (O) and samples containing large carrots presented the lowest expected overall liking scores. Therefore, consumers expected to like products that contained a variety of particles (CP) more, followed by samples with added small-medium carrot particles. In the perceived condition, liking overall was not significantly different between the commercial samples and samples containing small/medium (SM), medium/soft (MS) and medium/medium (MM) real carrots. In terms of perceived liking texture, no significant differences were found between the real product (CP) and samples with low and medium hard particles (SS, SM, MS, MM, and LS).

Table 4.7. The p-values and average expected and perceived liking scores for the different soup samples obtained with ANOVA. The superscript letters indicate significant differences between the samples ($p<0.05$). The subscript sign indicates a positive (+) or negative (-) disconfirmation between the perceived and expected intensities: -or+=p<0.05, -.-or++=p<0.01, - - - or +++=p<0.001.

		Overall Liking		Flavour Liking		Texture Liking	
		Expected	Perceived	Expected	Perceived	Expected	Perceived
p-values		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
References	O	4.40 ^{C}	5.56 $^{BCD}_{+++}$	5.21 ^{C}	5.90 $^{ABC}_{+}$	4.37 ^{C}	4.99 ^{CDEFG}
	CP	6.43 ^{A}	6.73 ^{A}	6.46 ^{A}	6.80 ^{A}	6.23 ^{A}	6.33 ^{A}
Real carrot particles	SS		5.69 ^{BCD}		5.77 ^{BC}		5.49 ^{ABCDE}
	SM	5.26 ^{B}	6.13 $^{ABC}_{+++}$	5.64 ^{BC}	6.29 $^{AB}_{++}$	5.17 ^{B}	5.77 $^{ABCD}_{+}$
	SH		5.61 ^{BCD}		5.77 ^{BC}		5.19 ^{BCDEF}
	MS		6.04 $^{ABC}_{+++}$		6.01 ^{ABC}		5.84 $^{ABC}_{+}$
	MM	5.23 ^{B}	6.30 $^{AB}_{+++}$	5.56 ^{BC}	6.27 $^{AB}_{++}$	5.20 ^{B}	6.09 $^{AB}_{++}$
	MH		5.59 ^{BCD}		5.74 ^{BC}		5.11 ^{BCDEF}
	LS		5.67 $^{BCD}_{++}$		5.79 ^{BC}		5.31 ^{ABCDEF}
	LM	4.83 ^{BC}	5.64 $^{BCD}_{++}$	5.33 ^{BC}	5.77 ^{BC}	4.91 ^{BC}	5.36 ^{ABCDEF}
	LH		5.34 ^{CD}		5.57 ^{BCD}		5.13 ^{BCDEF}
Model carrot particles	MS|0		5.03 ^{DE}		5.29 ^{CD}		4.44 $^{FGH}_{-}$
	MS|33		5.29 ^{CD}		5.71 ^{BC}		4.64 ^{EFGH}
	MS|66		5.36 ^{CD}		5.51 ^{BCD}		4.71 ^{EFGH}
	MS|100	5.23 ^{B}	5.63 ^{BCD}	5.56 ^{BC}	5.81 ^{BC}	5.20 ^{B}	4.90 ^{CDEFGH}
	MM|0		5.00 ^{DE}		5.10 ^{CD}		4.77 ^{DEFGH}
	MM|33		5.17 ^{DE}		5.33 ^{CD}		5.07 ^{BCDEFG}
	MM|66		5.56 ^{BCD}		5.69 ^{BCD}		5.07 ^{BCDEFG}
	MM|100		5.44 ^{BCD}		5.47 ^{BCD}		5.16 ^{BCDEF}
Chicken soup-based particles	MS|C	4.94 ^{BC}	4.90 ^{DE}	5.81 ^{B}	5.40 ^{BCD}	5.20 ^{B}	4.07 $^{GH}_{--}$
	MM|C		4.33 ^{E}		4.77 $^{D}_{---}$		3.89 $^{H}_{---}$

We suggest that the sample characteristics of medium particle size (M-) and moderate particle fracture stress (-S or -M) were the most familiar and congruent with the definition consumers had of creamy chicken soup. This resulted in relatively high hedonic responses for such samples.

Such explanation is supported by the outcome of the Ideal Profiling Method (IPM). This method was used to combine the perceived sensation intensities with the ideal intensities of the investigated attributes for the different products. The IPM provides an extended comparison of the tested soups with the consumer' ideal product. The ideal product might not be necessarily present among the evaluated soups. Therefore, the comparison between perceived sensations and consumer's ideal product provides a complete picture of the consumer's expectations towards the investigated soups, providing guidelines for specific products' improvement (Worch et al., 2013).

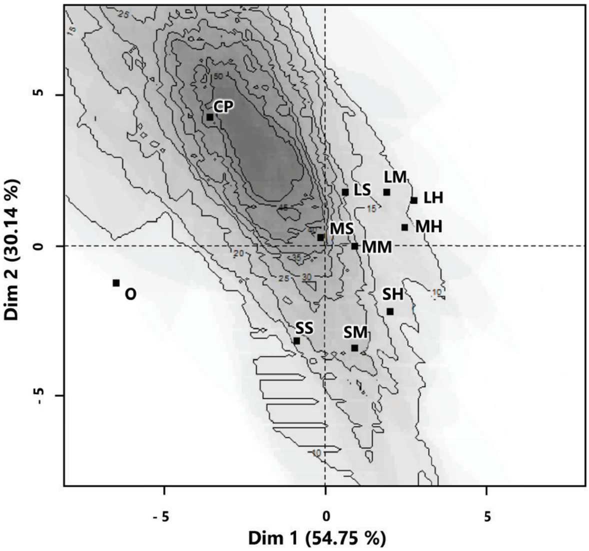


Figure 4.5. The ideal mapping including the reference samples (O and CP) and the samples containing real carrot particles (SS to LH).

Figure 4.5 presents the ideal mapping based on overall liking. It can be seen that the commercial product (CP) was closest to the ideal area (darkest area). This result is in line with the observations of the perceived liking where the commercial product displayed relatively high average liking scores, suggesting that the commercial product was effectively close to the consumer' ideal product. These results could be explained by three effects: (1) the commercial product is the result of extensive optimization for liking; (2) the commercial product was the most familiar (4.61±0.97 on a scale from 1 to 6) and most congruent with the definition of creamy chicken soup for the consumers; (3) a combination of the previous two points.

Although the commercial product was closer to consumer's ideal, some of the samples containing real carrot particles (SM, MS, MM) were not significantly different in terms of overall liking. The homogeneous sample (O) was outside the ideal area and this implies that heterogeneous samples containing real carrot particles were closer to the consumer' ideal than the homogeneous sample. This was also confirmed by the various panellists in a separate questionnaire; 85% of the participants corresponded to have a higher preference for the heterogeneous samples. Among the heterogeneous products with added carrots, the consumers' ideal product was closer to samples containing carrot particles with a low/medium fracture stress than a high fracture stress. Specifically, samples containing pieces with moderate fracture stress (σ_F: 40, 100 kPa) and a medium size (7x7x7 mm) were preferred. We suggest that the consumers' expectations matched the properties of the product as consumers might expect vegetables to become softer when they are present in a soup. We conclude that for the development of products with appropriate texture combinations, the mechanical properties of the different components providing texture contrast should match the product consumers' expectations to improve product palatability.

4.4 Conclusions

This study aimed to examine the effect of mechanical contrast and particle flavour concentration in soups on their expected and perceived sensory properties and liking, as well as on ideal product. Addition of carrot particles varying in size and fracture stress to soups significantly influenced the expected and perceived sensory properties. Particle size mainly influenced the expected textural attributes (chewiness, crunchiness and hardness) and flavour perceived sensations (carrot flavour). An increase in fracture stress (from 40 to 300 kPa) resulted in higher intensities of chewiness, crunchiness, hardness, and mouthfeel heterogeneity. A variation in flavour concentration (0, 33, 66, 100%) of added model carrot particles did not result in a significant difference in the hedonic response for particle containing soups. The addition of particles with an unfamiliar appearance and texture profile (chicken soup based gel particles) significantly decreased liking of the soup. Products with moderate mechanical contrast due to the presence of carrot particles of medium size (7x7x7mm) and low or medium hardness (σ_F: 40, 100 kPa) were closest to an ideal profile and resembled the commercial product the most in terms of liking. We conclude that addition of congruent and familiar particles that match consumer' expectations changes positively the sensory product profile of a common product and might enhance the consumer hedonic response.

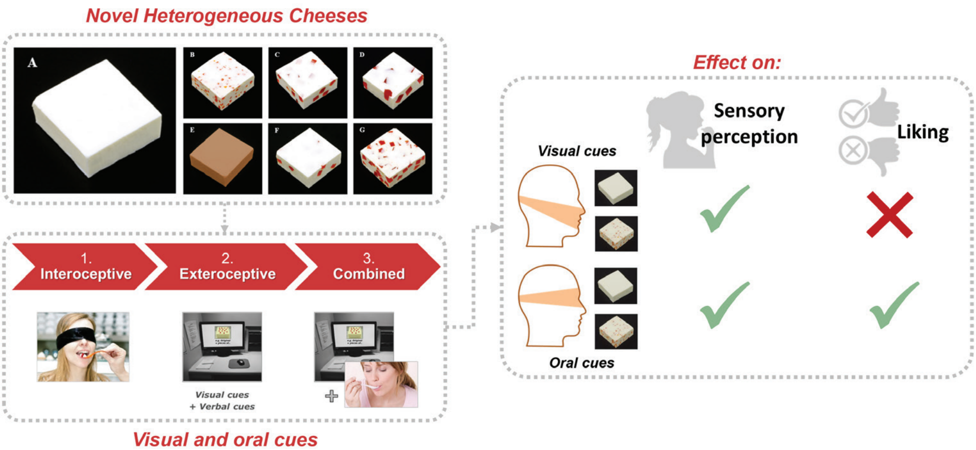
Appendix 4.1. Definition of descriptors of all sensory attributes per category (appearance, texture, flavour) used during the sensory study.

Descriptor	Definition
Appearance	
Visual particle size	Observation of the particle dimension on a scale from small to large.
Visual thickness	Expected force required to deform the sample and the perceived resistance to flow.
Texture	
Chewiness	The amount of work required to masticate the sample (or its components) into a state ready for swallowing.
Creaminess	Sensation of a thick, smooth and velvety texture in the mouth.
Crunchiness	Making a loud sound when chewed or crushed.
Hardness	Force required to compress and/or break the sample (or its components) between the teeth.
Mouth-coating	Sensation of a layer covering the mouth (film sensation inside the mouth).
Mouthfeel heterogeneity	Perception of texture contrast in the mouth. Sensory perception of different structures in the mouth during consumption (i.e. one sample contains soft and hard parts).
Particle size	Perception of the particles dimension in the mouth on a scale from small to large.
Thickness	Force required to deform the sample and the perceived resistance to flow.
Flavour	
Carrot flavour	Perception of carrot aroma.
Chicken flavour	Perception of chicken aroma.
Mushroom flavour	Perception of mushroom aroma.
Saltiness	Perception of a salty flavour in the mouth (salt-like).
Savouriness	Perception of glutamate (umami), spices, and herbs (broth-like).
Sourness	Perception of a sour flavour in the mouth.
Sweetness	Perception of a sweet flavour in the mouth (sugar-like).

Chapter 5

DON’T JUDGE NEW FOODS BY THEIR APPEARANCE!

HOW VISUAL AND ORAL SENSORY CUES AFFECT SENSORY PERCEPTION AND LIKING OF NOVEL, HETEROGENEOUS FOODS



This chapter is based on:

Santagiuliana, M., Bhaskaran, V., Scholten, E., Piqueras-Fiszman, B., Stieger, M., Don’t judge new foods by their appearance! How visual and oral sensory cues affect sensory perception and liking of novel, heterogeneous foods. *Food Quality and Preference* 77, 2019, p. 64-67.

Abstract

This study investigated how exteroceptive and interoceptive cues influence sensory perception and liking of novel, heterogeneous foods. Twelve heterogeneous cheeses were prepared by adding bell pepper pieces to homogeneous processed cheese matrices. Bell pepper pieces differed in size, hardness, and concentration. Consumers (n=73) evaluated cheeses in three conditions. In the first condition, subjects tasted cheeses and rated them on sensory properties and liking while being blindfolded (interoceptive condition). In the second condition, participants evaluated expected sensory properties and liking of cheeses presented as pictures together with product descriptions (exteroceptive condition). In the third condition, consumers tasted and evaluated cheeses while visual cues and product descriptions were provided (combined condition). The hardness and concentration of bell pepper pieces predominantly determined variations in sensory perception in the interoceptive and combined conditions, whereas bell pepper size or concentration influenced expected sensory properties in the exteroceptive condition the most. Consumers expected to like the cheeses with small-medium sized bell pepper pieces the most. However, from the other conditions, we observed that piece size does not play a role in determining liking, and that cheeses with soft pieces were actually preferred most. From the comparison of the three conditions, we conclude that both visual and oral sensory cues influence texture and flavour perception of heterogeneous cheeses. Consumers' liking was not influenced by the cheese's exteroceptive cues during the combined condition. In contrast, interoceptive cues as hardness played a large role in determining variations in consumer's hedonic responses. We conclude that for novel, heterogeneous foods liking after consumption is determined by textural product properties and depends to a large extent on the confirmation of consumers' sensory expectations.

5

5.1 Introduction

The acceptance of novel foods is determined by factors pertaining to both products and consumers (Szczesniak, 2002). From a product perspective, properties such as visual appearance, texture, and flavour are of primary importance to establish consumer sensory and hedonic responses (Pascua et al., 2013; Wei et al., 2012; Wilkinson et al., 2001; Zellner et al., 2010). Such responses are mediated, however, by consumer physiological and psychological factors as well as socially and culturally learned expectations (Piqueras-Fiszman & Spence, 2015; Shankar et al., 2009; Tan et al., 2017; Tuorila et al., 1998). To successfully design novel food products, the dynamic interrelationship between these complementary aspects of food consumption should be taken into consideration.

The introduction of particles into a product is a common strategy used to create novel food products. The addition of macroscopic particles (i.e. pieces of vegetables or fruits, chocolate chips, nuts) provides the product with a new appearance, texture, and sensory profile. A composite food with dispersed particles often presents contrasting flavours and textures within a single bite. This contrast in flavours and textures might establish an intra-oral variation in perception that could help to prevent adaptation of the sensory stimulus and lead to an enhanced palatability (Hyde & Witherly, 1993; Szczesniak & Kahn, 1984). Soup with pasta and vegetable pieces and yoghurt with granola or fruit pieces are examples of commonly consumed heterogeneous composite foods that are well appreciated by consumers. The presence of structural heterogeneities not only influences the dynamic sensory perception (Devezeaux de Lavergne et al., 2015; Emorine et al., 2014, 2015; Santagiuliana et al., 2018; Tanget al. 2017; van Eck et al., 2018), but it also affects food oral processing behaviour and related satiation responses (Laguna & Sarkar, 2016; Larsen et al. 2016a, 2016b; Tang et al., 2016; van Eck et al., 2019).

In our previous studies, we investigated the effect of addition of particles on perception of model and commercial foods (**Chapters 3** and **4**). We demonstrated that changes in size and fracture stress (hardness) of particles cause large differences in sensory profiles in model gels and soups. When unfamiliar gel pieces were added to such foods, liking of heterogeneous products decreased. However, when congruent and familiar pieces matching the consumers' expectations were added, the acceptance of soups increased (**Chapter 4**). Sensory profiles of heterogeneous soups were closer to the consumers' 'ideal' than the profile of the plain homogeneous soup. Soups belong to a product category that is commonly consumed with added pieces. To boost palatability of such a familiar product, it was important that changes in the sensory profiles due to increased texture contrast matched consumers' expectations.

As the consumers already expect some degree of heterogeneity in soups, it makes food innovation by particle addition for such products easier than for novel foods for which the consumer has no previous experience and expectations with the product properties. For unfamiliar new products, expectations are based on other aspects, such as the properties of similar foods, the product's visual appearance, orthonasal olfactory cues, and descriptive information (Burgess, 2016; Shankar et al., 2009; Tuorila et al., 1998; Vidal et al., 2013). In fact, the multisensory perception of food involves both cues that are stimulated prior (exteroceptive; e.g. product visual appearance) and during consumption (interoceptive; e.g. somatosensory and gustatory perception) (Piqueras-Fiszman & Spence, 2015). It is the confirmation or disconfirmation of expectations established on exteroceptive and/or interoceptive cues that mostly determines acceptance or rejection of food products (Burgess, 2016; Schifferstein et al., 1999).

Little is known about which factors contribute to the consumer's acceptance of novel heterogeneous foods. It is not clear how exteroceptive and interoceptive cues influence expected and perceived sensory properties and liking. For novel heterogeneous foods, we hypothesise that the expected sensory profile and liking are mainly related to exteroceptive cues, such as the visual appearance and recognition of particles present in the product. For product acceptance of novel food products, both exteroceptive and interoceptive cues have to be taken into account.

The aim of the study was to determine the influence of exteroceptive and interoceptive sensorial cues on consumer preferences and sensory perception of novel, heterogeneous cheeses. Model bell pepper pieces (bell pepper flavoured gellan gels differing in size and fracture stress) or real bell pepper pieces (varying in concentration) were added to processed cheeses to modify appearance, texture, and flavour. Cheeses were evaluated with a consumer test in three conditions (exteroceptive, interoceptive, and combined) using the Rate-All-That-Apply (RATA) method.

5.2 Materials and Methods

5.2.1 Materials

K-carrageenan (GENUGEL type CHP-2) and low acyl gellan gum (KELCOGEL® gellan gum) were purchased from CP Kelco (Rotterdam, France). Food colourant (Paprika Oleoresin WS, E160c) was kindly donated by Holland Ingredients (Meppel, The Netherlands). Red bell pepper, salt, unsalted crackers (Hollandia® Matzes B.V.), La Vache qui rit® Mini Cubes Natural (Fromageries Bel, Suresnes, France) and sunflower oil were purchased from a local supermarket. Kiri® (processed cream cheese) was provided by Bel Group (Fromageries Bel, Suresnes, France). All ingredients were food grade and samples were prepared in food-safe conditions.

Table 5.1. Samples codes for homogeneous and heterogeneous processed cream cheeses. Homogeneous plain (HO) and homogeneous bell pepper flavoured cheese (HOF) were included. For cheeses containing pieces, the first letter of the sample code denotes particle size (Small S-; Medium M-; Large L-), while the second number denotes the hardness of the pieces added (hardness expressed as fracture stress σ_F; Soft -20; Medium -100; Hard -250). The sample codes starting with the letter R indicate samples with real bell pepper pieces. The second and third letters of samples with real bell pepper pieces denote the concentration of the added pieces (Low -Lo; Medium -Me; High -Hi).

Sample Code	Particle size (mm)		Particle fracture stress (σ_F)		Particle concentration	
HO	-	-	-	-	-	-
HOF	-	-	-	-	-	-
S20	Small	2x2x2	Soft	20 kPa	Medium	15%
S100	Small	2x2x2	Medium	100 kPa	Medium	15%
S250	Small	2x2x2	Hard	250 kPa	Medium	15%
M20	Medium	4x4x4	Soft	20 kPa	Medium	15%
M100	Medium	4x4x4	Medium	100 kPa	Medium	15%
M250	Medium	4x4x4	Hard	250 kPa	Medium	15%
L20	Large	6x6x6	Soft	20 kPa	Medium	15%
L100	Large	6x6x6	Medium	100 kPa	Medium	15%
L250	Large	6x6x6	Hard	250 kPa	Medium	15%
RLo	Medium	4x4x4	-	-	Low	7.5%
RMe	Medium	4x4x4	-	-	Medium	15%
RHi	Medium	4x4x4	-	-	High	30%

5.2.2 Study design

In this study, 2 homogeneous and 12 heterogeneous cheeses were prepared (**Table 5.1**). Kiri® (processed cream cheese) was used as matrix for all samples. Twelve heterogeneous cheeses were designed varying in appearance and texture. Nine cheeses contained bell pepper flavoured gel pieces varying in size and hardness (fracture stress), and three cheeses contained real bell pepper pieces varying in concentration. This allowed studying the effect of both particle fracture stress and particle concentration on sensory perception and liking. Two homogeneous cheeses, a homogeneous plain (HO) and a homogeneous bell pepper flavoured cheese (HOF) were also included. **Table 5.1** reports the sample codes of all cheeses. For cheeses containing pieces, the first letter of the sample code denotes the particle size (Small S-; Medium M-; Large L-), while the second number denotes the hardness of the pieces added (hardness expressed as fracture stress σ_F; Soft -20; Medium -100; Hard -250). Cheeses containing real bell pepper pieces were all medium-sized. The samples codes for these samples start with the letter R, indicating that they were real bell pepper pieces. The second and third letters denote the concentration of the added pieces (Low -Lo; Medium -Me; High -Hi).

5.2.3 Sample Preparation

5

5.2.3.1 Model bell pepper gel particle preparation

Bell pepper model gels were designed to mimic real bell pepper pieces in terms of flavour, texture, and appearance (**Figure 5.1**). Model pieces varied in hardness (fracture stress, σ_F) and size and were incorporated into processed cream cheese to obtain samples with controlled mechanical contrast. To mimic the flavour profile of real bell pepper, two aqueous phases, a "roasted" and "concentrated" bell pepper juice, were combined. The flavour of the combined juices was found to be the closest to the flavour of real bell pepper during feasibility tests with consumers and discussions between researchers (data not shown).

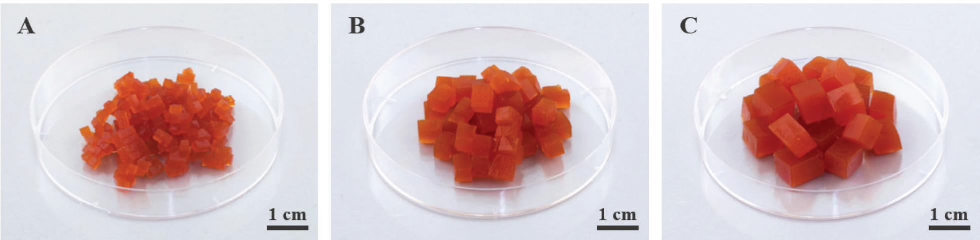


Figure 5.1. Pictures of model bell pepper pieces varying in size. A. Small (2x2x2 mm); B. Medium (4x4x4 mm); C. Large (6x6x6 mm).

Roasted bell pepper juice

To produce a "roasted" bell pepper juice, bell peppers were baked for 13 min at 270°C in an electrical oven (Rational, Mod. SCC101, Barcelona, Spain). Roasted bell peppers were then slit open and cooled down to room temperature for about 1 h. After removal of skin and seeds, bell pepper flesh was blended into a puree using a hand blender (Braun Multiquick 7, Kronberg im Taunus, Germany) for 5 min. The obtained mash was then centrifuged at 3000 g for 15 min. The supernatant was collected, filtered with a sieve (64 µm mesh size) and stored at -18°C for further use.

Concentrated bell pepper juice

For the preparation of the "concentrated" bell pepper juice, bell peppers were first peeled and deseeded. Their juice was extracted with a juicer (Philips HR 1861, Eindhoven, The Netherlands) and reduced to 66% of its initial weight by heating it in an open pan on a stove. The resulting concentrated juice was filtered with a sieve (64 µm mesh size) and cooled down in an ice bath for 20 min. A single batch was obtained and stored at -18°C for further use.

Table 5.2. Composition for model low acyl gellan gels with different target fracture stress (σ_F). All concentrations are expressed as % (w/w).

Particle Hardness	Target fracture stress (σ_F) / kPa	Low acyl gellan	Roasted bell pepper juice	Concentrated bell pepper juice	Paprika Oleoresin (red colourant)	Salt
Soft	20	0.60	49.35	49.35	0.50	0.20
Medium	100	1.70	48.80	48.80	0.50	0.20
Hard	250	3.80	47.75	47.75	0.50	0.20

Bell pepper model gel

A mixture of roasted and concentrated bell pepper juice in a ratio of 50:50 (w/w) was used as the liquid aqueous phase for all bell pepper model gels. As reported in **Table 5.2**, the liquid phase was mixed with red colourant, salt, and different concentrations of low acyl gellan gum. The acyl gellan gum concentration determined the gel fracture stress (target σ_F: 20, 100, 250 kPa). Acyl gellan solutions were placed in a water bath at 95°C for 45 min under continuous stirring to dissolve all acyl gellan. They were then poured into plastic containers and cooled in an ice bath for 20 min to set the gel. For the instrumental characterization, cylindrical gel pieces with a diameter of 23 mm and height of 15 mm were used. For the sensory study, bell pepper gels were cut into cubes of 2x2x2 mm, 4x4x4 mm, and 6x6x6 mm (**Figure 5.1**) using a Mandolin (Michel BRAS, Laguiole, France) and custom-made cutting frames.

5.2.3.2 Real bell pepper particle preparation

Real bell pepper pieces were obtained by cutting peeled and deseeded vegetables into quarters. Bell pepper pieces were placed in vacuum bags in which roasted bell pepper juice (10% w/w) and salt (0.5% w/w) were added. Bags were vacuum sealed at 95%, heated in a water bath at 90°C for 15 min and then placed in an ice bath to cool for approx. 15 min. Cubes of 20x20x5 mm were cut for the analysis of the mechanical properties, whereas cubes of 4x4x4 mm were cut for the sensory study. All samples were stored at 4°C and used within two days.

5.2.3.3 Preparation of homogeneous and heterogeneous processed cream cheeses

K-carrageenan was incorporated in the processed cream cheese (Kiri®) to control the mechanical properties of the plain homogeneous (HO) and heterogeneous cheeses. The gelling agent was incorporated by preparing a 2% (w/w) solution of κ-carrageenan using tap water. K-carrageenan was added to water and the mixture was heated in a water bath at 90°C for 30 min under continuous stirring to dissolve the κ-carrageenan. The solution was then placed in an ice bath for 20 min to cool and set. For the flavoured homogeneous sample (HFO), bell pepper flavour and colourant were added during this step to obtain a bell pepper flavoured κ-carrageenan gel. Also, a 3% (w/w) solution of κ-carrageenan was prepared, which was used for the HOF sample only. For this κ-carrageenan gel, the aqueous phase consisted of a mixture of roasted and concentrated bell pepper juice in a ratio of 50:50 (w/w) and 0.125% of red colourant was added. The solution was heated in a water bath at 90°C for 30 min under continuous stirring. The solution was then placed in an ice bath for 20 min to cool and set.

Homogeneous and heterogeneous processed cream cheeses were prepared by adding the κ-carrageenan gel (12.5% w/w) to the cream cheese in vacuum sealed bags. Samples were placed in a water bath at 65°C for 20 min to allow the cream cheese and gel to melt. Then, the molten cheese was poured into a vessel kept at 65°C and was manually mixed avoiding incorporation of air. For heterogeneous cheeses, model or real bell pepper pieces were incorporated at this point. The products were subsequently poured into squared petri dishes coated with a thin layer of sunflower oil and stored at 4°C for 16-18 hrs. Cheeses were cut with a custom-made cutting frame to obtain 20x20x12 mm cubes of approx. 5 g and stored at 4°C for a maximum of one week.

5.2.4 Mechanical properties of model bell pepper gels and homogeneous cheeses

To characterize the mechanical properties of the bell pepper model gels, fracture stress and fracture strain was determined using uniaxial compression tests using a Texture Analyzer (TA.XT plus, Stable Micro Systems-SMS). All bell pepper model gels fractured under uniaxial compression. A compression plate of 100 mm was used as a probe and the device was equipped with a 50 kg load cell. Compression strain was set at 30% with a crosshead velocity of 1 mm/s. Each sample type was measured in six replicates at room temperature (20 ±1°C). Averaged true fracture stress (kPa) and true strain (-) were calculated from the measurements for all bell pepper model gels, as previously described by Peleg (1987).

In contrast to the bell pepper model gels, the homogeneous cheeses (HO, HOF) and the real bell pepper pieces did not fracture under uniaxial compression (data not shown). Therefore, penetration tests were performed on homogeneous cheeses (H, HOF) and bell pepper pieces to determine the force (N) needed to reach 30% penetration, allowing for a comparison of instrumentally quantified texture properties between these samples which did not fracture. This test was performed using a Texture Analyser equipped with a 5 kg load cell and a cylindrical flat probe (Ø:4 mm). A crosshead velocity of 1 mm/s was used. Six replicates of each sample type were measured at room temperature (20 ±1°C) for homogeneous cheese (20x20x15 mm) as well as for real (20x20x5 mm) and bell pepper model gel pieces (Ø 23 mm x 5 mm).

5.2.5 Sensory Analysis

5.2.5.1 Subjects

A total of 73 subjects (53 female/20 male, age: 18-31 years) were recruited. Subjects were pre-screened based on self-reported criteria such as overall good health, BMI (18.5-25 kg/m^2), dental health (no dental implants; no missing teeth except wisdom teeth; no dental braces or piercings), and origin (born and living in European Union). Participants were excluded if they were smokers, had allergies or intolerances to cheese or bell pepper. During the recruitment, participants were asked to rate their familiarity with processed cream cheese on a scale from 1 to 6 (1= unfamiliar, 6= highly familiar) and their consumption frequency of processed cheese (once a week, once a month, every 3 months, never). Only consumers who consumed processed cream cheese at least once every 3 months were included in the study. Subjects signed an informed consent form in advance and received financial compensation for their participation in the study.

5.2.5.2 Sensory Sessions

An information session of approx. 1 hour was conducted at the beginning of the study to allow participants to become familiar with the different sessions, the sensory method, and the descriptors. A short demonstration was provided during that session to familiarize them with the different tasks and the proper evaluation procedures.

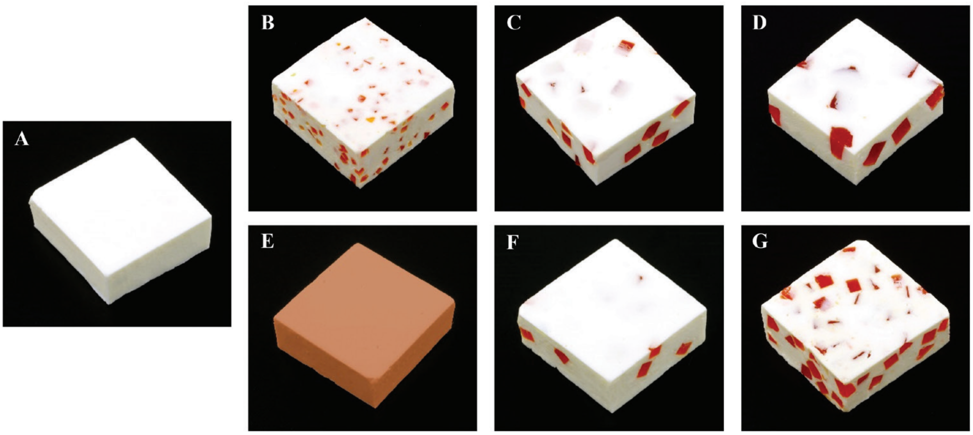


Figure 5.2. Pictures of processed cream cheeses used during the exteroceptive condition. A. Homogeneous cream cheese (HO); B. Cream cheese with small red bell pepper pieces at medium concentration (S-); C. Cream cheese with medium red bell pepper pieces at medium concentration (M-); D. Cream cheese with large red bell pepper pieces at medium concentration (L-); E. Homogeneous cream cheese with red bell pepper flavour (HFO); F. Cream cheese with medium red bell pepper pieces at low concentration (RLo); G. Cream cheese with medium red bell pepper pieces at high concentration (RHi). Pictures were printed to scale 1:1 relative to the real processed cheese product.

Although participants were informed that the test consisted of an evaluation of processed cream cheeses that may contain bell pepper, no information was provided regarding the form (as pieces or juice), type (model or real) and possible variation of bell pepper (i.e. hardness, concentration) nor the order of cheese samples during the different sessions. An extra warm-up sample (La Vache qui rit Mini Cubes®) was provided to participants at the very beginning of the actual sensory test.

The sensory test was divided into three subsequent conditions that were distributed over five test sessions of approx. 1 hour. In each condition, consumers had to fill out a questionnaire using EyeQuestion® software (The Netherlands). They were first asked to evaluate the cheeses based on overall liking, texture liking, and flavour liking using a nine-point hedonic scale ranging from “Dislike extremely” (1) to “Like extremely” (9). Then, subjects evaluated textural and flavour attributes using a Rate-All-That-Apply (RATA) methodology with nine-box scales (Meyners et al., 2016; Oppermann et al., 2017). Participants could always refer to a brochure for the explanation of the sensory attributes (**Appendix 5.1**). Attributes and their definitions were generated through discussions of researchers and consumers during feasibility tests (data not shown).

In the first condition (interoceptive condition; first two sessions performed in two consecutive weeks with a break of one week between sessions), participants were blindfolded with a sleeping mask and were not allowed to see the cheeses. Each product was provided to them directly in the mouth by the researchers and, only after that, participants were permitted to remove their mask to fill out the questionnaire. In this condition, subjects were asked to evaluate the liking and sensory perception of cheeses based on their somatosensory and gustatory perception (interoceptive cues). Participants were allowed to ask up to two portions of the same sample. During each of these two sessions, seven of the fourteen products were served in a randomized monadic sequence.

After a break of one week, participants evaluated the cheeses in a randomized monadic sequence based on their visual appearance using pictures (**Figure 5.2**, printed to scale 1:1) and related product descriptions (exteroceptive condition, third session). The product descriptions are provided in the caption of **Figure 5.2**. These objective descriptions were provided to avoid creation of erroneous expectations (e.g. recognition of pieces as strawberry rather than bell pepper pieces). No tasting was performed in the exteroceptive condition.

The third condition (combined condition; fourth and fifth sessions performed in two consecutive weeks with a break of one week between sessions) was conducted after a break of two weeks. During the combined condition, participants assessed liking and the sensory profile of two portions of each sample presented along with the sample description (same description as in the second condition, see caption of **Figure 5.2**). Thus, both visual and somatosensory and gustatory cues were involved. As in the first condition, seven of fourteen samples were given during each session in a randomized monadic sequence to avoid fatigue.

For all conditions, consumers were requested to refrain from eating 1 h before the session and were instructed to have a break of at least 1.5 min between sample evaluations. Participants were asked to rinse their mouths with water and the provided crackers between each sample. All the sessions were conducted in meeting facilities (Agrotechnology and Food Sciences Group, Wageningen University) in which the room was equipped with desk dividers. The order of the sensory attributes was randomized within each block of attribute category (texture and flavour) for each participant.

5.2.6 Data analysis

Analysis of Variance (ANOVA) was performed on the data obtained instrumentally with the measured instrumental value as dependent variable and sample type as independent variable (uniaxial compression tests and penetration tests). For the analysis of RATA outcomes were treated as continuous data as previously described (Meyners et al., 2016; Oppermann et al., 2017). To address the main objectives of the study, individual paired t-tests were performed between the different tested conditions to identify the effect of exteroceptive cues (combined minus interoceptive scores) and interoceptive cues (combined minus exteroceptive scores) on sensory perception and liking. To check how consumer perception and liking of processed cheese differed upon addition of particles or flavour, the sensory data obtained from the Interoceptive, Exteroceptive, and Combined conditions were analysed separately and, for each, an ANOVA was performed using sample as fixed factor and panellist as random factor. Such analysis was performed to allow a comparison between all products, and Tukey's HSD tests ($p<0.05$) were conducted as post-hoc pairwise comparisons. In addition to these general analyses across products, for each condition, the effects of particle size, fracture stress, and concentration on sensory perception were investigated. ANOVAs were performed on sample subsets considering only applicable cheeses containing model or real bell pepper pieces for each condition separately: the effects of particle size and concentration were considered for the exteroceptive condition as particle fracture stress could not be visually evaluated; particle size, particle fracture stress, their interaction (for cheeses containing model bell pepper pieces), and particle concentration (for cheeses containing real bell pepper pieces) were used as factors for the interoceptive and combined conditions. RStudio (version 3.4.0) with the use of the packages SensoMineR and FactoMineR was used for the data analysis.

5.3 Results

5

5.3.1 Mechanical properties of bell pepper model gels and homogeneous cheeses

For the soft, medium, and hard model gels, the measured fracture stress values were relatively close to the target values (σ_F: 20, 100, 250 kPa) (**Table 5.3**). For all samples, **Table 5.3** also reports the measured maximum force at 30% penetration depth. For bell pepper gels, the max force ranged from 0.9 N to 7.5 N. The instrumental hardness of real bell pepper was found to be 2.3 ±0.8 N, which is within the range of the bell pepper model gels. The fracture force of the real bell pepper was found to be closest to the medium hard model gel (MM, 3.3 N). The soft bell pepper model gel, homogeneous cream cheese (HO) and homogeneous cream cheese with flavour (HFO) presented comparable mechanical properties with a maximum penetration force of approx. 0.7-0.9 N.

Table 5.3. Mean values (±S.D.) for measured fracture stress and fracture strain of model bell pepper gels together with maximum force (N) needed to penetrate to 30% deformation of bell pepper model gels, real bell pepper and homogeneous cheeses (HO and HOF). Values within a column having the same superscript letters do not differ significantly (p > 0.05).

Sample	Target fracture stress (kPa)	Measured fracture stress (kPa)	Measured fracture strain (-)	Maximum force (N) at 30% deformation
Bell pepper gels	20	24 ± 3^{A}	0.21 ± 0.01^{A}	0.9 ± 0.1^{D}
	100	108 ± 4^{B}	0.25 ± 0.01^{B}	3.3 ± 0.1^{B}
	250	258 ± 9^{C}	0.31 ± 0.01^{C}	7.5 ± 0.1^{A}
Real bell pepper	-	-	-	2.3 ± 0.8^{C}
Homogeneous cream cheese (HO)	-	-	-	0.7 ± 0.7^{D}
Homogeneous flavoured cream cheese (HOF)	-	-	-	0.7 ± 0.1^{D}

5.3.2 Sensory Analysis

5.3.2.1 Interoceptive condition: Sensory perception of homogeneous and heterogeneous processed cheeses

5

In the interoceptive condition, consumers based their evaluations only on somatosensory and gustatory perception (interoceptive cues). The homogeneous cheese (HO) received the highest intensity scores for creamy, mouth-coating, melting, smooth, and dairy flavour (see **Appendix 5.2**). Flavour addition to the homogeneous cheese (HFO) significantly increased intensity of bell pepper flavour and decreased dairy flavour intensity. When pieces were added to processed cheeses, significant differences for all textural attributes were found (**Table 5.4**, see the first column: product effect). For flavour attributes, bell pepper flavour, dairy flavour and sweetness were significantly different, while savouriness, sourness, and saltiness did not differ significantly.

Most attributes were affected by particle fracture stress, and fewer attributes were affected by particle size. Particle size had a significant effect on chewiness, lumpiness, perceived particle size and grittiness perception (**Table 5.4**, see the size effect). Grittiness was most affected, as cheeses containing small pieces (S-) were perceived as more gritty than cheeses with medium (M-) and large-sized pieces (L-). For samples containing soft particles, an increase in particle size from small (S-) to large (L-) increased lumpiness perception significantly. No other effects on perception were observed when the size of added pieces was varied.

An increase in particle fracture stress from 20 kPa (-20) to 250 kPa (-250) led to several significant changes in the samples' sensory profile. Chewiness, crumbliness, crunchiness, hardness, lumpiness, particle size, mouthfeel heterogeneity and grittiness (for S- samples) increased with particle fracture stress, whereas creaminess, melting, smoothness, mouth-coating and dairy flavour perception decreased (**Table 5.4**, see fracture stress effect). Significant interactions between particle size and fracture stress were found for chewiness, crumbliness, lumpiness, particle size, mouthfeel heterogeneity and grittiness, indicating that the perception of such attributes was not affected by size itself only, but that the evaluation was also influenced by changes in particle hardness.

Table 5.4. ANOVA of sensory attributes during interoceptive condition. All 14 cheeses were included in the analysis of the product effect with panellist as a random factor. The stars indicate significant differences between samples (*=p<0.05, **=p<0.01, ***=p<0.001). The + and - signs indicate that an increase of the considered variable lead to an increase (+) or decrease (-) of intensity of the sensory attribute.

	Product effect	Size [a]	Fracture stress [a]	Size*Fracture stress [a]	Concentration [b]
Chewiness	***	+ *	+ ***	+ **	
Crumbliness	***		+ ***	+ *	
Crunchiness	***		+ ***		
Creaminess	***		- ***		
Hardness	***		+ ***		
Lumpiness	***	+ *	+ ***	+ *	+ ***
Mouth-coating	***		- *		
Melting	***		- ***		
Particle size	***	+ ***	+ ***	+ *	+ ***
Stickiness	***				
Mouthfeel heterogeneity	***		+ ***	+ ***	+ **
Smoothness	***		- ***		
Grittiness	***	- ***	+ ***	+ ***	+ **
Bell pepper flavour	***				+ ***
Dairy flavour	***		- **		
Savoury	***				
Sourness					
Sweetness	***				
Saltiness					

a: In these ANOVAs considering the particle size, fracture stress, and their interaction, only cheeses containing model bell pepper pieces were included.
b: In this ANOVA considering the particle concentration, only cheeses containing real bell pepper pieces were included.

For cheeses containing real bell pepper pieces, the variation in concentration significantly affected crunchiness and bell pepper flavour (**Table 5.4**, see the concentration effect). Intensity of these attributes increased with increasing concentration of bell pepper pieces (RHi). With an increase in concentration of real pieces from 7.5% (RLo) to 30% (RHi), attributes such as lumpiness, particle size, and mouthfeel heterogeneity also showed a significant increase.

These results indicate that consumer sensory perception of novel, heterogeneous cheeses based on somatosensory and gustatory perception was mainly influenced by changes in particle fracture stress (hardness) and concentration, whereas particle size variations affected only few attributes (e.g. grittiness, chewiness and lumpiness).

5.3.2.2 Exteroceptive condition: Sensory perception of homogeneous and heterogeneous processed cheeses

In the exteroceptive condition, subjects evaluated images of homogeneous and heterogeneous cheeses (**Figure 5.2**) without tasting them, thus ratings were solely based on exteroceptive cues (samples' visual appearance and product description). Almost all attributes were significantly different between cheeses (**Table 5.5**, see the first column: product effect). The only exceptions were the attributes sweetness and sourness, which were not significantly different between cheeses. The homogeneous cheese (HO) received the highest expected scores in terms of creaminess, mouth-coating, melting, stickiness, smoothness (see **Appendix 5.2**). The different colour and description of HOF compared to that of HO led to significantly higher expectations of bell pepper flavour, savouriness and sweetness, and significant lower expectations of creaminess, dairy flavour, and sourness.

Upon addition of model bell pepper pieces (S-; M-; L-), consumers' expected sensory perception of heterogeneous products was largely influenced by the size of added pieces (**Table 5.5**, see the size effect). The attributes chewiness, crunchiness, hardness, lumpiness, particle size, mouthfeel heterogeneity and bell pepper flavour showed significantly higher ratings with increasing particle size from small (S-) to large (L-). Only the attributes grittiness and smoothness increased with decreasing particle size. These results indicate that variation in particle size in novel, heterogeneous cheeses can largely affect the expected sensory product properties.

For cheeses containing real pieces, an increase in concentration from 7.5% (RLo) to 30% (RHi) was associated to a significant increase of several attributes such as chewiness, crumbliness, crunchiness, hardness, lumpiness, particle size, mouthfeel heterogeneity and bell pepper flavour (**Table 5.5**, see the concentration effect). Conversely, creaminess, smoothness, melting, mouth-coating and dairy flavour perception decrease significantly as a result of higher pieces concentration.

We conclude that visual cues as the visual recognition of particles, their size and concentration in combination with product description can largely affect consumer expected perception of novel, heterogeneous products.

Table 5.5. ANOVA of sensory attributes during exteroceptive condition. All 14 cheeses were included in the analysis of the product effect with panellist as a random factor. The stars indicate significant differences between the samples (*=p<0.05, **=p<0.01, ***=p<0.001). The + and - signs indicate that an increase of the considered variable lead to an increase (+) or decrease (-) of intensity of the sensory attribute.

	Product effect	Size [a]	Concentration [b]
Chewiness	**	+ ***	+ ***
Crumbliness	***		+ **
Crunchiness	***	+ ***	+ ***
Creaminess	***		- ***
Hardness	***	+ ***	+ ***
Lumpiness	***	+ ***	+ ***
Mouth-coating	***		- *
Melting	***		- ***
Particle size	***	+ ***	+ ***
Stickiness	***		
Mouthfeel heterogeneity	***	+ **	+ ***
Smoothness	***	- **	- ***
Grittiness	***	- ***	
Bell pepper flavour	***	+ ***	+ ***
Dairy flavour	***		- ***
Savoury	**		
Sourness			
Sweetness			
Saltiness	**		

a: In these ANOVAs considering the particle size, only cheeses containing model bell pepper pieces varying in size (S-; M-; L-) were included.
b: In this ANOVA considering the particle concentration, only cheeses containing real bell pepper pieces were included.

5.3.2.3 Combined condition: Sensory perception of homogeneous and heterogeneous processed cheeses

During the third and last condition, participants tasted and evaluated all cheeses while seeing them and having the product description available (combined condition). The evaluation was a result of the visual, somatosensory and gustatory perception, which means that consumers based their evaluations on both exteroceptive and interoceptive cues. All attributes showed significant differences between cheeses (**Table 5.6**, see the first column: product effect). As observed for the exteroceptive and interoceptive condition, the attributes creaminess, smoothness and dairy flavour had the highest intensities for the homogeneous sample (HO, see **Appendix 5.3**). The addition of bell pepper flavour into the homogeneous sample (HFO) decreased the perception of creaminess, mouth-coating, melting, stickiness, smoothness and dairy flavour significantly.

Table 5.6. ANOVA of sensory attributes during Combined condition. All 14 cheeses were included in the analysis of the product effect with panellist as a random factor. The stars indicate significant differences between the samples (*=p<0.05, **=p<0.01, ***=p<0.001). The + and - signs indicate that an increase of the considered variable lead to an increase (+) or decrease (-) of intensity of the sensory attribute.

	Product effect	Size [a]	Fracture stress [a]	Size*Fracture stress [a]	Concentration [b]
Chewiness	***	+ **	+ ***	+ **	+ **
Crumbliness	***		+ *		+ **
Crunchiness	***		+ ***		+ **
Creaminess	***		- ***		- *
Hardness	***	+ **	+ ***	+ *	
Lumpiness	***	+ **	+ ***		+ ***
Mouth-coating	***		- ***	- *	- **
Melting	***		- ***		
Particle size	***	+ ***	+ ***	+ ***	+ ***
Stickiness	***		- *		
Mouthfeel heterogeneity	***		+ ***		+ ***
Smoothness	***		- ***	- *	- ***
Grittiness	***	- ***	+**	+ **	+ *
Bell pepper flavour	***				+ ***
Dairy flavour	***				- **
Savoury	***				
Sourness	***				
Sweetness	***				+ **
Saltiness	***				

a: In these ANOVAs considering the particle size, fracture stress, and their interaction, only cheeses containing model bell pepper pieces were included.
b: In this ANOVA considering the particle concentration, only cheeses containing real bell pepper pieces were included.

In this condition, an increase in size of model bell pepper pieces significantly increased chewiness, hardness, lumpiness, and particle size, while it significantly decreased grittiness perception (**Table 5.6**, see the size effect). These results are in line with the ones seen for the interoceptive condition with the exception of the attribute hardness, which was not found to be significantly affected during the interoceptive condition. This suggests that oral hardness evaluation might be influenced by visual cues.

An increase in fracture stress of added pieces from 20 kPa (-20) to 250 kPa (-250) led to significantly higher scores for the attributes chewiness, crumbliness, crunchiness, hardness, lumpiness, particle size, mouthfeel heterogeneity and grittiness and lower values for the attributes creaminess, mouth-coating, melting, stickiness and smoothness (**Table 5.6**, see fracture stress effect). In line with the interoceptive condition, grittiness was mainly perceived for cheeses containing small pieces (S100, S250). Chewiness, hardness, particle size, and grittiness were significantly augmented by interactions between particle size and fracture stress during the combined condition, whereas perception of mouth-coating and smoothness decreased significantly. These results indicate that pieces hardness (fracture stress) can significantly change oral sensory perception of heterogeneous cheeses, independently from the presence of visual cues.

When the concentration of real pieces increased from 7.5% (RLo) to 30% (RHi), hardness, melting, stickiness, savoury, sourness and saltiness showed no significant difference (**Table 5.6**, see the concentration effect). In contrast, an increase in particle concentration to 30% led to significantly higher scores for the attributes chewiness, crumbliness, crunchiness, lumpiness, particle size, mouthfeel heterogeneity, grittiness, bell pepper flavour and sweetness, whereas significantly lower scores were found for the perception of creaminess, mouth-coating, smoothness, and dairy flavour.

These results show that consumer' sensory perception of heterogeneous processed cheeses was largely influenced by the presence of particles, their fracture stress and concentration when both visual and oral sensorial cues were present. Size of added pieces also affected product hardness perception in such combined inform, which was not observed in the interoceptive condition, suggesting that visual cues may have influenced consumers' texture perception.

5.3.2.4 Comparison of sensory perception of processed cheeses between exteroceptive, interoceptive and combined condition

Influence of exteroceptive cues on sensory properties of novel, heterogeneous cheeses

To investigate how exteroceptive cues affected the sensory properties of novel, heterogeneous cheeses, the attribute scores of the interoceptive condition were subtracted from the ratings of the combined condition. **Figure 5.3** summarizes the number of cheeses that were found to be significantly different between the two conditions (combined – interoceptive) for all attributes. The presence of exteroceptive cues led to significant differences for texture-related attributes (e.g. crunchiness, particle size, hardness) in several products. For instance, crunchiness increased significantly for eleven out of twelve cheeses containing pieces when comparing the combined with the interoceptive condition. This indicates that exteroceptive cues (i.e. visual recognition of pieces and their descriptions) led to a more intense perception of crunchiness. Similarly, visual and descriptive information affected perception of the attribute "particle size" as five cheeses presented significantly higher scores, while one cheese presented significantly lower scores when the ratings from the combined condition were compared to the ones from the interoceptive condition. These results indicate that the presence of visual cues and product description can significantly influence textural perception. Exteroceptive cues did not affect flavour or taste-related attributes as savouriness, sweetness, saltiness, bell pepper flavour and had a limited effect on the ratings of dairy flavour. We conclude that congruent visual and descriptive cues can influence texture perception of heterogeneous processed cheeses, but their contribution to flavour perception is limited.

Influence of interoceptive cues on sensory properties of novel, heterogeneous cheeses

The influence of interoceptive cues on sensory properties of novel, heterogeneous cheeses was investigated by subtracting the attribute scores of the exteroceptive condition from the ratings of the combined condition. **Figure 5.4** shows that interoceptive cues (e.g. textural and flavour properties) played an important role in determining differences in texture and flavour attributes between exteroceptive and combined conditions. A variation of product properties such as particle fracture stress and concentration led to a significant increase (e.g. mouth-coating, melting, smoothness, creaminess) or decrease (e.g. chewiness, crunchiness, particle size) of many textural attributes in comparison to what they expected.

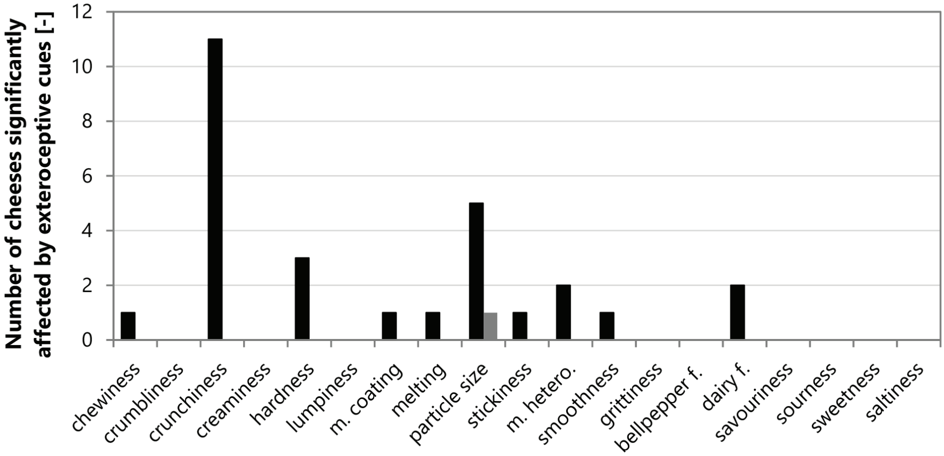


Figure 5.3. Effect of exteroceptive cues on the sensory perception of novel, heterogeneous cheeses. Bars indicate the number of cheeses that were found to be significantly different (p<0.05) between combined and interoceptive condition (combined - interoceptive) per attribute. In total, twelve cheeses were evaluated. Black bars indicate the number of cheeses with a positive difference between combined and interoceptive condition per attribute and grey bars indicate the number of cheeses with a negative difference between combined and interoceptive condition per attribute.

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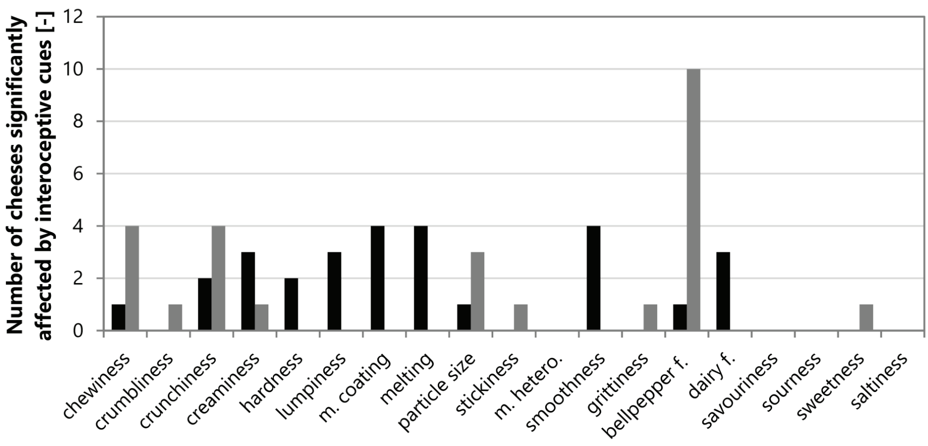

Figure 5.4. Effect of interoceptive cues on the sensory perception of novel, heterogeneous cheeses. Bars indicate the number of cheeses that were found to be significantly different (p<0.05) between combined and exteroceptive condition (combined - exteroceptive) per attribute. In total, twelve cheeses were evaluated. Black bars indicate the number of cheeses with a positive difference between combined and interoceptive condition per attribute and grey bars indicate the number of cheeses with a negative difference between combined and exteroceptive condition per attribute.

We relate these differences mainly to the variation in fracture stress of added pieces as this property could not be easily judged from the cheeses' visual appearance. Differences between the exteroceptive and combined profiles were also seen for flavour attributes, as bell pepper flavour was found to be significantly different for eleven cheeses (**Figure 5.4**). Significant negative differences were found for ten cheeses, meaning that the perceived bell pepper flavour was lower than expected. This possibly indicates that the visual recognition of red bell pepper pieces and related descriptions provoked higher expected perceptions of such flavour during exteroceptive condition than the combined condition. Such large discrepancy in scores was not observed for other flavour attributes as savouriness, sourness, sweetness, saltiness, which differed only between a limited number of cheeses. For these flavour attributes, no descriptive information was provided during the exteroceptive condition and therefore their evaluation was based on visual cues. We conclude that visual and descriptive information regarding product flavour attributes can significantly affect expected perception, although the actual perception will depend on the product properties (interoceptive cues).

5.3.2.5 Liking

In the interoceptive condition, the homogeneous cheeses (HO; HOF) had the highest scores for liking overall and liking texture, although these did not differ significantly from cheeses containing soft pieces (see **Appendix 5.5**). Flavour liking showed no significant differences for any of the cheeses suggesting that the presence or absence of particles did not affect product flavour appreciation. In the case of texture liking or overall liking, the addition of particles had an effect. Only particle hardness (fracture stress) seemed to play an important role. Overall, for heterogeneous cheeses the presence of hard pieces (high σ_F , -250) led to significantly lower liking scores than the presence of softer pieces. With respect to particle size and particle concentration, the hedonic responses were not influenced. In the exteroceptive condition, the homogeneous cheese (HO) presented higher values for all hedonic responses (see **Appendix 5.5**). Cheeses containing bell pepper flavour (HOF), small pieces (S-) or a low concentration of real bell pepper pieces (RL) were not significantly different from the homogeneous product (HO), and therefore equally liked. An increase in size from small (S-) to large (L-), significantly decreased the expected hedonic response in terms of liking overall and texture. However, for a small increase in particle size from small (S-) to medium (M-), liking overall, flavour, and texture was not significantly different. The hedonic responses were not influenced by a variation in particle concentration. This result suggests that particle size significantly affect the expected palatability of heterogeneous processed cheeses.

In the combined condition, most cheeses showed no significant difference in terms of overall liking (see **Appendix 5.5**). Only cheeses containing medium and large sized hard pieces (M250; L250) were liked significantly less (4.7-4.9) than cheeses with small and soft pieces (S20, L20) with scores of 6.1-6.2. The particle size of these soft pieces (-20) did not have an influence on the liking scores, as these were not significantly different from the homogeneous cheeses (HO; HFO). Also with respect to particle concentration, no significant differences in hedonic responses were found. We conclude that consumer hedonic responses for novel, heterogeneous cheeses during interoceptive and combined conditions were similarly affected by product variations as an increase in fracture stress of added pieces resulted in a decrease in liking in both conditions.

Influence of exteroceptive and interoceptive cues on liking perceived over the three different conditions

The hedonic responses of the three conditions were compared to investigate the influence of exteroceptive and interoceptive cues on consumer's liking ratings. The results of the comparisons for overall liking, flavour liking and texture liking are summarized in **Table 5.7**. **Table 5.7** shows that exteroceptive cues (i.e. product visual appearance and product description) did not significantly contribute to modify overall liking, as none of the C-I values were found to be significantly different. However, overall liking was affected by interoceptive cues, as sample HO, M20 and L20 showed values above 0.5, which were found to be significantly different. In fact, the somatosensory and gustatory cues (i.e. textural and flavour oral sensory perceptions) negatively affected the overall liking rating of the homogeneous cheese (HO) and positively influenced the rating of cheeses containing medium- and large-sized soft pieces (M20, L20). For flavour liking and texture liking, both interoceptive and exteroceptive cues showed an effect by either decreasing (HO, HFO) or increasing (e.g. M250, L20, RLo) their rated scores. Considering that no significant differences were found in terms of overall liking as effect of exteroceptive cues, we conclude that the congruent product visual appearance and product description did not contribute to consumer's hedonic response of homogeneous and novel heterogeneous cheeses. On the contrary, somatosensory and gustatory cues had a relatively large role in determining positive (e.g. cheese containing soft pieces) or negative (homogeneous cheeses) contribution to overall liking, flavour liking and especially texture liking.

Table 5.7. Mean difference in overall liking, flavour liking, texture liking evaluated under interoceptive, exteroceptive and combined conditions. (C-I) denotes Combined minus Interoceptive liking scores; (C-E) denotes Combined minus Expected liking scores. Stars depict significant differences between liking scores at p<0.05.

		Product						
Effect due to:		HO	S20	S100	S250	M20	M100	M250
Overall liking	exteroceptive cues (C-I)	-0.3	0.3	0.4	0.1	0.3	0.5	0.8
	interoceptive cues (C-E)	**-0.5***	0.1	-0.1	-0.6	**0.8***	0.5	0.1
Flavour liking	exteroceptive cues (C-I)	-0.4	0.4	0.4	0.1	0.2	0.2	**0.6***
	interoceptive cues (C-E)	**-0.7***	0.1	0	-0.2	**0.6***	0.5	0.2
Texture liking	exteroceptive cues (C-I)	-0.1	0.5	0.4	0.2	0.6	0.4	**0.9***
	interoceptive cues (C-E)	-0.5	0.4	-0.3	-0.7	**1.0***	0.2	-0.1
		HOF	L20	L100	L250	RLo	RMe	RHi
Overall liking	exteroceptive cues (C-I)	-0.5	0.4	0	-0.2	0.4	0.5	0.3
	interoceptive cues (C-E)	-0.3	**1.0***	0.3	0	0.4	0.3	0.5
Flavour liking	exteroceptive cues (C-I)	-0.4	0.3	0	-0.3	0.2	0.3	0.2
	interoceptive cues (C-E)	-0.3	0.6	0.3	-0.1	0.1	0.2	0.4
Texture liking	exteroceptive cues (C-I)	-0.4	**0.7***	0.4	0.3	**0.6***	0.6	0.6
	interoceptive cues (C-E)	**-0.7***	**1.6***	0.6	0.1	**0.6***	0.2	**0.7***

5.4 Discussion

The present study aimed to determine the influence of exteroceptive and interoceptive sensorial cues on consumer preferences and sensory perception of novel, heterogeneous cheeses. Addition of pieces varying in fracture stress and concentration changed significantly the expected and perceived perception of texture and flavour attributes. A variation in particle size mainly influenced the expected profile, while the contribution to product sensory perception was limited during the interoceptive and combined conditions. During these latter conditions, an increase in particle fracture stress or concentration led to lower perceived intensities for attributes mostly related to homogeneity (e.g. creaminess, mouth-coating, smoothness), whereas the intensity increased with an increase in particle fracture stress for heterogeneity-related attributes (e.g. chewiness, crunchiness, lumpiness) as previously found in our studies on heterogeneous foods (**Chapters 2**, **3** and **4**). The paired comparisons of the different conditions have shown that both visual cues and somatosensory and gustatory cues can significantly influence texture and flavour perception of homogeneous and heterogeneous cheeses, indicating that both visual and oral sensorial cues can be used to tune the perception of a heterogeneous product. These findings support the notion that perception of foods depends on the integration of multisensory cues (Prescott, 2015; Spence, 2016; Spence & Shankar, 2010; Verhagen & Engelen, 2006; Zampini & Spence, 2005; Zampini et al., 2008) and they prove that visual cues affect consumer texture perception.

The hedonic results suggest that exteroceptive cues provided in this experiment (visual recognition of particle and objective product description) had no effect on perceived liking of the tested cheeses. However, it should be considered that a significant decrease in the expected hedonic responses was observed when the particle size increased from small to large. These findings suggest that for novel heterogeneous foods, the selection of particle size will impact the consumer hedonic expectations and possibly affect the consumer’s willingness to try the novel product. We conclude that for the development of novel, heterogeneous cheeses, small-medium sized particles should be used to increase willingness of people to try the new product.

Particle fracture stress significantly affected product liking as the presence of hard pieces (σ_F =250) decreased significantly the consumer’ hedonic response. The product used in our study (processed cream cheese) is usually homogeneous in texture.

Hence, consumers expect its texture to be homogeneous. Before the sensory test, consumers were informed that they were about to assess a processed cream cheese that may contain bell pepper (no information regarding the form of bell pepper was provided). We observed that consumers preferred products that were closer to the familiar texture of the original product as large differences from the original product gave rise to a decrease in liking. This observation is supported by the study of Hong et al. (2014), in which it was shown that texture preferences of traditional Korean cookies were strongly correlated with familiarity scores of consumers from different countries (Korea, Japan and France). The authors suggested that the preferences for certain textural properties of food depend on the consumers' previous experience with similar products. We demonstrated that for cheeses containing pieces with no/little mechanical contrast, not only product liking was maintained, but disconfirmations of sensory expectations (e.g. expected bell pepper flavour) did not give rise to a decrease in hedonic responses. Although this study did not show large variations in liking of the novel products between the first and last condition, longer periods of repeated exposure could possibly further improve the appreciation for the novel cheeses by the consumers (Hekkert et al., 2013; Pliner, 1982).

This study not only provides important insights into the variables to take into account when designing novel heterogeneous products, but it highlights important consequences of macroparticles addition (i.e. pieces) on consumer perception. When model bell pepper or real bell pepper pieces were added into the processed cheese, the perception of some positive attributes (e.g. creaminess, smoothness) was reduced, although this did not affect product liking for most cheeses. The incorporation of pieces could be used to design products for a specific purpose. For example, healthier products could be obtained by engineering gel pieces with specific macro/micronutrients (e.g. protein, fibres, vitamins, dietary minerals) that can be easily added into a homogeneous matrix to obtain target nutrition for specific consumer groups (i.e. elderlies). Furthermore, the addition of pieces could beneficially affect oral processing behaviour, i.e. a prolonged oral processing time (van Eck et al., 2019). A prolongation of oral processing time could possibly yield different oro-sensory exposures, which might eventually influence satiation (Morell et al., 2018; Tarrega et al., 2016).

5.5 Conclusions

This study discussed the effect of addition of bell pepper pieces varying in size, hardness (fracture stress), and concentration into processed cheeses on sensory perception and liking, while decoupling the influence of visual and oral sensory cues on consumer' response. Sensory perception of heterogeneities in a processed cheese was largely dominated by the fracture stress and concentration of the added bell pepper pieces. An increase in fracture stress from 20 to 250 kPa led to an increase in perception of a variety of heterogeneity-related attributes (chewiness, crumbliness, crunchiness, hardness, lumpiness and mouthfeel heterogeneity). A variation in particle size influenced the expected product sensory profile but had a minor role in varying actual sensory perception. With respect to liking, consumers preferred homogeneous cheeses and heterogeneous cheeses containing soft pieces independently from their size. An increase in particle size from 2x2x2 mm to 6x6x6 mm significantly decreased the expected palatability of heterogeneous processed cheeses. Through the comparison of the tested conditions (interoceptive, exteroceptive, combined), we determined that both exteroceptive cues (visual information) and interoceptive cues (somatosensory and gustatory) can significantly influence texture and flavour perception of heterogeneous processed cheeses. On the contrary, visual appearance and product description did not contribute to the consumer's hedonic response of novel, heterogeneous cheeses. Somatosensory and gustatory cues, which were mainly determined by properties of the bell pepper pieces (fracture stress, concentration), had a large role in determining the consumer's hedonic responses. We conclude that for novel heterogeneous processed cheeses, the size of added pieces mainly determined the expected liking and possibly affect consumer's attractiveness to the new product. However, actual product liking of such novel products was determined by particle texture and matching of consumers' expectation for the specific product type.

Appendix 5.1. Explanation of attribute descriptors used during the sensory study.

Descriptor	Definition
Texture	
Chewiness	The amount of work required to masticate the sample (or its components) into a state ready for swallowing
Creaminess	Sensation of a thick, smooth and velvety texture in the mouth
Crunchiness	Making a loud sound when chewed or crushed
Crumbliness	The extent to which the samples breaks into smaller pieces or fragments
Hardness	Force required to compress and/or break the sample (or its components) between the teeth
Lumpiness	Perception of lumps (large irregularity) in the sample
Grittiness	Perception of small granules (sandy/grainy) in the sample
Melting	The degree to which the sample melts during mastication
Mouth-coating	Sensation of a layer covering the mouth (film sensation inside the mouth)
Mouthfeel heterogeneity	Perception of texture contrast in the mouth. Sensory perception of different structures in the mouth during consumption (i.e. one sample contains soft and hard parts)
Smooth	A uniform perception of the product in the mouth during mastication
Sticky	The degree to which the sample sticks in the mouth or between the teeth
Particle size	Perception of the particles dimension in the mouth on a scale from small to large
Flavour	
Bell pepper flavour	Perception of bell pepper aroma
Dairy flavour	Perception of milky/creamy aroma
Saltiness	Perception of a salty flavour in the mouth (salt-like)
Savouriness	Perception of glutamate (umami), spices and herbs (broth-like)
Sourness	Perception of a sour flavour in the mouth
Sweetness	Perception of a sweet flavour in the mouth (sugar-like)

Appendix 5.2. Mean perceived intensity scores of all attributes in the exteroceptive condition. The superscript letters obtained from Tukey’s HSD indicate a significant difference between samples (p<0.05) for an attribute.

		Chewiness	Crumbliness	Crunchiness	Creaminess	Hardness	Lumpiness	Mouth-coating	Melting	Particle size	Stickiness	Mouthfeel heterogeneity	Smoothness	Grittiness	Bell pepper flavour	Dairy flavour	Savoury	Sourness	Sweetness	Saltiness
Control samples	HO	2.0^{e}	1.3^{c}	0.4^{d}	7.1^{a}	1.4^{c}	1.0^{c}	6.2^{a}	6.1^{a}	0.9^{e}	4.8^{a}	1.1^{d}	7.0^{a}	1.2^{c}	0.4^{e}	7.5^{a}	2.8^{b}	2.9	2.8^{b}	3.3
	HOF	2.2^{de}	1.5^{c}	0.6^{d}	6.5^{b}	1.6^{bc}	1.2^{c}	6.0^{a}	6.0^{a}	1.0^{e}	4.8^{a}	1.8^{d}	6.9^{a}	1.3^{c}	6.4^{bc}	5.3^{de}	3.8^{a}	2.5	3.7^{a}	3.2
Bell pepper gel particles	S-	2.9^{bc}	3.3^{ab}	1.9^{bc}	5.5^{c}	1.8^{bc}	3.9^{b}	4.7^{bc}	4.5^{bc}	3.1^{d}	3.9^{b}	5.7^{b}	4.1^{bc}	3.7^{a}	5.8^{c}	5.9^{bc}	3.5^{a}	2.7	3.3^{ab}	3.1
	M-	3.2^{ab}	3.1^{ab}	2.4^{b}	5.1^{cd}	2.6^{a}	4.9^{a}	4.5^{bc}	4.1^{cd}	5.3^{b}	3.6^{b}	5.9^{ab}	3.6^{cd}	2.3^{b}	6.2^{bc}	5.7^{cd}	3.7^{a}	2.7	3.4^{ab}	3.1
	L-	3.9^{a}	3.2^{ab}	3.1^{a}	5.2^{cd}	2.9^{a}	5.3^{a}	4.4^{bc}	4.3^{cd}	6.8^{a}	3.8^{b}	6.3^{ab}	3.6^{cd}	2.4^{b}	6.7^{b}	5.8^{cd}	3.6^{a}	2.6	3.7^{a}	3.2
Real bell pepper particles	RLo	2.7^{cd}	2.6^{b}	1.7^{c}	6.0^{b}	2.1^{b}	3.7^{b}	4.9^{b}	5.0^{b}	4.1^{c}	3.9^{b}	4.8^{c}	4.7^{b}	2.4^{b}	4.6^{d}	6.4^{b}	3.2^{ab}	2.7	3.1^{b}	3.0
	RHi	3.9^{a}	3.6^{a}	3.1^{a}	4.7^{d}	3.0^{a}	5.5^{a}	4.2^{c}	3.8^{d}	6.1^{a}	3.5^{b}	6.7^{a}	3.2^{d}	2.9^{b}	7.4^{a}	5.1^{e}	3.6^{a}	2.6	3.7^{a}	3.1

Appendix 5.3. Mean perceived intensity scores of all attributes in the interoceptive condition. The superscript letters obtained from Tukey's HSD indicate a significant difference between samples (p<0.05) for an attribute.

		Chewiness	Crumbliness	Crunchiness	Creaminess	Hardness	Lumpiness	Mouth-coating	Melting	Particle size	Stickiness	Mouthfeel heterogeneity	Smoothness	Grittiness	Bell pepper flavour	Dairy flavour	Savoury	Sourness	Sweetness	Saltiness
Control samples	HO	1.9^{cd}	1.1^{g}	0.4^{g}	6.8^{a}	1.2^{f}	1.4^{f}	5.9^{a}	5.5^{a}	1.4^{g}	4.4^{a}	1.8^{e}	6.4^{a}	1.3^{e}	1.3^{d}	6.9^{a}	3.2	2.7	2.5^{b}	3.6
	HOF	2.1^{cd}	1.2^{fg}	0.3^{g}	6.2^{ab}	1.6^{bcdef}	1.4^{f}	5.6^{ab}	5.5^{a}	1.4^{g}	4.0^{ab}	2.3^{e}	6.1^{ab}	1.3^{e}	3.2^{c}	6.1^{b}	3.4	2.7	2.9^{ab}	3.2
Small sized bell pepper gels	S20	1.7^{d}	2.5^{bcde}	0.5^{fg}	5.6^{bcde}	1.5^{cdef}	2.5^{f}	4.9^{bcd}	4.8^{ab}	2.4^{f}	3.2^{bcd}	3.8^{d}	4.9^{cd}	3.1^{b}	3.8^{bc}	5.9^{bcd}	3.5	2.7	3.0^{ab}	3.1
	S100	2.2^{bcd}	3.2^{ab}	0.9^{defg}	5.5^{bcde}	1.6^{bcdef}	4.1^{bcd}	4.6^{cd}	4.7^{abc}	3.2^{def}	3.2^{bcd}	5.0^{abc}	4.1^{defg}	4.7^{a}	4.4^{b}	5.8^{bcd}	3.8	2.6	3.2^{ab}	3.4
	S250	2.7^{abc}	3.6^{a}	1.2^{def}	4.9^{ef}	1.9^{abcde}	4.5^{abc}	4.6^{cd}	4.2^{bcd}	3.8^{cde}	2.8^{d}	5.3^{ab}	3.6^{fg}	4.6^{a}	4.3^{b}	5.4^{bcd}	3.8	2.6	2.8^{ab}	3.3
Medium sized bell pepper gels	M20	2.1^{cd}	2.2^{de}	0.8^{efg}	5.8^{bc}	1.3^{def}	3.3^{de}	4.8^{bcd}	4.8^{ab}	2.8^{ef}	3.3^{bcd}	4.2^{cd}	5.2^{bc}	2.5^{bcd}	4.5^{b}	5.8^{bcd}	3.6	2.6	3.3^{a}	3.4
	M100	2.6^{abc}	3.0^{abcd}	1.2^{def}	5.2^{cdef}	2.0^{abcd}	4.5^{abc}	4.8^{bcd}	4.3^{bcd}	4.5^{abc}	3.3^{bcd}	5.3^{ab}	4.1^{defg}	2.9^{bc}	4.6^{b}	5.8^{bcd}	3.8	2.7	3.1^{ab}	3.4
	M250	3.1^{a}	3.3^{ab}	1.2^{de}	4.5^{f}	2.2^{ab}	5.3^{a}	4.1^{d}	3.8^{d}	4.8^{ad}	3.0^{cd}	5.6^{ad}	3.3^{g}	3.4^{b}	4.2^{b}	5.2^{d}	3.0	3.4	2.4^{ab}	3.0
Large sized bell pepper gels	L20	2.0^{cd}	2.3^{cde}	0.7^{efg}	5.8^{bc}	1.3^{ef}	3.0^{e}	4.7^{cd}	4.8^{ab}	3.1^{def}	3.3^{bcd}	3.8^{d}	4.8^{cde}	2.1^{cde}	4.5^{b}	5.8^{bcd}	3.2	2.9	3.1^{ab}	3.0
	L100	2.5^{abc}	3.0^{abcd}	1.2^{def}	5.2^{cdef}	2.2^{abc}	4.6^{abc}	4.6^{cd}	4.4^{bcd}	4.6^{abc}	3.1^{cd}	5.1^{abc}	4.0^{defg}	2.8^{bc}	4.3^{b}	5.6^{bcd}	3.5	2.7	3.1^{ab}	3.3
	L250	3.2^{a}	3.2^{abc}	1.5^{cd}	4.9^{ef}	2.2^{ab}	4.6^{abc}	4.3^{d}	3.9^{cd}	4.9^{a}	3.1^{cd}	5.3^{ab}	3.5^{fg}	2.8^{bc}	4.5^{b}	5.2^{cd}	3.3	2.6	3.2^{ab}	3.4
Real bell pepper particles	RLo	2.6^{abc}	2.0^{ef}	2.0^{bc}	5.7^{bcd}	1.9^{abcde}	3.3^{de}	5.0^{bc}	4.6^{bcd}	3.9^{bcd}	3.7^{abc}	4.7^{bcd}	4.5^{cde}	1.8^{de}	4.6^{b}	5.8^{bcd}	3.7	2.7	2.9^{ab}	3.5
	RMe	3.0^{ab}	2.4^{bcde}	2.3^{ab}	5.4^{cde}	2.3^{a}	3.9^{cd}	4.8^{cd}	4.4^{bcd}	4.4^{abc}	3.4^{bcd}	5.4^{ab}	4.2^{def}	2.8^{bc}	5.6^{a}	5.4^{bcd}	4.0	2.5	3.0^{ab}	3.3
	RHi	3.3^{a}	2.7^{abcde}	2.7^{a}	5.0^{def}	1.8^{abcdef}	5.0^{ab}	4.5^{cd}	4.3^{bcd}	5.3^{a}	3.0^{cd}	5.8^{a}	3.9^{efg}	2.7^{bcd}	6.4^{a}	5.4^{bcd}	3.9	2.7	3.2^{a}	3.1

Appendix 5.4. Mean perceived intensity scores of all attributes in the combined condition. The superscript letters obtained from Tukey's HSD indicate a significant difference between samples ($p<0.05$) for an attribute.

		Chewiness	Crumbliness	Crunchiness	Creaminess	Hardness	Lumpiness	Mouth-coating	Melting	Particle size	Stickiness	Mouthfeel heterogeneity	Smoothness	Grittiness	Bell pepper flavour	Dairy flavour	Savoury	Sourness	Sweetness	Saltiness
Control samples	HO	2.1^{hi}	1.1^{f}	0.4^{h}	7.2^{a}	1.4^{fg}	0.9^{f}	6.1^{a}	5.8^{a}	0.6^{g}	4.6^{a}	1.0^{c}	7.2^{a}	0.8^{e}	0.3^{e}	7.3^{a}	2.8^{b}	3.8^{a}	2.2^{d}	3.7^{a}
	HOF	2.2^{ghi}	1.8^{ef}	0.5^{h}	5.2^{efg}	1.9^{cdefg}	1.2^{f}	5.1^{bcde}	4.3^{de}	0.9^{g}	3.7^{b}	1.6^{c}	5.6^{b}	2.2^{cd}	4.9^{bcd}	5.4^{d}	3.6^{a}	2.9^{b}	3.2^{bc}	3.6^{ab}
Small sized bell pepper gels	S20	1.9^{i}	2.9^{abc}	1.1^{gh}	6.1^{bc}	1.3^{g}	2.9^{e}	5.4^{bc}	5.4^{ab}	2.5^{f}	3.7^{b}	4.1^{b}	5.4^{b}	3.3^{b}	4.4^{cd}	6.5^{b}	3.7^{a}	2.9^{b}	3.4^{abc}	3.3^{abc}
	S100	2.7^{defgh}	3.5^{a}	1.9^{def}	5.2^{fg}	2.1^{cde}	4.0^{bc}	4.6^{de}	4.8^{bcde}	2.7^{f}	3.5^{b}	5.7^{a}	4.2^{d}	4.2^{a}	4.8^{cd}	6.2^{bc}	3.5^{a}	2.7^{b}	3.7^{ab}	3.5^{ab}
	S250	3.1^{cdef}	3.3^{ab}	2.1^{de}	4.8^{g}	2.3^{bcd}	3.9^{bcd}	4.4^{e}	4.1^{e}	2.9^{ef}	3.2^{b}	6.1^{a}	3.5^{d}	4.5^{a}	4.8^{cd}	6.1^{bc}	3.5^{a}	2.5^{b}	3.3^{bc}	2.9^{bc}
Medium sized bell pepper gels	M20	2.3^{fghi}	2.6^{bcd}	1.4^{efg}	6.0^{bcd}	1.6^{defg}	3.3^{cde}	5.3^{bcd}	5.2^{abc}	3.8^{d}	3.9^{ab}	3.9^{b}	5.2^{b}	2.3^{cd}	4.8^{cd}	6.2^{b}	3.6^{a}	2.7^{b}	3.6^{abc}	3.4^{abc}
	M100	3.1^{bcde}	2.9^{abc}	2.3^{cd}	5.4^{cdefg}	2.5^{abc}	4.4^{ab}	4.5^{de}	4.4^{cde}	4.8^{c}	3.4^{b}	5.6^{a}	4.0^{d}	2.9^{bc}	5.1^{bcd}	6.2^{bc}	3.6^{a}	3.1^{b}	3.4^{abc}	3.5^{ab}
	M250	3.5^{abc}	3.3^{ab}	2.5^{cd}	4.9^{fg}	2.9^{ab}	4.9^{a}	4.6^{de}	4.1^{e}	5.1^{bc}	3.3^{b}	6.1^{a}	3.5^{d}	2.6^{bcd}	4.6^{cd}	6.0^{bcd}	3.4^{a}	3.5^{b}	2.9^{bc}	3.3^{abc}
Large sized bell pepper gels	L20	2.3^{efghi}	2.7^{bcd}	1.3^{fg}	6.2^{b}	1.5^{efg}	3.3^{cde}	5.5^{ab}	5.4^{ab}	4.9^{c}	3.8^{b}	4.1^{b}	5.4^{b}	2.0^{cd}	4.9^{bcd}	6.4^{b}	3.5^{a}	2.7^{b}	3.7^{ab}	3.2^{abc}
	L100	3.2^{bcd}	3.0^{abc}	2.3^{cd}	5.3^{defg}	2.4^{abc}	4.8^{ab}	4.8^{cde}	4.5^{cde}	5.9^{ab}	3.7^{b}	5.5^{a}	4.3^{cd}	2.5^{bcd}	5.2^{bc}	6.1^{bc}	3.6^{a}	3.0^{b}	3.4^{abc}	3.2^{abc}
	L250	3.8^{ab}	3.3^{ab}	2.8^{bc}	4.9^{fg}	3.0^{a}	5.1^{a}	4.5^{de}	4.2^{e}	6.3^{a}	3.6^{b}	6.1^{a}	3.7^{d}	2.4^{cd}	4.9^{bcd}	6.1^{bc}	3.5^{a}	3.0^{b}	3.4^{abc}	3.3^{abc}
Real bell pepper particles	RLo	2.9^{cdefg}	1.9^{de}	2.8^{bc}	5.9^{bcde}	2.0^{cdef}	3.1^{de}	5.6^{ab}	5.1^{bcd}	3.7^{de}	3.9^{ab}	4.0^{b}	5.2^{bc}	1.8^{d}	4.3^{d}	6.5^{b}	3.3^{ab}	3.0^{b}	2.9^{c}	3.4^{abc}
	RMe	3.5^{abcd}	2.3^{cde}	3.4^{ab}	5.6^{bcdef}	2.4^{abc}	4.3^{ab}	5.1^{bcde}	4.8^{bcde}	4.9^{c}	3.8^{b}	5.4^{a}	4.2^{d}	2.2^{cd}	5.7^{b}	5.9^{bcd}	3.6^{a}	2.6^{b}	3.6^{ab}	2.9^{bc}
	RHi	4.1^{a}	2.9^{abc}	3.8^{a}	5.2^{fg}	2.5^{abc}	4.8^{ab}	4.5^{e}	4.6^{cde}	6.0^{a}	3.2^{b}	6.2^{a}	3.9^{d}	2.2^{cd}	6.8^{a}	5.5^{cd}	3.6^{a}	2.6^{b}	4.0^{a}	2.8^{c}

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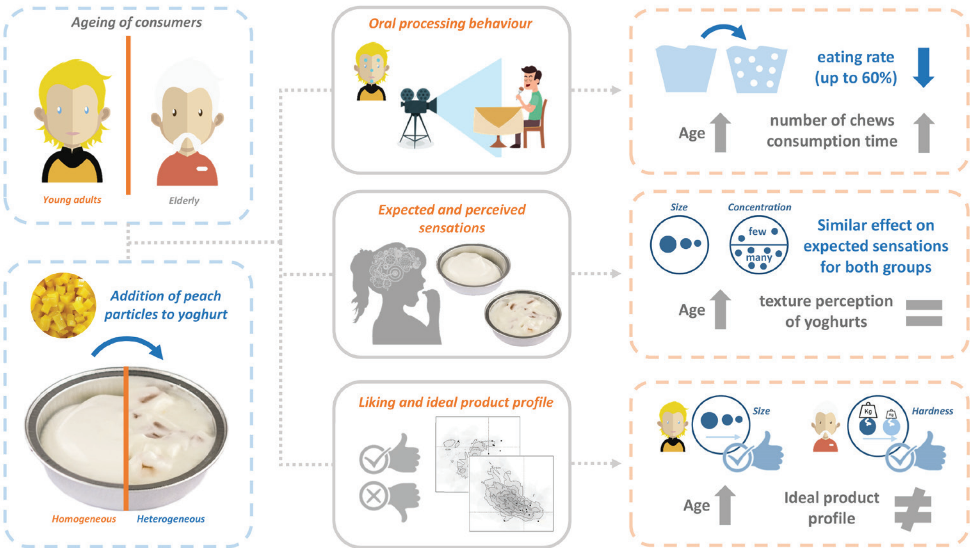
Appendix 5.5. Mean perceived liking intensity scores of the different attributes obtained with ANOVA for the Interoceptive, Expected and Combined condition. The superscript letters obtained from Tukey's HSD indicate significant difference between the samples (p<0.05).

	Interoceptive			Exteroceptive			Combined		
	Liking Overall	Liking Flavour	Liking Texture	Liking Overall	Liking Flavour	Liking Texture	Liking Overall	Liking Flavour	Liking Texture
HO	6.5^{a}	6.4	6.3^{a}	6.7^{a}	6.7^{a}	6.8^{a}	6.2^{a}	6.0	6.3^{a}
HOF	6.3^{ab}	6.3	5.9^{ab}	6.1^{abc}	6.2^{ab}	6.2^{ab}	5.8^{ab}	5.9	5.5^{ab}
S20	6.1^{ab}	6.2	5.6^{abc}				6.4^{ab}	6.7	6.1^{abc}
S100	5.8^{abc}	6.1	5.0^{cd}	6.3^{ab}	6.6^{ab}	5.7^{bc}	6.2^{abc}	6.6	5.4^{bc}
S250	5.7^{abc}	6.3	4.7^{cde}				5.8^{abc}	6.4	5.0^{cd}
M20	6.1^{ab}	6.3	5.5^{abc}				6.4^{ab}	6.6	6.1^{abc}
M100	5.7^{abc}	6.3	4.8^{cde}	5.7^{bc}	6.1^{ab}	5.0^{cd}	6.2^{abc}	6.6	5.2^{cde}
M250	5.0^{c}	6.1	4.0^{e}				5.0^{c}	5.7	4.0^{e}
L20	6.1^{ab}	6.2	5.5^{abc}				6.5^{ab}	6.5	6.2^{abc}
L100	5.8^{abc}	6.2	4.8^{cde}	5.4^{c}	5.9^{b}	4.6^{d}	5.7^{abc}	6.2	5.2^{cde}
L250	5.6^{bc}	6.2	4.4^{de}				5.4^{bc}	5.9	4.7^{de}
RLo	6.0^{ab}	6.2	5.3^{bc}	6.0^{abc}	6.3^{ab}	5.4^{cd}	6.4^{ab}	6.4	5.9^{bc}
RMe	5.8^{ab}	6.2	5.0^{cd}	-	-	-	6.3^{ab}	6.5	5.6^{cd}
RHi	5.6^{bc}	6.2	4.8^{cde}	5.4^{c}	6.0^{b}	4.6^{d}	5.9^{bc}	6.4	5.3^{cd}

Chapter 6

HETEROGENEOUS BITES

HOW ADDITION OF PARTICLES TO YOGHURT AFFECTS EXPECTATIONS, SENSORY PERCEPTION AND ORAL BEHAVIOUR OF CONSUMERS DIFFERING IN AGE



This chapter is submitted as:

Aguayo-Mendoza*, M., Santagiuliana*, M., Ong, X., Piqueras-Fiszman, B., Scholten, E., Stieger, M., How addition of peach gel particles to yogurt affects expectations, sensory perception and oral behavior of consumers differing in age. (**The authors have contributed equally to this work*)

Abstract

Addition of particles to foods, such as fruit pieces to dairy products or vegetable pieces to soup, is a convenient approach to alter nutritional composition, appearance, perception and acceptance. The aim of this study was to investigate the effect of addition of peach gel particles to yoghurt on oral behaviour, expected, perceived, and ideal sensory properties of consumers differing in age. One homogeneous yoghurt and seven yoghurts with peach gel particles were prepared. The added peach gel particles varied in size, fracture stress, or concentration. Oral behaviour of n=62 Dutch, young adult (21±2 years) and n=62 Dutch elderly (70±5 years) participants was characterized by video recordings, and yoghurts' sensory properties were scored on nine-point scales. Elderly consumed yoghurts with higher number of chews and longer consumption time leading to lower eating rate than young adults. Addition of particles, regardless of characteristics, increased number of chews, consumption time, and decreased eating rate up to 60% for both consumer groups, with an average decrement of 110 g/min for young and of 63 g/min for elderly consumers. With increasing peach gel hardness and concentration, the number of chews and consumption time increased while eating rate decreased. Peach gel particle size did not affect eating behaviour. Expected and perceived sensory properties of yoghurts with added peach gel particles were similar for young adult and elderly consumers. Only small differences were observed for expected and perceived flavour attributes, crumbliness, juiciness, and perceived particle size. Thus, ageing seems to affect sensory perception of semi-solid foods to a limited extent only. Yoghurts containing soft and medium hard peach gel particles were defined as the ideal yoghurt by elderly consumers. In contrast, young adult consumers did not have a defined ideal profile for yoghurt. We conclude that changes in food texture by addition of particles can be used as a strategy to steer eating rate and potentially impact food intake of young adult and elderly consumers while maintaining or enhancing food palatability. Additionally, particle characteristics can be modified to target specific consumer groups that might differ in eating capabilities.

6.1 Introduction

The principal role of oral processing is the transformation of food into a bolus that can be safely swallowed to continue through the digestive system. It basically involves two elements, food structural changes and physiological actions, making oral processing considerably different between foods and subjects (Foegeding et al., 2017). Several studies investigated how physical differences between homogeneous foods and differences in consumer physiology related to ageing affect oral processing. Koç et al. (2014) showed for food gels that an increment in fracture stress of 6.5 folds can double consumption time and number of chews. With respect to bite size, Aguayo-Mendoza et al. (2019) observed that bite size of yoghurts decreased by 20% when the consistency K (Pa s) increased by 16 folds. These observations indicate that large variations in rheological and mechanical properties of foods have a significant impact on oral behaviour. Ketel, Kohyama and Mioche (2019; 2002; 2004) reported that elderly chewed foods such as rice, cheese, bread and meat, for longer time and with more chews than young adult consumers. Ageing has an impact on oral physiology as muscle activity decreases and dental status deteriorates. These changes have several consequences on eating capability, sensory perception, and food enjoyment (Laguna & Chen, 2016), leading to a reduced food intake and a weakened nutritional status of the elderly population. Food developers aiming to boost satisfaction and to increase food intake in elderly need to find new strategies to provide products that are more pleasant and easier to consume; thus, better understanding the ability of elderly consumers to orally process foods and gaining further insights into their sensory perception is of critical importance.

The addition of food particles into macroscopically homogeneous food matrices, such as fruit pieces in yoghurt or vegetable pieces in soups, is a convenient approach to alter nutritional composition, sensory perception, acceptance and food intake. Depending on the properties of the particles, this addition might lead to the perception of texture contrast. Such texture contrast has been suggested to be the main reason for the high palatability of many composite foods (Lévy et al., 2006; Szczesniak & Kahn, 1984). Recent studies have shown that addition of particles can largely affect consumer expectations, sensory perception, and liking of soups and processed cheeses (**Chapters 3**, **4** and **5**). When considering a liquid matrix, the addition of carrot pieces to chicken soups made the sensory profile closer to the ideal product profile compared with chicken soups without particles (**Chapter 4**). Thus, particle addition can be a valuable approach to change expected and perceived sensory perception, while enhancing consumer appreciation. However, the consumers' response to the addition of particles in foods may have a different effect for consumers differing in age. Differences in either social and cultural factors (Piqueras-Fiszman & Spence, 2015) or physiological characteristics (Morley, 2001) might result in opposite expectations or hedonic responses. For instance, reduced eating capabilities might lead to different ideal product properties and preferences for the elderly (i.e. preference for easy-to-swallow foods) than for young adults (i.e. preference for more chewy/hard foods).

In addition, several studies have demonstrated that addition of particles to homogeneous foods can reduce food and energy intake within a meal (Larsen et al., 2016; Morell et al., 2018; Tang et al., 2016; Tarrega et al., 2016). Addition of particles leads to an earlier satiation by providing additional sensory stimulation or by prolonging oro-sensory exposure time. These studies did not focus on the elderly population and little is known on the effect of particle addition on oral behaviour for elderly.

To summarize, adding particles to foods seems to be a promising and convenient way to steer eating behaviour, improve palatability, and influence food intake. Yet, the applicability of this approach has not been investigated for elderly consumers. Therefore, the aim of this study was to investigate the effect of the addition of peach gel particles varying in size, fracture stress and concentration to yoghurt on oral processing behaviour, expected, perceived and ideal sensory profiles of consumers differing in age. We hypothesize that oral processing is influenced by size, fracture stress, and concentration of added particles. Elderly consumers are expected to display longer oral processing time than young, adult consumers. We hypothesize that both expectations and sensory perception of heterogeneous yoghurts might differ between young adults and elderly due to diverse physiological and psychological characteristics. Finally, we hypothesize that the ideal yoghurt of elderly consumers is a homogeneous yoghurt, since yoghurts without pieces are easier to eat and swallow.

6.2 Material and methods

6.2.1 Materials

Optimel® Greek style peach yoghurt was provided by FrieslandCampina (Amersfoort, The Netherlands). Agar was purchased from Caldic Ingredients B.V. (Rotterdam, The Netherlands). Holland Ingredients B.V. (Meppel, The Netherlands) kindly provided annatto (orange food colorant, WS 2.5%, E160b). Titanium dioxide (TiO_2, E171), riboflavin (yellow food colorant, 10% PWS, E101) and peach aroma were purchased from Pomona Aroma B.V. (Hedel, The Netherlands). Canned peaches (PLUS, Utrecht, The Netherlands) and crackers without salt (Bayman Barendrecht, The Netherlands) were purchased from a local supermarket. All ingredients were food safe and samples were prepared under food safe conditions.

6.2.2 Sample preparation

6.2.2.1 Peach gel preparation

Peach gel particles varying in size and fracture stress (σ_F) were prepared using agar as gelling agent and peach extract to provide flavour. Canned peaches were used to prepare the peach extract. Canned peaches were drained from the syrup and rinsed with tap water. Peaches were then blended using a hand blender (Braun MQ 745, Kronberg im Taunus, Germany) and the obtained puree was centrifuged at 3900 g for 20 min (Beckman Coulter Allegra X-30R, Fullerton, USA). The supernatant (peach extract) was collected and sieved (mesh size 63μm). The peach extract was stored at -20ºC for a maximum period of 4 weeks.

Table 6.1. Composition of the model peach gels varying in fracture stress. All concentrations are given in weight percentage (% w/w).

Target fracture stress (kPa)	Peach extract	Agar	Peach aroma	TiO_2	Riboflavin	Annatto
20	98.5	1.4	0.049	0.039	0.025	0.024
60	97.3	2.5	0.049	0.039	0.024	0.023
100	96.3	3.6	0.048	0.039	0.024	0.023

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Peach gels were prepared by combining the peach extract with agar in different concentrations as shown in **Table 6.1**. The concentration of agar was varied to obtain gels with different target fracture stresses (σ_F: 20, 60, and 100 kPa). Peach aroma, TiO_2, riboflavin and annatto were added to resemble the appearance and flavour of real peach pieces. The concentrations used are provided in **Table 6.1**. To prepare the gels, solutions were heated under continuous stirring in a water bath at 95ºC for 45 min. The heated solutions were poured either in disposable plastic containers to obtain samples for the sensory evaluation or in 30 ml syringes (Terumo, Leuven, Belgium) for instrumental sample characterization. Solutions were placed on ice for 1 h to initiate gel formation. After cooling, gels for the sensory evaluation were cut in cubes of 3x3x3, 7x7x7, and 10x10x10 mm using a mandolin (Michel BRAS, Laguiole, France) (**Figure 6.1**). The gels for instrumental characterization were cut into cylinders with a diameter of 23 mm and a height of 15 mm and measured ~24 hrs after preparation. Gels for the sensory evaluation were stored at 4ºC for a maximum of one week.

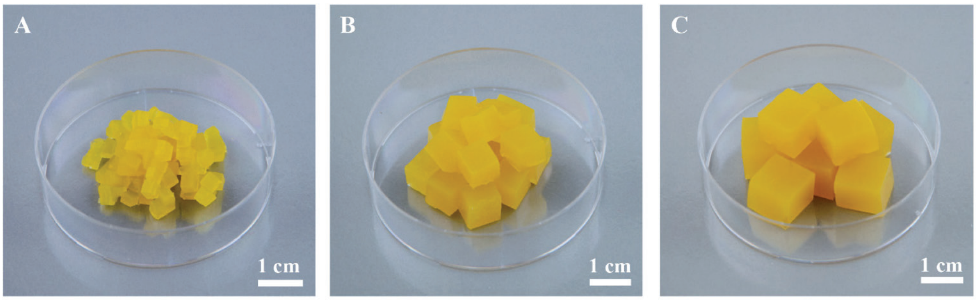

Figure 6.1. Peach gels varying in size; (a) small 3x3x3 mm, (b) medium 7x7x7 mm and (c) large 10x10x10 mm peach gel particles.

6.2.2.2 Yoghurt preparation

Optimel® Greek style peach flavoured yoghurt was sieved to remove the peach pieces present in the commercially available yoghurt and then stored at 4ºC for a maximum of one week. Eight yoghurts were obtained by adding peach gel particles to the yoghurt matrix in different concentration and with different size and hardness. The properties of the different samples and the corresponding codes are depicted in **Table 6.2**. The sample codes consist of four letters and one number. The first two letters indicate particle size, Sm(-), Me(-), and La(-) for small, medium, and large particles respectively, the next two letters indicate the fracture stress, (-)So, (-) Me, and (-)Ha for soft, medium, and hard particles, whereas the subscript number indicates the particle concentration, 10, 15, and 20 for low (10%), medium (15%), and high (20%). The sample code for the homogeneous yoghurt without particles is HO. This incomplete factorial experimental design was chosen to reduce the number of evaluated samples yet allowing for an investigation of the different variables considered. By comparing (HO), $SmMe_{15}$, $MeMe_{15}$, and $LaMe_{15}$ the effect of particle size on oral behaviour and perception was studied while keeping peach gel particle fracture stress and concentration constant; by comparing (HO), $MeSo_{15}$, $MeMe_{15}$, and $MeHa_{15}$ the effect of particle hardness (fracture stress) on oral behaviour and perception was studied while particle size and concentration were constant; and finally by comparing (HO), $MeMe_{10}$, $MeMe_{15}$, and $MeMe_{20}$ the effect of particle concentration on oral behaviour and perception was studied while particle size and fracture stress were constant.

Peach gel particles at 4ºC were added to the yoghurt less than 5 min before serving to prevent changes in mechanical properties. The serving temperature of the yoghurt with particles was 4ºC.

Table 6.2. Samples codes for homogeneous yoghurt without particles (HO) and heterogeneous yoghurts with added particles. The first two letters indicate particle size, Sm(-), Me(-) and La (-) for small, medium and large particles respectively, the second letter indicates the fracture stress, (-)So, (-)Me and (-)Ha for soft, medium and hard particles, whereas the subscript number indicates the particle concentration, 10, 15 and 20 for low, medium and high.

Sample code	Particle size (mm)	Fracture stress σ_F (kPa)	Particle concentration (% w/w)
HO	-	-	-
$SmMe_{15}$	3x3x3	60	15
$MeSo_{15}$	7x7x7	20	15
$MeMe_{15}$	7x7x7	60	15
$MeMe_{10}$	7x7x7	60	10
$MeMe_{20}$	7x7x7	60	20
$MeHa_{15}$	7x7x7	100	15
$LaMe_{15}$	10x10x10	60	15

6.2.3 Sample characterization

6.2.3.1 Uniaxial compression tests of model peach gels

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To determine the mechanical properties of the model peach gel particles, uniaxial compression tests were performed with a Texture Analyzer (TA.XT plus, Stable Micro Systems-SMS). A compression plate with a diameter of 100 mm combined with a load cell of 50 kg was used. Measurements were performed with a crosshead velocity of 1 mm/s and a compression strain of 70%. Gels varying in target fracture stress (σ_F: 20, 60, 100 kPa) were cut in a cylindrical form (diameter of 23 mm and a height of 15 mm) and measured at 20°C. To prevent friction between the sample and the compression plate, the top of the sample surface was lubricated with paraffin oil. Average real fracture stress and strain of each gel type were obtained from the measurements of at least four replicates. Fracture stress (σ_F) of model peach gels increased significantly [$F(2,14) = 4645.4$, $p<0.001$] with increasing concentration of gelling agent. Fracture stress of soft (-So), medium (-Me) and hard (-Ha) model peach gels were 21 ±1 kPa, 63 ±1 kPa and 99 ±2 kPa, respectively. True fracture strain (-) differed significantly [$F(2,14) = 18.60$, $p<0.01$] but only little between soft (-So), medium (-Me) and hard (-Ha) model peach gels and were determined as 0.30 ±0.01, 0.33 ±0.01 and 0.34 ±0.01, respectively.

6.2.3.2 Viscosity measurements of yoghurt

Rheological properties of yoghurt were determined using a rheometer (MCR 302, Anton Paar GmbH, Graz, Austria) with a C-CC17/T200/TI cup (diameter of 18.08 mm) and a CC17/TI cylinder (diameter of 16.66 mm and length of 24.95 mm). The rheometer was set in a rotational mode with shear rates increasing from 1-1000 s^{-1} and then decreasing from 1000-1 s^{-1} in a time period of 2.5 min. After pouring the yoghurt into the cup, a waiting time of 2 min was applied to reach equilibrium prior to measuring. The yoghurt was measured in triplicate at 4°C (storage/serving temperature) and 20°C (room temperature). Flow curves were obtained by measuring viscosity as a function of the shear rate. The obtained results at a shear rate from 1 to 1000 were then fitted using the Ostwald-de Waele model:

$$\eta = k\,\dot{y}^{(n-1)} \qquad (1)$$

where η is the viscosity (Pa.s), *k* the consistency (Pa.s), $\dot{y}$ the shear rate (s^{-1}) and n the flow behaviour index (-). The yoghurt measured at 4ºC displayed a consistency

k of 3.45 ±0.03 Pa·s and had a power law index n of 0.38. At 20ºC, the consistency significantly decreased ($p < 0.001$) to k = 2.92 ±0.05 Pa·s, while power law index remained unchanged as n = 0.38.

6.2.4 Characterization of oral processing behaviour and sensory evaluation

6.2.4.1 Participants

For this study, 62 young, adult Dutch participants (n=62, 9 male/53 female, average age 21±2 years) and 62 elderly Dutch participants (n=62, 24 male/38 female, average age 70±5 years) were recruited. Before participation, the subjects were asked to fill in a screening questionnaire in order to check whether they met the selection criteria. The selection criteria were based on nationality and ethnicity (Dutch with Caucasian ethnicity), age (between 18-25 years or above 60 years), BMI (18-30 kg/m^2), good general health (self-reported) and good dental status (a maximum of two dental implants or missing teeth). Participants were allowed to join the study if they had no braces or piercings in the mouth, did not use any medication that influences the chewing behaviour, were not pregnant or lactating, had general normal taste and smell functions, were non-smokers, and did not have allergies or intolerances to the food products used in this study. The subjects that met all the requirements were invited to an information session, where they received an explanation of the study set up and signed an informed consent form. After completion of the study, participants received financial compensation for their participation. The study was conducted in line with the Declaration of Helsinki.

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6.2.4.2 Oral processing behaviour characterization

To determine the oral processing behaviour, each participant was individually video recorded in a well-lit room while consuming yoghurts at a serving temperature of 4ºC. Before starting the video recording, the researcher placed four circular stickers on the participant's face, serving as markers, to perform the analysis of the video recordings. Two stickers were placed on the forehead spaced 5 cm apart horizontally, one on the tip of the nose (reference point), and one on the centre of the chin (mobile point).

Participants were seated in a chair in front of a table with a video camera (Logitech c270, Apples, Switzerland). The camera was set approximately 50 cm from the participant's face to ensure a complete picture of the face without distracting or discomforting the participants. They were instructed to hold their head straight by looking at an indicated point on a computer screen and not to block their mouth or face while eating. They received a fixed bite size of 10 g of yoghurt sample (**Table 6.2**), served on a 6 ml table spoon (dimensions: 10.3x4x0.7 cm). Yoghurts were provided in randomized order and in monadic sequence. Participants were asked to ingest the entire content of the spoon at once, consume it as they would normally do, and to indicate the swallowing moments by raising a hand. After the last swallowing moment, the video recording was stopped.

From the video recording, consumption time (s), number of chews (-), number of swallows (-), chewing rate (chews/s) and eating rate (g/min) were extracted using Kinovea software (version 0.8.12) as described by Aguayo-Mendoza et al. (2019). The changes over time in the spatial position of the stickers placed on each participant's face relative to each other were extracted as X-Y coordinates. Then, the vertical displacement was computed as the difference between the nose's position and the chin marker at each time point. The number of chews was calculated by implementing a first derivative zero-crossing peak detection of the jaw's vertical displacement. Consumption time was defined as the time period when participants placed the sample in the mouth until the last swallow. Number of swallows were recorded by counting the number of times the participant raised the hand. Chewing rate indicates the number of chews per second whereas eating rate indicates the amount of food consumed per time unit (g/min).

6.2.4.3 Sensory evaluation of heterogeneous yoghurts

For the determination of the expected and perceived sensory profile, a two-step approach (Expected-Perceived) was used. In the first step (Expected), participants rated expected liking (overall liking, flavour liking, texture liking) and expected perceived intensity of different sensory attributes by looking at pictures of yoghurt (**Figure 6.2**, printed in real size) together with an objective and neutral description of the yoghurt (without tasting the product). The descriptions are specified in the caption of **Figure 6.2** (codification and exact sizes excluded). Participants indicated expected liking and expected perceived intensity of 13 attributes using a nine-point scale ranging from “not” to “very”. The list of sensory attributes, which were selected and tested during feasibility tests (data not shown), and their definitions are reported in **Table 6.3**. The pictures were provided to the participants in a counterbalanced sequential monadic fashion.

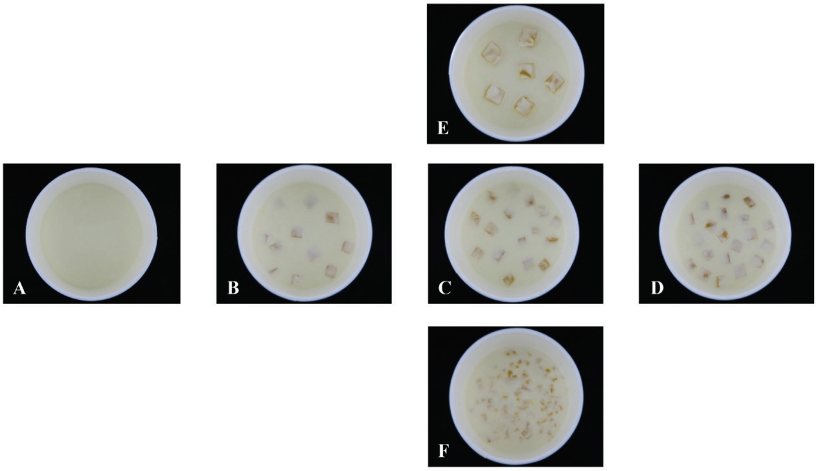

Figure 6.2. Pictures of yoghurts provided during the expected condition of the sensory study. A. Homogeneous yoghurt without peach gel particles (HO). B. Yoghurt with low concentration (10% w/w) of peach gel particles of medium size (7x7x7 mm; Me-10). C. Yoghurt with medium concentration (15% w/w) of peach gel particles of medium size (7x7x7 mm; Me-$_{15}$). D. Yoghurt with high concentration (20% w/w) of peach gel particles of medium size (7x7x7 mm; Me-$_{20}$). E. Yoghurt with medium concentration (15% w/w) of large peach gel particles (10x10x10 mm; La-$_{15}$). F. Yoghurt with medium concentration (15% w/w) of small peach gel particles (3x3x3 mm; Sm-$_{15}$).

The second step (Perceived) took place at least one week after the first step (Expected) and was divided into two separate sessions of 45 min each with a break of one week between sessions. Participants indicated perceived and ideal intensities of the different sensory attributes after tasting the yoghurts with and without particles at a serving temperature of 4°C using the Ideal Profile Method (IPM). Such a method allows a comparison of the sensory profile of the tested yoghurts with the participants’ ideal product profile (Worch et al., 2013). Participants also evaluated all samples on liking using a nine-point scale. Participants were asked not to eat for one hour prior to the sensory sessions. In each session, they were provided with four different samples of

40 g and a spoon similar to the one used during characterization of oral processing behaviour. Samples were presented in a monadic sequence with a randomized order. Participants were instructed to collect a spoonful of the sample containing an equal amount of particles each time, to rinse their mouth with water and to eat unsalted crackers between the evaluation of different samples while waiting for at least 1.5 min.

Table 6.3. Sensory descriptors and definitions used for quantification of expected and perceived sensory profiles.

Descriptor	Definition
Texture	
Chewiness	The amount of work required to masticate the sample (or its components) into a state ready for swallowing.
Creaminess	Sensation of a thick, smooth and velvety texture in the mouth.
Crumbliness	The extent to which the sample breaks into smaller pieces or fragments.
Dryness	Perception of a dry feeling in the mouth.
Hardness	Force required to compress and/or break the sample (or its components) between the teeth.
Juiciness	The amount of juice/moist released during consumption.
Particle size	Perception of the particle dimension in the mouth prior to the chewing process, on a scale from small to large.
Smoothness	A uniform perception of the product in the mouth during mastication.
Thickness	Force required to deform the sample and the perceived resistance to flow.
Flavour	
Dairy flavour	Perception of milky aroma.
Peach flavour	Perception of peach aroma.
Sourness	Perception of a sour flavour in the mouth.
Sweetness	Perception of a sweet flavour in the mouth (sugar like).

6.2.5 Data analysis

Oral processing behaviour data were analysed conducting factorial ANOVA analyses using IBM® SPSS® Statistics (version 24.0). The effect of age on oral behaviour (consumption time, number of chews, number of swallows, chewing rate, and eating rate) was determined using all samples. The effect of particle size, particle fracture stress and particle concentration on oral behaviour was determined using only the samples differing in the parameter of interest, while maintaining the other parameters constant (e.g. effect of particle fracture stress at 20, 60, and 100 kPa, with a constant particle size of 7x7x7 mm and particle concentration of 15% w/w). Main effects were considered statistically significant at $p<0.05$. When effects were significant, post hoc pairwise comparisons were performed using Bonferroni's adjustment.

Results with respect to expected sensory perception and the perceived sensory perception were analysed using R language (version 3.2.3). First the data were analysed separately by ANOVA considering young and elderly participants independently. Such analysis was performed to allow a comparison between all products, and when effects were significant, post-hoc pairwise comparisons were conducted with Tukey's HSD test ($p<0.05$). Two separate approaches were used to compare perception between participant groups. In the first approach, sensory perception data were analysed by Multiple Factor Analysis (MFA) to assess the configurational similarity of product spaces obtained from the young adult and elderly participants separately. Similarly, separated ideal product mappings for young adult and elderly participants were obtained from the combination of perceived and ideal intensities of the attributes for the different products according to the Ideal Profile Method (IPM). From the two ideal product mappings obtained, the product ideal profile of each participant group was compared. In the second approach, individual paired t-tests between the two participant groups were performed on the intensity scores of expected or perceived sensations. This approach allowed to identify the effect of participant age on specific sensory attributes in both Expected and Perceived condition.

The data regarding mechanical properties were analysed using Analysis of Variance (ANOVA) with $p<0.05$ and Tukey's HSD as post-hoc test. Two-tailed t-tests were used to compare viscosity measurements of yoghurt at different temperatures.

6.3 Results and discussion

6.3.1 Oral processing behaviour

6.3.1.1 Effect of age on oral processing behaviour of yoghurts

Oral processing behaviour was characterized and compared between young adult (n=62, age 21±2 years) and elderly (n=62, age 70±5 years) participants. Age had a significant effect on consumption time [$F(1,911) = 54.60$, $p<0.001$], number of chews [$F(1,911) = 50.95$, $p<0.001$] and eating rate [$F(1,911) = 29.31$, $p<0.001$]. **Figure 6.3** shows that elderly required significantly longer time (11.2 s ± 5.2) and more chews

(15.3 ± 7.6) than young adults (consumption time: 9.0 s ± 4.1; number of chews: 12.3 s ± 6.1). Moreover, elderly consumed yoghurts with a lower eating rate (68.0 g/min ± 0.6) than young adults (90.4 g/min ± 87). These differences between young adults and elderly in oral processing behaviour may be explained by physiological changes related to ageing such as the decrease of density of the mastication muscles and consequently the weakening of bite force. This reduction of bite force induces the subject to increase the number of chews and the consumption time until the bolus reaches a swallowable consistency (Field & Duizer, 2016; Ketel et al., 2019; Kohyama et al., 2002; 2003; Mishellany-Dutour et al., 2008).

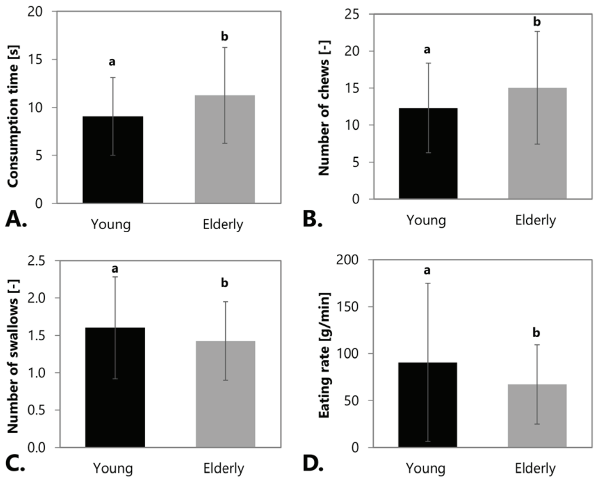

Figure 6.3. Oral processing behaviour of young adults (n=62, age 21±2 years) and elderly (n=62, age 70±5 years) masticating yoghurts. Mean ± SD values averaged over all yoghurts (Table 6.2) are shown for A) consumption time, B) number of chews, C) number of swallows, and D) eating rate. Different superscript letters indicate significant differences between consumer groups.

It should be noted that the young adult and elderly consumers were healthy and had good dental status with a maximum of two missing teeth or implants. Hence, the observed differences in eating behaviour between the two groups are probably not caused by differences in dental status between groups. The number of swallows significantly differed between groups [$F(1,911) = 24.61$, $p<0.001$]. It was observed that young adults swallowed more times than elderly, probably because the threshold volume to trigger a swallow is lower in young adults than in elderly (Shaker et al., 1994). In contrast, chewing rate did not differ significantly between young adults and elderly [F(1,911) = 0.59, p=0.442] suggesting that the central pattern generator in the brain, that controls chewing frequency is not affected by ageing (Morquette et al., 2012).

6.3.1.2 Effect of particle size on oral processing behaviour of young adults and elderly

To investigate the effect of peach gel particle size added to yoghurts, we compared the homogeneous yoghurt, the yoghurts with peach gel particles of 3x3x3 mm (small), 7x7x7 mm (medium), and 10x10x10 mm (large), while keeping the fracture stress and concentration constant at 60 kPa and 15% (w/w), respectively. The addition of peach gel particles to yoghurt had a significant effect on consumption time [F(3,451) = 55.28, p<0.001], number of chews [F(3,451) = 55.78, p<0.001], number of swallows [F(3,451) = 11.65, p<0.001], eating rate [F(3,451) = 41.71, p<0.001], and chewing rate [F(3,451) = 9.62, p<0.001] (**Figure 6.4**).

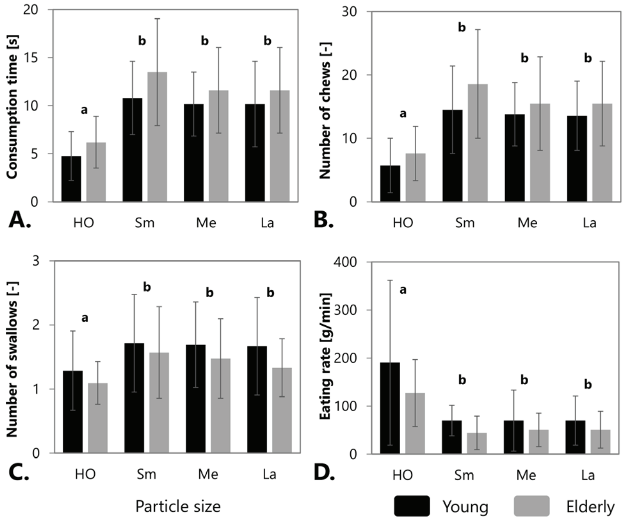

Figure 6.4. Oral processing behaviour of yoghurts without and with peach gel particles differing in particle size: (HO) yoghurt without particles, (Sm) yoghurt with particles of 3x3x3 mm, (Me) yoghurt with particles of 7x7x7 mm and (La) yoghurt with particles of 10x10x10 mm. All particles had a fracture stress of 60 kPa and were added at a concentration of 15% (w/w). Mean ± SD values are shown for A) consumption time, B) number of chews, C) number of swallows and D) eating rate. Different superscript letters indicate significant differences between samples within each oral behaviour descriptor (p<0.05). Dark bars indicate young adult consumers (n=62, age 21±2 years) whereas light bars depict elderly consumers (n=62, age 70±5 years).

The addition of peach gel particles more than doubled the number of chews and consumption time, and decreased eating rate by up to 60% compared to yoghurts without particles, with an average decrement of 110.2 g/min for young adults and of 63.2 g/min for elderly consumers. We suggest that addition of particles to yoghurts is a feasible and convenient strategy that can potentially be used to manipulate food and energy intake within a meal since changes in oral behaviour caused by modification of food texture have been related to satiation responses (McCrickerd et al., 2017; Tarrega et al., 2016).

Although the presence of peach gel particles affected oral behaviour, changes in particle size did not significantly affect any of the parameters describing oral processing behaviour. All yoghurts had a constant particle weight concentration (15% w/w). Therefore, increasing the size of the particle was accompanied by a decrease in the number of particles in the yoghurt. Consequently, yoghurts with the largest particle size (10x10x10 mm) had fewer particles whereas yoghurts with the smallest particles (3x3x3 mm) had more particles present. Size and number could have induced counteracting effects, and therefore no real changes were observed.

6.3.1.3 Effect of particle fracture stress on oral processing behaviour of young adults and elderly

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To investigate the effect of particle hardness on oral processing behaviour, the three samples with particles that varied in fracture stress (20, 60, and 100 kPa) with constant particle size of 7x7x7 mm at concentration of 15% w/w, were compared to each other together with the HO sample. The addition of peach gel particles significantly influenced all oral processing parameters. Between the yoghurts with particles differing in fracture stress, a significant effect was found on consumption time [$F(3,452) = 62.05$, $p<0.001$], number of chews [$F(3,452) = 66.96$, $p<0.001$], and eating rate [$F(3,452) = 38.59$, $p<0.001$] (**Figure 6.5**). We observed that in average for both consumer groups, an increment of 80 kPa (from 20 to 100 kPa) in fracture stress of the particles increased consumption time and number of chews by approximately 40% whereas eating rate decreased by 30%. These findings demonstrate that oral behaviour adapted to fracture stress of the particles. These results are in line with other studies that demonstrated that with increasing food hardness, consumption time and number of chews increase and eating rate decreases (Aguayo-Mendoza et al., 2019; Engelen et al., 2005). Furthermore, the results show that between groups elderly consumers are slightly less affected by the increments in particle fracture stress than young adults.

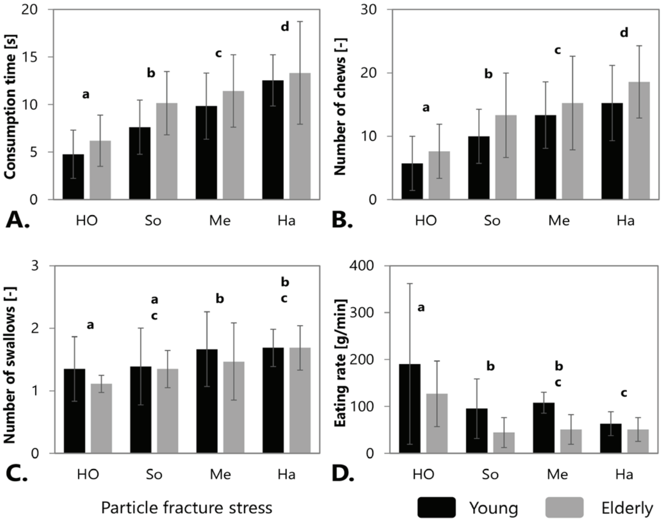

Figure 6.5. Oral processing behaviour of yoghurts without and with added peach gel particles differing in particle fracture stress (kPa): (HO) yoghurt without particles, (So) yoghurt with particles with fracture stress of 20 kPa, (Me) yoghurt with particles with fracture stress of 60 kPa and (Ha) yoghurt with particles with fracture stress of 100 kPa. All particles had a size of 7x7x7 mm and were present at a concentration of 15%(w/w). Mean ± SD values are shown for A) consumption time, B) number of chews, C) number of swallows and D) eating rate. Different superscript letters indicate significant differences between samples within each oral behaviour descriptor (p<0.05). Dark bars indicate young adult consumers (n=62, age 21±2 years) whereas light bars depict elderly consumers (n=62, age 70±5 years).

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For number of swallows and chewing rate, the results are slightly different. Although particle fracture stress had a significant effect on the number of swallows [$F(3,452) = 11.15$, $p<0.001$], this effect was present only when medium or hard particles were added to the yoghurt, but not when soft particles were added. Soft particles may be easy to deform and compressed between the tongue and palate, and therefore little chewing effort is required. Subjects are therefore not required to increase the number of swallows since these particles may directly be swallowed without the need to remain in the mouth for further chewing. Medium and hard particles needed a longer oral processing time due to a mechanism that involves continuous chewing of large particles until they are softened and reduced in size to the point that they are ready to be swallowed. This long process of chewing leads to several swallows. Chewing rate was least influenced by particle hardness. While the addition of particles had a significant influence [$F(3,452) = 11.26$ $p<0.001$], there was no difference between yoghurts containing particles varying in particle hardness. This is consistent with other literature that shows that chewing rate is relatively constant and independent of the food properties (Aguayo-Mendoza et al., 2019; Andersone et al., 2002).

6.3.1.4 Effect of particle concentration on oral processing behaviour of young adults and elderly

Particle concentration had a significant effect on consumption time [$F(3,451) = 56.48$, $p<0.001$] and number of chews [$F(3,451) = 61.06$, $p<0.001$]. **Figure 6.6** shows that in yoghurts with peach gel particles, an increment in concentration (w/w) by 10% from 10 to 20% caused an increment of the number of chews and consumption time of 20%. From 11.8 to 14.3 chews and 8.8 s to 10.6 s for young adults and from 14.6 to 17.7 chews and 11.0 s to 12.8 s for elderly. However, smaller increments on particle concentration of 5% (w/w) (e.g. 10–15% or 15–20%) did not cause significant differences in number of chews nor consumption time.

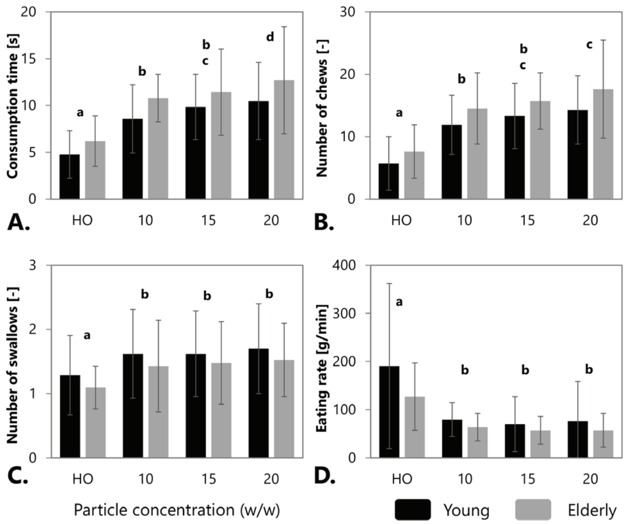

Figure 6.6. Oral processing behaviour of yoghurts without and with peach gel particles differing in particle concentration: (HO) yoghurt without particles, (10) yoghurt with a particle concentration of 10%, (15) yoghurt with a particle concentration of 15%, and (20) yoghurt with a particle concentration of 20% (w/w). All particles had a size of 7x7x7 mm and fracture stress of 60 kPa. Mean ± SD values are shown for A) consumption time, B) number of chews, C) number of swallows and D) eating rate. Different superscript letters indicate significant differences between samples within each oral behaviour descriptor (p<0.05). Dark bars indicate young adult consumers (n=62, age 21±2 years) whereas light bars depict elderly consumers (n=62, age 70±5 years).

Eating rate [F(3,451) = 34.44, p<0.001], number of swallows [F(3,451) = 12.01, p<0.001] and chewing rate [F(3,451) = 9.72, p<0.001] significantly differed between the homogeneous yoghurt and the heterogeneous yoghurts with peach gel particles, but not between yoghurts with particles differing in concentration.

6.3.2 Sensory properties

6.3.2.1 Expected sensory properties of yoghurts without and with added peach gel particles of young adults and elderly

The expected sensory profiles based on picture evaluations of yoghurts without and with added peach gel particles by young adults and elderly were compared using Multiple Factor Analysis (MFA). **Figure 6.7A** shows the first two dimensions of the consensus MFA map (explaining 88.29% of the total variance), whereas **Figure 6.7B** reports the loading plot of the two groups considering all products.

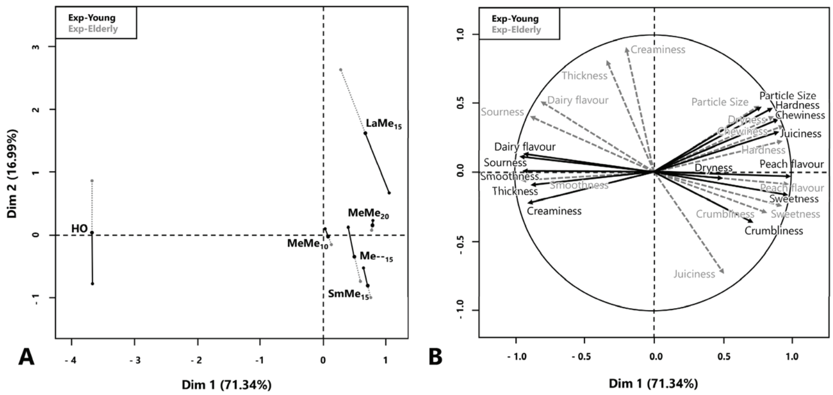

Figure 6.7. A. Consensus MFA sample space (first two components) with superimposed partial points from expected sensory properties for young adult (n=62, age 21±2 years) and elderly (n=62, age 70±5 years) consumers. B. Loading plot of expected attributes for young adults (continuous, black) and elderly (dashed, grey).

Considering the proximity of the partial product configurations (**Figure 6.7A**), small differences in expected sensory properties of yoghurts between the two consumer groups can be observed for four of the six yoghurts tested ($SmMe_{15}$; $MeMe_{10}$; $MeMe_{20}$, $MeMe_{15}$). The expected sensory profiles differed considerably between the two consumer groups for two yoghurts only; the homogeneous yoghurt (HO) and the yoghurt containing large medium hard particles ($LaMe_{15}$). The homogeneous yoghurt (HO) differed (see **Appendix 6.1**) in terms of expected chewiness, juiciness, particle size, peach flavour (significantly higher for elderly), and smoothness, dairy flavour, and sourness (significantly higher for young adults). For yoghurts containing large medium hard particles ($LaMe_{15}$), differences in crumbliness, dryness, thickness (significantly higher for elderly), and peach flavour, and sweetness (significantly higher for young adults) were observed.

When the positions of the expected sensory attributes of the two groups are compared in **Figure 6.7B**, similar tendencies are observed. For both groups, the left side of the plot is characterized by the presence of homogeneous-related attributes (i.e. smoothness, creaminess, dairy flavour) and the right side is linked to particle-related attributes (i.e. chewiness, sweetness, peach flavour). For both groups, expected sensory properties were influenced in a similar manner by the presence, concentration and size of added peach gel particles (see **Appendix 6.2** and **6.3**). Similar outcomes were obtained in our previous studies investigating sensory perception of soups and cheeses with added vegetable particles (**Chapters 4** and **5**), suggesting that the addition of particles and variation in their properties (i.e. size and concentration) can change the expected sensory profile in a similar manner in different types of foods.

Addition of peach gel particles to yoghurts resulted in a different expected sensory profile compared to that of the homogeneous yoghurt for both consumer groups. Considering **Figure 6.7A**, the first dimension is mostly described by the presence or absence of peach particles (HO being further left compared to the rest of the samples), while the second dimension can be linked to the size of the particles (small to large from bottom to top).

From the comparison of expected attribute values between young adults and elderly reported in **Appendix 6.1**, additional insights can be obtained when the significant differences of attributes for all the products are examined (i.e. across-attribute comparison). Overall, the expected sensations differed between the two groups mainly in terms of expected crumbliness, juiciness, peach flavour, sourness and sweetness (**Appendix 6.1**). Elderly expected all yoghurts containing peach gel particles to be significantly crumblier and with lower intensities of peach flavour and sweetness than the younger adults. These results suggest that the expected sensory profiles between young adults and elderly mainly differ in expected product flavour.

In summary, the results show that, although a few differences (i.e. crumbliness, juiciness, peach flavour, sourness and sweetness) were noticed between the young adult and elderly, large variations in the expected sensory profiles were noticed only for two out of the six yoghurts; the homogeneous yoghurt and yoghurt containing large peach gel particles. We conclude that expected sensory properties for both groups are influenced by the product properties (i.e. presence, concentration and size of added particles) in a similar way and that age does not considerably affect textural expectations of sensory properties in yoghurts.

6.3.2.2 Perceived sensory properties of yoghurts without and with added peach gel particles by young adults and elderly

Multiple Factor Analysis (MFA) was used to compare the perceived sensory properties of all products for the two groups, as previously done for the expected sensory properties. The consensus MFA map considering the first two dimensions (explaining 68.70% of the total variance) is depicted in **Figure 6.8A**, while the correlation plot of the two groups is reported in **Figure 6.8B**.

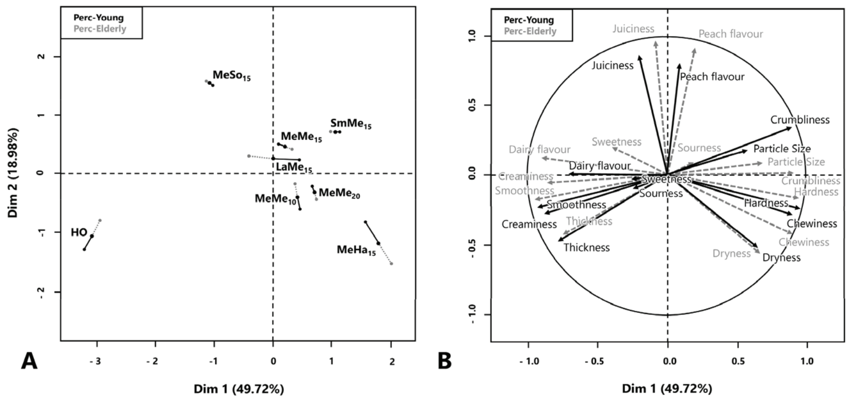

Figure 6.8. A. Consensus MFA sample space (first two components) with superimposed partial points from perceived sensory properties for young adult (n=62, age 21±2 years) and elderly (n=62, age 70±5 years) consumers. B. Loading plot of perceived attributes for young adults (continuous, black) and elderly (dashed, grey).

Overall, in both **Figure 6.8A** and **6.8B**, very similar profiles can be observed for the two consumer groups as both product locations and sensory attributes showed only small differences between the groups.

The minor discrepancies across all products between young adults and elderly can be further examined by looking at the comparison between averaged values of perceived attributes intensities (across-attribute comparison; **Appendix 6.4**). Consumer groups varying in age differed in sweetness and sourness perception, as elderly perceived most of the yoghurts as less sweet and sour than the young adults, probably as a result of sensitivity deterioration. Changes in sensory acuity due to age-related impairments have been reported by many other studies (Fukunaga et al., 2005; Kennedy et al., 2010; Kremer et al., 2007; Mojet et al., 2003). Regarding textural attributes, differences in the averaged scored intensity between groups were only observed for crumbliness and particle size, for which elderly participants gave significantly lower scores than young participants. This suggests that the ageing of healthy participants mainly affects taste perception but influences texture perception of semi-solid foods only marginally.

The mean values of the different sensory attributes (**Appendix 6.5** and **6.6**) show that a variation in particle size influenced perception of creaminess, thickness, and particle size for young adults, while for elderly, such a variation only significantly affected crumbliness and particle size. No significant effects of particle size on chewiness, dryness, hardness, juiciness, smoothness, sourness, sweetness, dairy and peach flavour were observed in either group. For both consumer groups, increasing the particle fracture stress from 20 to 60 to 100 kPa ($MeSo_{15}$, $MeMe_{15}$, $MeHa_{15}$) resulted in a significant increase in perceived chewiness and hardness, while it significantly decreased smoothness. Yoghurts containing soft particles were perceived as smoother, less chewy and hard compared to the yoghurts containing hard particles ($MeHa_{15}$) for both young and elderly participants. For both consumer groups, a variation in particle concentration (10, 15 or 20% w/w) did not yield any significant difference in product perception.

We conclude that age has only a very limited effect on perceived sensory properties of yoghurts without and with added peach gel particles. For both young adults and

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elderly, an increase in particle size led to a decrease in creaminess and thickness perception, while higher hardness and chewiness were perceived with an increase in particle hardness and concentration, respectively. We conclude that ageing marginally affected texture perception of semi-solid heterogeneous products (i.e. lower crumbliness and particle size for elderly), whereas larger effects were found for taste perception (e.g. perceived sourness and sweetness).

6.3.3.3 Expected and perceived liking of yoghurts without and with added peach gel particles by young adults and elderly

Table 6.4 reports the averaged values for overall liking, flavour liking, and texture liking in the expected and perceived conditions for young adults and elderly.

Table 6.4. Mean expected and perceived liking scores per sample for young adults (n=62, age 21±2 years) and elderly (n=62, age 70±5 years) separately. Superscript letters indicate significant differences between samples within each row (p<0.05).

Expected Liking											
		F-value	p-value	SmMe$_{15}$	MeSo$_{15}$	MeMe$_{15}$	MeMe$_{10}$	MeMe$_{20}$	MeHa$_{15}$	LaMe$_{15}$	HO
Young	Overall liking	9.89	<0.001	5.0^{b}	6.0^{a}	6.0^{a}	5.9^{a}	5.8^{a}	6.0^{a}	4.9^{b}	5.5^{ab}
	Flavour liking	8.01	<0.001	5.9^{a}	6.1^{a}	6.1^{a}	6.2^{a}	6.1^{a}	6.1^{a}	5.7^{a}	5.1^{b}
	Texture liking	11.03	<0.001	4.0^{b}	5.2^{a}	5.2^{a}	5.0^{a}	5.1^{a}	5.2^{a}	4.0^{b}	5.8^{a}
Elderly	Overall liking	1.72	0.103	5.5^{a}	5.5^{a}	5.5^{a}	5.6^{a}	5.8^{a}	5.5^{a}	5.1^{a}	5.9^{a}
	Flavour liking	2.60	0.013	5.6^{a}	5.5^{ab}	5.5^{ab}	5.4^{ab}	5.6^{a}	5.5^{ab}	5.2^{ab}	4.9^{b}
	Texture liking	2.32	0.025	5.1^{ab}	5.2^{ab}	5.2^{ab}	5.4^{a}	5.3^{a}	5.2^{ab}	4.5^{b}	5.3^{a}
Perceived Liking											
Young	Overall liking	11.43	<0.001	5.1^{d}	6.0^{b}	5.9^{bc}	5.6^{bcd}	5.3^{cd}	5.4^{bcd}	5.4^{bcd}	6.8^{a}
	Flavour liking	2.97	0.004	5.9^{ab}	6.4^{a}	5.8^{ab}	6.0^{ab}	5.5^{b}	5.8^{ab}	5.8^{ab}	6.4^{a}
	Texture liking	24.32	<0.001	3.6^{d}	5.7^{b}	5.4^{bc}	5.4^{bc}	5.0^{bc}	4.8^{c}	4.9^{c}	6.9^{a}
Elderly	Overall liking	3.82	<0.001	5.2^{ab}	5.8^{a}	5.1^{ab}	5.4^{ab}	5.1^{ab}	4.7^{b}	5.9^{a}	5.9^{a}
	Flavour liking	2.91	0.005	5.3^{ab}	5.7^{a}	5.1^{ab}	5.4^{ab}	5.0^{ab}	4.5^{b}	5.7^{a}	5.5^{ab}
	Texture liking	3.22	0.002	4.9^{b}	5.6^{ab}	5.3^{ab}	5.4^{ab}	5.3^{ab}	4.9^{b}	5.9^{a}	5.9^{a}

During the first tested condition (Expected), participants based their expected hedonic responses on visual cues and product description. From **Table 6.4**, small variations in expected liking ratings can be seen. In terms of overall liking and liking texture, young adults expected to like yoghurts containing small and large peach gel particles significantly less than the homogeneous yoghurt (HO) and yoghurts containing medium-sized particles (Me-$_{15}$). Considering expected overall liking, no differences between the samples were observed for the elderly. For such older group, however, yoghurt containing large particles (LaMe$_{15}$) were expected to be liked in texture significantly less than homogeneous yoghurt and yoghurts with medium-sized particles at low and high concentration (MeMe$_{10}$, MeMe$_{20}$). Thus, no large differences in expected liking were observed between young and elderly consumers.

When the actual perceived hedonic responses are concerned (**Table 6.4**), homogeneous yoghurts were preferred over yoghurts with hard particles in terms of overall liking, flavour and texture by both consumer groups. Young adults liked the texture of homogeneous yoghurts more than yoghurts containing soft, medium and hard peach gel particles and evaluated the texture of yoghurts containing small particles as the least liked in texture. Also for the elderly, yoghurts containing small (SmMe$_{15}$) or hard particles (MeHa$_{15}$) were significant less liked than the homogeneous yoghurt and the yoghurts with medium or soft particles.

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For the young participants, variation in particle size affected significantly the hedonic response as yoghurt with medium-sized particles was liked more than products containing small and large particles. Such effect of particle size was not observed for the elderly group. In this group, the effect of particles hardness was more prominent; an increase in particle hardness (MeHa$_{15}$) decreased overall liking significantly. For both consumer groups, particle concentration did not affect hedonic responses.

We conclude that the expected liking of heterogeneous yoghurts was mainly influenced by particle size, with medium-sized peach gel particles being expected to be the most liked. For young consumers, perceived liking was mainly affected by variation in particle size, whereas for elderly, this was mostly affected by particle hardness.

6.3.3.4 Ideal profile

The perceived and ideal intensities of the investigated attributes for the different yoghurts were combined using the Ideal Profiling Method (IPM). As the consumers' ideal product might not be necessarily present among the evaluated yoghurts, the comparison between perceived sensations and ideal intensities allows to gain a more comprehensive understanding of consumers' expectations and preferences towards the investigated yoghurts. The ideal mapping based on liking overall for all samples is presented for young adults in **Figure 6.9A** and for elderly in **Figure 6.9B**.

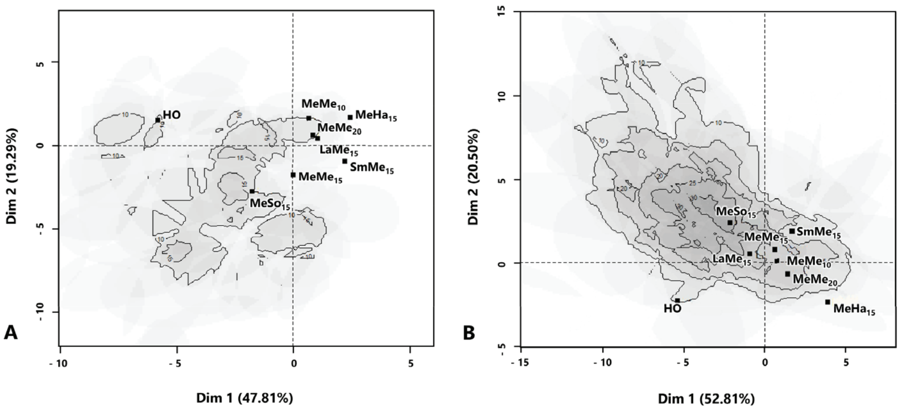

Figure 6.9. Ideal mapping of young adults (A) (n=62, age 21±2 years) and elderly (B) (n=62, age 70±5 years) based on overall liking.

For young adults (**Figure 6.9A**), no clear agreement on the sensory properties of an ideal product was reached. This indicates that the belief of ideal products among the young adults was scattered around the different product sensory properties. In contrast, for elderly (**Figure 6.9B**), agreement on the sensory properties of an ideal product was reached with samples containing soft particles ($MeSo_{15}$) being closest to the ideal product (darkest area in the figure). For the elderly consumers, yoghurts containing hard particles ($MeHa_{15}$) were the farthest away from the darkest area of the map implying that these samples differed considerably from their ideal product.

The IPM suggests that the ideal profile for elderly consists in a yoghurt containing soft particles, whereas young adults do not seem to have a strongly defined ideal profile. We explain the difference between consumer groups considering the peach gel particles used in this study. We speculate that these particles might have been less liked by young adults than elderly consumers, especially in terms of texture (see **Table 6.4**). The relatively low scores of perceived texture liking might clarify the discrepancy between expected (i.e. heterogeneous yoghurts preferred) and perceived liking (i.e. homogeneous yoghurts preferred) for the young consumer group. On the contrary, elderly did generally like the peach gel particles added to yoghurts and, therefore, this determined a confirmation of their expectations and proper formation of their ideal product profile. Therefore, for the development of heterogeneous products, we recommend that the added particles should be tested independently from the dispersing matrix, especially when the product is targeted to different consumer groups.

We conclude that the addition of soft particles or gels could be used as an efficient strategy to modify an existing elderly-targeted food product. For young adults, further participant investigation and/or segmentation might be required to implement such a strategy.

6.3.4 Practical applications

Particle addition to yoghurt is a convenient approach that can be applied in two manners depending on the consumer characteristics. For example, consumers aiming to reduce food intake can benefit from the reduction of eating rate generated upon particle addition and an increase in particle fracture stress. A reduced eating rate has shown to decrease meal portion size and ad libitum food intake within a meal (Ferriday et al., 2016; Hogenkamp & Schiöth, 2013; Robinson et al., 2014). In order to benefit from the aforesaid approach, the particles added should not increase the food energy density and should preferable be low caloric.

The approach can also be used to increase food intake. This may especially be relevant for the elderly population. The elderly consumers described the yoghurt containing soft and medium size particles at medium concentration (15% w/w) as their ideal product. The preferred composite foods over homogeneous foods suggests that such composite foods could lead to a higher food intake. Pleasantness of food is an important determinant of food choice and food intake (Hetherington, 1998). Thus, manufacturing yoghurts containing nutrient-rich particles that meet the ideal particle characteristics may be an appropriate strategy to increase elderly's food enjoyment and boost nutrient intake. It has to be kept in mind, that the characteristics of the food should not change the oral behaviour to such extent that consumption time is increased to large extent. This would again lead to a decrease in food intake.

6.4 Conclusions

The findings of this study highlight that particle addition to macroscopically homogeneous products such as yoghurt prolong oral processing time and decrease eating rate in healthy young adult and elderly consumers. The present study showed that in heterogeneous yoghurts, elderly had a lower eating rate and higher number of chews than young participants. Particularly, increasing particle concentration and particle fracture stress increased consumption time and number of chews. Only small differences in expected and perceived textural profiles of heterogeneous yoghurts were found between young adults and elderly consumers. Larger discrepancies in perception between the two groups were found mainly for flavour-related attributes. Differences were also found between the ideal product profile as young adults did not have a defined ideal profile for yoghurt, whereas yoghurts containing soft and medium hard peach gel particles were defined as the ideal yoghurt by elderly consumers. We conclude that addition of soft-solid particles to yoghurts can be used as an effective strategy to change oral processing behaviour and possibly impact food intake within a meal. This approach can be employed to tune sensory perception and enhance product palatability especially in products directed to the elderly population.

Appendix 6.1 Comparison between expected intensities of different descriptors between young adults and elderly consumers. The presence of arrows shows a significant difference between the two groups. ↓ indicate that expected perception of that attribute was significantly higher for young adults, whereas ↑ indicate that expected perception of that attribute was significantly higher for elderly consumers. The superscript *, **, * depicts significant difference between scores at p<0.05, p<0.01 and p<0.001 respectively.**

	Chewiness	Creaminess	Crumbliness	Dryness	Hardness	Juiciness	Particle size	Smoothness	Thickness	Dairy flavour	Peach flavour	Sourness	Sweetness
HO	↑ **					↑ ***	↑ *	↓*		↓ ***	↑ ***	↓ ***	
$SmMe_{15}$	↑ *		↑ *			↑ **					↓*	↓**	↓**
$MeSo_{15}$			↑ ***			↓*					↓***	↓*	↓***
$MeMe_{15}$			↑ ***			↑ *					↓***	↓*	↓***
$MeMe_{10}$			↑ *			↑ **	↑ *				↓*	↓*	↓**
$MeMe_{20}$			↑ *						↑ *		↓**		↓**
$MeHa_{15}$			↑ ***			↑ *					↓***	↓*	↓***
$LaMe_{15}$			↑ **	↑ *			↑ ***		↑ ***		↓***		↓**

Appendix 6.2 Mean expected intensities of different descriptors per sample for young Dutch adults. Superscript letters indicate significant differences between samples within a column with (p<0.05).

	Chewiness	Creaminess	Crumbliness	Dryness	Hardness	Juiciness	Particle size	Smoothness	Thickness	Dairy flavour	Peach flavour	Sourness	Sweetness
F value	14.40	2.94	4.86	0.42	19.28	4.89	139.92	19.57	0.28	14.04	94.22	7.81	26.69
P value	<0.001	0.005	<0.001	0.889	<0.001	<0.001	<0.001	<0.001	0.959	<0.001	<0.001	<0.001	<0.001
HO	1.1^{d}	6.2^{a}	1.1^{c}	1.8^{a}	1.2^{d}	4.0^{c}	0.0^{d}	8.1^{a}	4.7^{a}	7.7^{a}	1.5^{c}	6.3^{a}	3.5^{c}
$SmMe_{15}$	2.5^{c}	5.1^{b}	2.6^{a}	2.1^{a}	2.6^{c}	4.9^{b}	2.6^{c}	4.8^{c}	4.4^{a}	5.4^{ab}	6.2^{ab}	4.5^{c}	6.2^{ab}
$MeSo_{15}$	3.0^{bc}	5.4^{b}	1.7^{b}	1.9^{a}	3.3^{b}	5.3^{ab}	5.3^{b}	5.6^{b}	4.3^{a}	6.1^{b}	6.5^{a}	4.7^{bc}	6.1^{ab}
$MeMe_{15}$	3.0^{bc}	5.4^{b}	1.7^{b}	1.9^{a}	3.3^{b}	5.3^{ab}	5.3^{b}	5.6^{b}	4.3^{a}	6.1^{b}	6.5^{a}	4.7^{bc}	6.1^{ab}
$MeMe_{10}$	2.8^{bc}	5.5^{b}	1.7^{b}	1.9^{a}	3.2^{b}	5.2^{ab}	5.6^{b}	5.4^{bc}	4.4^{a}	6.1^{b}	5.8^{b}	5.0^{b}	5.6^{b}
$MeMe_{20}$	3.3^{ab}	5.2^{b}	1.9^{b}	1.8^{a}	3.7^{ab}	5.4^{ab}	5.7^{b}	5.4^{bc}	4.3^{a}	5.9^{b}	6.7^{a}	4.5^{c}	6.4^{a}
$MeHa_{15}$	3.0^{bc}	5.4^{b}	1.7^{b}	1.9^{a}	3.3^{b}	5.3^{ab}	5.3^{b}	5.6^{b}	4.3^{a}	6.1^{b}	6.5^{a}	4.7^{bc}	6.1^{ab}
$LaMe_{15}$	3.7^{a}	5.0^{b}	1.7^{b}	2.0^{a}	4.3^{a}	5.6^{a}	7.6^{a}	5.2^{bc}	4.3^{a}	6.0^{b}	6.3^{ab}	4.8^{bc}	5.7^{b}

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Appendix 6.3 Mean expected intensities of different descriptors per sample for elderly Dutch consumers. Superscript letters indicate significant differences between samples within a column with (p<0.05).

	Chewiness	Creaminess	Crumbliness	Dryness	Hardness	Juiciness	Particle size	Smoothness	Thickness	Dairy flavour	Peach flavour	Sourness	Sweetness
F value	10.04	0.74	6.10	0.83	11.06	1.38	92.85	7.87	1.37	1.37	9.75	0.99	4.40
P value	<0.001	0.641	<0.001	0.564	<0.001	0.210	<0.001	<0.001	0.277	<0.001	<0.001	0.441	<0.001
HO	1.4^{c}	5.8^{a}	1.4^{c}	2.0^{a}	1.4^{c}	5.4^{a}	0.3^{e}	7.3^{a}	5.3^{a}	6.3^{a}	2.7^{b}	4.8^{a}	3.9^{c}
$SmMe_{15}$	3.2^{b}	5.5^{a}	3.7^{a}	2.5^{a}	3.0^{b}	5.8^{a}	2.6^{d}	4.9^{b}	5.0^{a}	5.3^{c}	5.4^{a}	4.1^{a}	5.4^{ab}
$MeSo_{15}$	3.3^{b}	5.4^{a}	2.8^{b}	2.5^{a}	3.6^{ab}	6.0^{a}	5.4^{c}	5.4^{b}	4.9^{a}	5.6^{bc}	5.1^{a}	4.1^{a}	5.2^{ab}
$MeMe_{15}$	3.3^{b}	5.4^{a}	2.8^{b}	2.5^{a}	3.6^{ab}	6.0^{a}	5.4^{c}	5.4^{b}	4.9^{a}	5.6^{bc}	5.1^{a}	4.1^{a}	5.2^{ab}
$MeMe_{10}$	3.4^{ab}	5.7^{a}	2.4^{b}	2.4^{a}	3.3^{ab}	5.9^{a}	6.3^{b}	5.4^{b}	4.9^{a}	5.6^{cd}	5.1^{a}	4.3^{a}	4.8^{b}
$MeMe_{20}$	3.5^{ab}	5.6^{a}	2.5^{b}	2.6^{a}	4.0^{a}	5.8^{a}	6.0^{bc}	5.3^{b}	5.1^{a}	5.7^{abc}	5.6^{a}	4.1^{a}	5.5^{a}
$MeHa_{15}$	3.3^{b}	5.4^{a}	2.8^{b}	2.5^{a}	3.6^{ab}	6.0^{a}	5.4^{c}	5.4^{b}	4.9^{a}	5.6^{bc}	5.1^{a}	4.1^{a}	5.2^{ab}
$LaMe_{15}$	4.1^{a}	6.3^{a}	2.7^{b}	2.8^{a}	3.9^{a}	5.3^{a}	7.6^{a}	5.0^{b}	5.5^{a}	5.9^{ab}	5.0^{a}	4.4^{a}	4.9^{ab}

Appendix 6.4 Comparison between perceived intensities of different descriptors between young adults and elderly consumers. The presence of arrows shows a significant difference between the two groups. ↓ indicate that perception of that attribute was significantly higher for young adults, whereas ↑ indicate that perception of that attribute was significantly higher for elderly consumers. The superscript *, **, * depicts significant difference between scores at p<0.05, p<0.01 and p<0.001 respectively.**

	Chewiness	Creaminess	Crumbliness	Dryness	Hardness	Juiciness	Particle size	Smoothness	Thickness	Dairy flavour	Peach flavour	Sourness	Sweetness
HO											↓*	↓*	↓**
$SmMe_{15}$						↑ *							↓*
$MeSo_{15}$			↓***				↓***					↓**	↓***
$MeMe_{15}$			↓*				↓*					↓***	↓***
$MeMe_{10}$			↓*		↓*								↓**
$MeMe_{20}$			↓*				↓*				↓*	↓**	↓**
$MeHa_{15}$												↓**	↓***
$LaMe_{15}$			↓*				↓**						↓*

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Appendix 6.5 Mean perceived intensities of different descriptors per sample for young Dutch adults. Superscript letters indicate significant differences between samples within a column with (p<0.05).

	Chewiness	Creaminess	Crumbliness	Dryness	Hardness	Juiciness	Particle size	Smoothness	Thickness	Dairy flavour	Peach flavour	Sourness	Sweetness
F value	10.38	4.01	6.24	0.77	15.51	6.89	112.87	6.59	4.62	0.66	1.14	0.33	0.65
P value	<0.001	<0.001	<0.001	0.610	<0.001	<0.001	<0.001	<0.001	<0.001	0.704	0.337	0.941	0.714
HO	1.3^{c}	6.8^{a}	1.4^{b}	3.2^{a}	1.5^{c}	3.5^{c}	0.1^{d}	6.9^{a}	6.4^{a}	5.5^{a}	5.4^{a}	3.8^{a}	6.4^{a}
SmMe$_{15}$	2.3^{b}	5.6^{c}	3.6^{a}	3.3^{a}	3.1^{b}	3.8^{bc}	1.8^{c}	4.8^{c}	5.0^{c}	5.1^{a}	5.8^{a}	3.5^{a}	6.3^{a}
MeSo$_{15}$	1.6^{c}	6.1^{bc}	2.8^{a}	3.0^{a}	1.9^{c}	5.3^{a}	4.2^{b}	5.9^{b}	5.3^{bc}	5.4^{a}	5.8^{a}	3.8^{a}	6.2^{a}
MeMe$_{15}$	2.3^{b}	6.1^{bc}	3.0^{a}	3.4^{a}	2.8^{b}	4.4^{b}	4.7^{b}	5.6^{bc}	5.4^{bc}	5.0^{a}	5.9^{a}	3.9^{a}	6.5^{a}
MeMe$_{10}$	2.3^{b}	6.1^{bc}	3.1^{a}	3.7^{a}	3.3^{ab}	3.7^{bc}	4.6^{b}	5.5^{bc}	5.6^{bc}	5.4^{a}	5.5^{a}	3.7^{a}	6.2^{a}
MeMe$_{20}$	2.7^{ab}	5.8^{bc}	3.2^{a}	3.3^{a}	3.5^{ab}	3.9^{bc}	4.7^{b}	5.6^{bc}	5.4^{bc}	5.3^{a}	5.4^{a}	3.7^{a}	6.1^{a}
MeHa$_{15}$	3.2^{a}	5.8^{bc}	3.3^{a}	3.7^{a}	3.9^{b}	3.4^{c}	4.8^{b}	5.1^{bc}	5.3^{bc}	5.1^{a}	5.4^{a}	3.8^{a}	6.3^{a}
LaMe$_{15}$	2.7^{ab}	6.2^{ab}	3.4^{a}	3.5^{a}	3.3^{ab}	3.9^{bc}	6.5^{a}	5.3^{bc}	5.8^{ab}	5.4^{a}	6.0^{a}	3.6^{a}	6.3^{a}

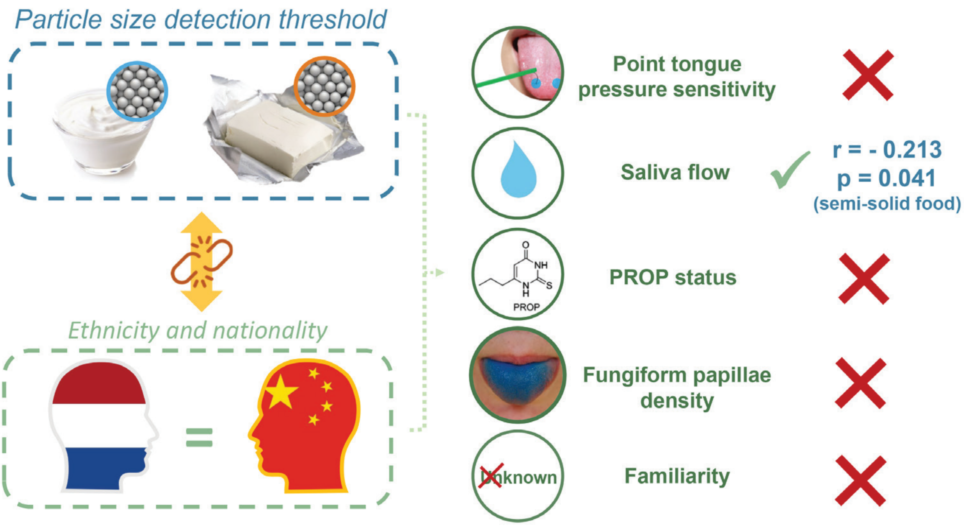
Appendix 6.6 Mean perceived intensities of different descriptors per sample for elderly Dutch. Superscript letters indicate significant differences between samples within a column with (p<0.05).

	Chewiness	Creaminess	Crumbliness	Dryness	Hardness	Juiciness	Particle size	Smoothness	Thickness	Dairy flavour	Peach flavour	Sourness	Sweetness
F value	5.40	2.47	7.21	1.79	9.39	1.86	41.07	6.86	2.43	0.31	1.94	1.25	0.49
P value	<0.001	0.017	<0.001	0.088	<0.001	0.074	<0.001	<0.001	0.019	0.947	0.062	0.726	0.841
HO	1.4^{d}	6.5^{a}	1.3^{d}	2.9^{a}	1.4^{c}	4.0^{a}	0.2^{e}	7.0^{a}	6.3^{a}	5.4^{a}	4.5^{a}	3.0^{a}	5.5^{a}
SmMe$_{15}$	2.2^{ab}	5.6^{bc}	3.3^{a}	3.1^{a}	3.4^{ab}	4.6^{a}	2.1^{d}	4.9^{c}	5.2^{b}	5.0^{a}	5.4^{a}	3.3^{a}	5.4^{a}
MeSo$_{15}$	1.5^{cd}	5.8^{abc}	1.6^{cd}	2.7^{a}	1.7^{c}	5.0^{a}	2.9^{c}	5.8^{b}	5.4^{b}	5.3^{a}	5.7^{a}	2.8^{a}	5.2^{a}
MeMe$_{15}$	2.0^{bcd}	5.8^{abc}	2.1^{bc}	3.3^{a}	2.6^{bc}	4.6^{a}	4.0^{b}	5.1^{bc}	5.6^{ab}	5.1^{a}	5.2^{a}	3.0^{a}	5.2^{a}
MeMe$_{10}$	2.4^{ab}	5.9^{abc}	2.3^{bc}	3.4^{a}	2.7^{b}	4.3^{a}	4.0^{b}	5.5^{bc}	5.4^{b}	5.2^{a}	5.2^{a}	3.5^{a}	5.1^{a}
MeMe$_{20}$	2.6^{ab}	5.6^{b}	2.4^{bc}	3.0^{a}	3.1^{ab}	4.0^{a}	3.9^{b}	5.2^{bc}	5.4^{b}	5.1^{a}	5.0^{a}	2.9^{a}	5.1^{a}
MeHa$_{15}$	2.8^{a}	5.3^{c}	2.9^{ab}	3.9^{a}	3.7^{a}	3.8^{a}	4.5^{b}	4.9^{c}	5.5^{b}	4.9^{a}	4.7^{a}	2.8^{a}	5.3^{a}
LaMe$_{15}$	2.2^{acd}	6.1^{ab}	2.1^{bc}	3.0^{a}	2.7^{b}	4.4^{a}	5.3^{a}	5.6^{bc}	5.9^{ab}	5.2^{a}	5.1^{a}	3.1^{a}	5.3^{a}

Chapter 7

A GRITTY STORY

EXPLORING VARIABILITY IN DETECTION THRESHOLDS OF MICROPARTICLES THROUGH PARTICIPANT CHARACTERISTICS



This chapter is based on:

Santagiuliana, M., Sampedro Marigómez, I., Broers, L., Hayes, E. J., Piqueras-Fiszman, B., Scholten, E. , Stieger, M. Exploring variability in detection thresholds of microparticles through participant characteristics. *Food & Function* 10, 2019, p. 5386-5397.

Abstract

This study explored how product familiarity and physiological characteristics of participants affect detectability of microparticles in viscous and semi-solid foods. Cellulose particles differing in size (50-780 μm) were added (1.5% w/w) to two dairy products, quark (viscous curd cheese) and processed cheese. Discrimination thresholds for added microparticles were determined by 47 Dutch, Caucasian and 45 Chinese, Asian women using the Method of Constant Stimuli. Particle size detection thresholds did not significantly differ between the two groups, but differed significantly between the two products. Detection threshold estimates for particle size were lower in viscous, low-fat quark than in semi-solid, high-fat processed cheese (52 μm versus 86 μm). This suggests that particle detection depends on product properties such as product consistency and composition, but not on factors linked to ethnicity and/or nationality of participants. We found no evidence to support a relationship between product familiarity and particle size detection thresholds in either product. A positive but weak correlation was found between stimulated saliva flow and particle size detection threshold in processed cheese ($r = 0.21$, $p = 0.041$), suggesting active salivation might enhance sensitivity for microparticle detection in semi-solid foods. PROP status and fungiform papillae density did not correlate with particle size detection threshold for either food. We conclude that matrix properties were the main contributors to particle size detection thresholds in young, healthy participants who differed in nationality and ethnicity. These data suggest that product characteristics are the central factor that should be considered for modifications when dealing with foods in which particles lead to negative sensations such as grittiness.

7

7.1 Introduction

Many foods contain microparticles that vary in type, origin, and properties. Particles can be either an endogenous constituent of the food (e.g. protein aggregates, starch granules, and insoluble fiber) (Liu et al., 2016b; Modler et al., 1989; Petersson et al., 2013), or an added exogenous ingredient that provides consumers with specific nutraceutical components (e.g. vitamins, bioactive peptides, minerals) (Chen et al., 2006; Ellis & Jacquier, 2009; Lopez et al., 2016, 2018; Mcclements et al., 2009; van Leusden et al., 2016). Perception and consumer acceptability of foods may be affected by the presence of such microparticles. The perception is often affected negatively, as the presence of small hard particles mainly relates to perception of grittiness (Imai et al., 1997; 1998; Tyle, 1993) or roughness (Bakke & Vickers, 2008; Engelen et al., 2005). Such sensations negatively influence the hedonic responses of consumers to specific products. For example, Lopez et al. (2016) reported that addition of spherical cellulose beads to a model liquid food resulted in a decrease of product acceptability as a function of both particle size and concentration; increasing these parameters led to higher grittiness, which decreased product acceptability (Lopez et al., 2018).

In food products, many of the negative effects associated with the presence of microparticles can be mitigated through product manipulations. Such modifications can focus on the particles themselves or the continuous phase the particles are distributed in. Physical properties of the particles (i.e. size, concentration, hardness, shape) and their effect on consumer perception have been studied extensively in model systems and common food products like soups or custards (Cayot et al., 2008; Chojnicka-Paszun et al., 2014; Engelen et al., 2005; Petersson et al., 2013; Rohart et al., 2015; **Chapter 3**; Strassburg et al., 2009; Tyle, 1993). For example, Engelen and colleagues (2005) showed that perception of SiO_2 and polystyrene particles varying sizes (2–230 µm) in custards was largely affected by particle properties. Generally, detectability of particles is high when particles are large, hard, irregularly shaped and/or present at high concentration. Detectability is also influenced by the properties of the surrounding matrix, as dispersed particles are more difficult to detect when the viscosity of the continuous phase is high (Engelen et al., 2005; Liu et al., 2016a; 2016b).

Most prior work has focused on the effect of the product properties on perception and detectability of microparticles, so potential variability across consumers remains under-studied. Inter-individual differences in microparticle detection may arise from different psychological and physiological factors (Engelen et al., 2005). Acceptability may depend on factors beyond physical properties of foods, such as oral tactile sensitivity or consumer expectations for the product. Product familiarity and related expectations have been shown to influence acceptability of a variety of products (Beveridge, 1997; **Chapter 3**; Tan et al., 2017a). Differences in the level of familiarity for a certain product containing microparticles may result in different expectations regarding sensory properties (Hong et al., 2014; Jellinek & Köster, 1983; Tan et al., 2017b). Expectations may lead to opposite hedonic responses, depending on whether a smooth homogeneous (without particles) or heterogeneous (with particles) product was expected (**Chapters 4** and **5**; Szczesniak, 2002). We hypothesize that presence of microparticles may be a cause for product rejection when expectations are not met. Alternatively, a product with detectable particles may still be acceptable if they anticipate the presence of microparticles, or when the consumer has no specific expectations regarding the sensory properties of the product.

Moreover, the sensitivity of the somatosensory system may also be influenced by multiple physiological parameters. Prior work suggests that oral perception of foods can be associated with fungiform papillae density (FPD), 6-n-propylthiouracil (PROP) taster status, and salivary flow rate. For example, when given milk–cream mixtures, an individual's FPD was positively correlated to creaminess perception (Hayes & Duffy, 2007, 2008) and had a significant influence on fat content perception (Nachtsheim & Schlich, 2013). While the majority of prior research on PROP has focused on taste perception, some data suggest that FPD may also be related to the perception of oral texture (e.g. Piochi et al., 2018). When considering the effect of staling or presence of fibres in bread on perception of rough sensations, Bakke and Vickers (2008, 2011) found that higher FPD was not related to perceived roughness. The same study, however, found that panellists who perceived greater PROP intensity also perceived greater roughness from the bread, suggesting that PROP status may predict differences in food texture sensitivity. Elsewhere, people who reported higher bitterness from PROP (i.e. supertasters) also showed enhanced sensitivity of tactile pressure when tested with Von Frey monofilaments (Yackinous & Guinard, 2001). These monofilaments consist of nylon threads and are commonly used to measure tactile pressure sensitivity of the skin. The filaments apply a defined force to a relatively small contact area upon bending of the thread (Aktar et al., 2015b; Etter et al., 2017; Levin et al., 1978). Here, we hypothesized that lingual tactile sensitivity, as measured with Von Frey monofilaments, might correlate with the perception of hard microparticles, as their presence in food might apply localized pressure on the tongue surface during consumption. Finally, considering the well-reported contribution of salivary lubrication during food oral manipulation (Chen, 2015; Engelen & Van Der Bilt, 2008; Nachtsheim & Schlich, 2013; Sarkart et al., 2019; van Eck et al., 2019), we also hypothesized salivary flow would influence sensitivity of microparticle detection via dilution and lubrication effects.

Variation in oral physiology affecting texture perception could also potentially arise from differences in sex, age, dental status, oral processing strategies and ethnicity. Sex differences have been previously described in terms of salivary flow, maximum bite force, and mastication frequency (Clark & Solomon, 2012; Palinkas et al., 2010; Percival et al., 1994), with men presenting higher values for these parameters than women. Age also has the potential to affect texture perception due to either decreased eating capabilities or dental status (Kälviäinen et al., 2003; Laguna et al., 2016a; 2016b). Such physiological age-related changes can also affect mastication of the product, which is known to influence perceived texture of food (Devezeaux de Lavergne et al., 2017; Foegeding et al., 2011; Jeltema et al., 2016; Kieser et al., 2011; Lucas et al., 2004; Mosca & Chen, 2016). Nevertheless, few studies have investigated potential variation in oral physiology and texture perception between consumers who differ in terms of ethnicity. With growing business opportunities of the Asian food market, the interest in better understanding how Western and Asian consumers differ in terms of sensory perception and oral processing behaviour is currently increasing (Ketel et al., 2019; Mosca et al., 2019; Pedrotti et al., 2019). To date, it has been reported that Asian subjects from China have a larger oral volume and consume foods and beverages at higher eating rate than Caucasian subjects from the Netherlands and USA, although it is not known whether such differences can lead to differences in food perception (Ketel et al., 2019; Xue & Hao, 2006). Here we hypothesize that consumer's ethnicity might influence texture perception of products containing microparticles.

In summary, prior work investigated the influence of endogenous microscopic constituents or exogenous microparticles added to foods, but little is known about how participant characteristics may affect the perception of foods containing microparticles. Detection of microparticles may not only be related to physical properties of the product, but may also be influenced by both product familiarity and physiological characteristics of participants. Here, we explored how consumer familiarity and physiological characteristics of participants affected oral detectability of microparticles in foods. Detection thresholds of cellulose particles were determined for a viscous (quark) and semi-solid food (processed cheese). Two groups of women (Dutch, Caucasian and Chinese, Asian) were recruited to determine whether product familiarity, consumption habits, and physiological characteristics (fungiform papillae density, PROP status, point pressure sensitivity on the tongue, and salivary flow) affect detectability of microparticles in viscous and semi-solid products.

7.2 Materials and Methods

7.2.1 Materials

Low-fat quark "Magere Milde kwark" (soft, viscous curd cheese; nutritional composition: 0.1% fat, 10.3% protein, 2.8% sugars, 0.1% salt) was provided by FrieslandCampina (Wageningen, The Netherlands). Kiri® (soft, semi-solid, processed cream cheese; nutritional composition: 29.5% fat, 9% protein, 2% sugars, 1.4% salt) was provided by Bel Group (Fromageries Bel, Suresnes, France). K-carrageenan (GENUGEL type CHP-2) was purchased from CP Kelco (Rotterdam, The Netherlands). Microcrystalline cellulose particles (PrimecelTM type PH-301; Cellets®, type Cellets 90, Cellets 127, Cellets 263, Cellets 500, Cellets 780 and Cellets 1000) were kindly provided by Harke Pharma (Mülheim an der Ruhr, Germany). A blue food colorant (Bharco Foods, NL) was purchased at a local supermarket. All ingredients were food grade, and samples were prepared under food-safe conditions.

7.2.2 Participants and methodology

7.2.2.1 Stimuli

A viscous curd cheese (quark) and a semi-solid processed cheese (Kiri®) were used as food matrices to investigate detection thresholds of added microparticles. Microcrystalline cellulose particles varying in size (average diameter of 50, 127, 263, 350, 500, 780 µm) were added at a constant concentration (1.5% w/w) to both matrices. The matrices and the embedded microparticles were both white, so any visual cues indicating the presence of microparticles were minimized. Microscopic images of the microparticles can be found in **Figure 7.1**. As the morphology of the microparticles can also affect participant detection thresholds, spherical smooth particles (microcrystalline pellets) were used for the size range of 127-780 µm (Lopez et al., 2016). Microparticles with an average diameter of 50 µm (microcrystalline fragments) displayed a more irregular shape. The more irregular shape of the smallest microparticles might potentially enhance the detectability (larger perceived size relative to spherical microparticles), but this is not expected to influence the results (i.e. comparison of across groups of participants).

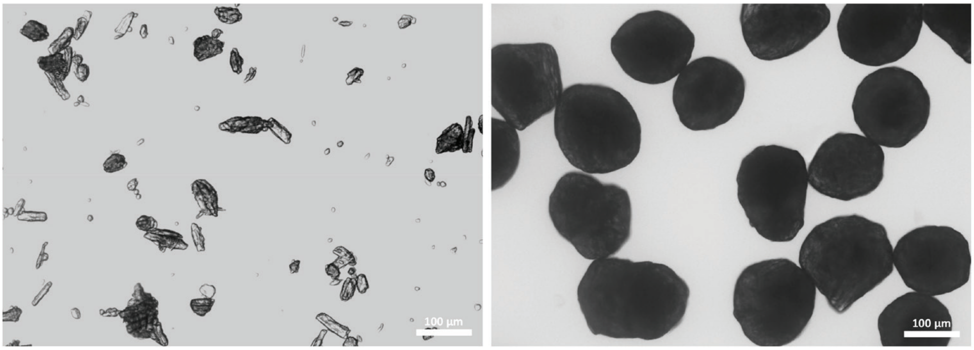


Figure 7.1. Appearance of microcrystalline cellulose particles having an average size of 50 µm (left) and 126 µm (right).

The method of particle incorporation differed between the two products. For quark, particles were added by manually mixing the cellulose particles into the matrix. For processed cheese, the method described in **Chapter 5** was used. Briefly, a 2% (w/w) κ-carrageenan solution was first prepared using tap water. The mixture was heated in a water bath at 90°C for 30 min to obtain a gel after cooling. Next, the processed cheese was melted together with the κ-carrageenan gel (12.5% w/w) in vacuum sealed bags by placing them in a hot water bath (65°C for 20 min). Cellulose particles were added to the molten cheese, which was kept at 65°C in a vessel and manually mixed continuously. Consequently, molten cheese was poured into square petri dishes and stored at 4°C for 16-18 hours. Cheese cubes (20 x 20 x 12 mm) of ~5 g were obtained, whereas portions of 10 g were used for the viscous quark. Cellulose particles were incorporated in both matrices no more than 3 days prior to sensory evaluation.

7.2.2.2 Participants

Two groups of untrained participants were recruited as a part of a single-blind study investigating the perception threshold of microparticles in the two foods. The two groups were composed of 47 Dutch, Caucasian women (mean age ± SD of 21.4 ±2.4 years; range of 18-29 years) and 45 Chinese, Asian women (mean age ± SD of 23.3 ±1.7; range of 21-27 years). Self-reported criteria of nationality and ethnicity (Dutch Caucasians; Chinese Asians), age (between 18-35 years), health status (absence of recognized diseases), and BMI (18.5-26.5 kg/m^2) were used as inclusion criteria. Men were excluded to reduce intragroup variability in physiological parameters. Other exclusion criteria were the presence of allergies, pregnancy, smoking habit, missing teeth (except wisdom teeth) or dental implants, and self-reported deficits in taste or smell. Implementation of these criteria provided two relatively homogeneous groups of young, healthy women with different nationality and ethnicity, which were expected to differ mostly in their level of product familiarity. Participants were naïve about the experimental procedures and purpose of this study; they received financial compensation for their participation. Written informed consent was obtained from all participants. All tests were conducted in accordance with the Declaration of Helsinki.

The experiment was conducted at Wageningen University & Research (WUR) over three sessions: a familiarization session of 20 min, and two test sessions of 45 min each. The sessions were completed by all participants within 6 weeks. Participants were asked to refrain from eating 1 h before the start of the sessions. In the first visit (the familiarization session), participants were instructed how to complete the sensory and physiological tests. In the second session, conducted in sensory booths, participants rated their familiarity with quark and processed cheese on a five point scale, where 1 =unfamiliar and 5 =very familiar, and indicated their consumption frequency for these products (once or more per day, once a week, once a month, every 3 months, never). Participants then assessed different samples using the methods of Constant Stimuli, which consists of a balanced series of 2-Alternative Forced Choice tests (Lawless & Heymann, 2010). Before data collection began, participants were given a warm-up sample consisting of quark with added cellulose beads (average size: 1000 µm). This allowed them to become acquainted with the stimulus and attribute definition (Grittiness: perception of particles in the mouth). Each participant was then given a pair of samples (either two samples of quark, or two samples of processed cheese) consisting of a sample without added particles and a sample with added particles. They were asked to taste and swallow each sample. After tasting the pair, they were asked to indicate the grittiest sample within the pair. A plastic spoon (quark) or fork (processed cheese) was provided. Small, bite-sized portions of both products were served to minimize possible differences in oral processing behaviour between the two consumer groups (Ketel et al., 2019). Participants rinsed their mouth with water and took a break of at least 1 min between evaluations of different pairs. For each product, a total of seven pairs were evaluated by all participants: six pairs varied in the size of particles added to the heterogeneous sample, and one pair contained two homogeneous samples as a control. Serving order within a pair was counterbalanced, and product type (quark first or processed cheese first) was also counterbalanced. Participants were requested to refrain from eating 1 h before the tasting session.

Two separate approaches were used to determine detection threshold estimates. In the first approach, the cumulative proportion of correct identification of the grittier sample (relative to the homogeneous reference) at each particle size was plotted (separately for each food matrix). The threshold value for the group was defined as the particle size that corresponded to 75% correct responses (i.e. half way between chance (0.5) and perfect (1.0) performance in a 2-AFC task) (Ennis & Jesionka, 2011; Lawless & Heymann, 2010; Perry et al., 2019). In the second approach, an individual Best Estimated Threshold (BET) was calculated for each participant and product type as the geometric mean of the highest concentration missed on the 2-AFC test and the next higher concentration (see Lawless and Heymann, (2010)). The two methods allowed to calculate the overall particle detection threshold of the tested population (n=92) for each product (either quark or processed cheese) via the dose-response psychometric function and the estimated thresholds of each individual per product type respectively.

The final session (the physiological characterization session) was performed in a meeting space equipped with desk dividers, with a maximum of two participants at a time. Participants followed a defined protocol which was explained by the researchers ahead of time. The different physiological parameters were collected in fixed order: salivary flow rate, determination of PROP status, point pressure sensitivity via Von Frey monofilaments, and quantification of fungiform papillae density (FPD). These are explained in detail in section 7.2.3.

7.2.3 Physiological characteristics of participants

7.2.3.1 Saliva flow rate

Salivary flow rates for unstimulated (USF) and stimulated (SSF) saliva were determined for each participant. They were first asked to swallow, and then to bend their heads forwards. Next, participants were instructed to spit every 30 s for a total period of 5 min into a lidded cup that had been pre-weighted. After a resting period of 3 min, they were asked to perform the same task while chewing on a piece (5x5 cm) of Parafilm® (Bemis Company, Inc., Neenah, USA). Immediately after collection, cups were placed on ice and weighted. USF and SSF (ml/min) were quantified by calculating the total mass of saliva collected within 5 min in each condition, assuming that 1 g of saliva corresponds to 1 ml.

7.2.3.2 PROP status determination

Responses to 6-n-propylthiouracil (PROP) were determined using the method described by Yang et al. (2018). A 0.32 mM PROP solution (Sigma Aldrich) was prepared by dissolving the compound in demineralized water. Before evaluating the intensity, participants were instructed on how to use a general Labelled Magnitude Scale (gLMS), with “the strongest imaginable sensation of any kind” as top anchor and “barely detectable” as bottom anchor (Dinnella et al., 2018). The PROP solution was provided in duplicate via saturated cotton swabs. After rinsing their mouth with demineralized water, participants were instructed to roll the cotton bud across the tongue tip for ~3 s and wait for ~20 s without swallowing before rating the perceived bitterness on a gLMS. Next, participants were instructed to rinse their mouth again and wait 3 min before proceeding with the same task for the next sample. Using means of the two ratings, participants were classified using arbitrary cut-offs (Tepper et al., 2001). Participants who rated PROP below "moderate" were classified as non-tasters (NT), participants were classified as medium-tasters (MT) when the ratings were above "moderate" but below "very strong" and participants with scores above "very strong" were classified as supertasters (ST). PROP phenotypes were used as both continuous and discrete variables (NT, MT, ST) to test possible relationships with particle size detection thresholds.

7.2.3.3 Point pressure detection thresholds on the tongue

Point pressure detection thresholds on the tongue were determined using Von Frey monofilaments (Baseline® Tactile™, Fabrication Enterprises, New York, USA) (Breen et al., 2019; Furukawa et al., 2019). For testing tactile sensitivity on the tongue, participants were instructed to rest their chin on an adjustable lab lift and to close their eyes or wear a blindfold if preferred. They were asked to extend their tongue, and two blue round dots (Ø of ~5 mm) were made by the researcher using a cotton swab saturated with food colourant. These dots were used to define a consistent region of testing on the left and right side of the tongue; these marks were placed ~0.5 cm from the tip and ~0.5 cm from the tongue midline. A temporal two alternative forced choice (2-AFC) task was used to establish the lingual tactile detection thresholds in a three-down one-up staircase procedure (Etter et al., 2017; Gescheider et al., 1994; Tracey et al., 2012). In practice, participants were asked to indicate in which of two sequential trials they could perceive the applied stimulus in either the left or right side of the tongue. Participants were informed that one of the trials would include no stimulus. In each test, the researcher said "trial 1" and "trial 2" and applied the stimulus in only one of the two trials; the trial containing the stimulus was randomly determined by the researcher. Participants indicated which trial of the pair contained the stimulus by using their fingers to signal one or two. After three consecutive correct detections, the force applied was decreased by changing the Von Frey monofilament. Following a single incorrect response, the force applied was increased. No feedback was provided.

Filaments with target forces of 0.08, 0.20, 0.39, 0.68, 1.57, and 3.92 mN were used. Target forces were validated empirically using a lab balance by determining the mean force of 5 applications before and 5 applications after the completion of the entire experiment. As the values provided by the supplier differed slightly from those determined empirically, effective stress values were calculated based on the actual applied force and contact area of each filament. Contact area of filaments was quantified using a micrometre. The determined stress values were 16.08, 21.48, 36.77, 49.62, 86.79, 133.08 mN/mm^2 respectively and these will be used for the remainder of the manuscript. When testing the sensitivity of the participants, 133.08 mN/mm^2 was chosen as a starting level. Participants were asked to retract their tongue after each trial pair to keep it moistened. If participants could correctly identify the lowest stimulus (16.08 mN/mm^2) six times consecutively, the test was stopped, as the probability of hitting this floor by chance guessing is 0.0156 (=0.56). Left and right sides of the tongue were tested independently in a randomized fashion. The absolute detection threshold values were determined as five crossings or reversals of a given monofilament. After completing each individual test, the monofilaments were cleaned with a 4% Korsolex (Hartmann Group, Heidenheim an der Brenz, Germany) solution and demineralized water.

7.2.3.4 Fungiform papillae density

Estimates of fungiform papillae density (FPD) were determined using the Denver Papillae Protocol (Nuessle et al., 2015). Briefly, after rinsing with some water, participants were asked to dry their tongue with tissue paper. With the help of a mirror, they were asked to dye the anterior part of their tongue using a cotton swab that was soaked in a 50:50 (w/w) solution of water and blue food colourant. Example pictures of the procedure and optimum colour applications were provided to the participants during this step. Participants rested their chin on a lab lift and extended their tongues, holding it steady. Pictures were taken using a 16.3-megapixel digital camera (Pentax K30). The lighting was controlled using two studio LCD lamps (Ledgo E268C), which were set to the maximum brightness. Initially, pictures of the entire anterior tongue were taken. Then, pictures were taken after application of rings of filter paper (external diameter of 2.5 cm; Macherey-Nagel GmbH & Co. KG, Düren,

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Germany) with a 10 mm diameter circular cut-out on the left and right side of the tongue tip (approx. 0.5 cm from the tip and 0.5 cm from the tongue midline). Two researchers independent counted the papillae manually within the 10 mm circular cut-outs (area of 78.5 mm^2) for both left and right tongue side. In the case of misplacement of the paper ring or unclear pictures, the picture of the entire anterior part of the tongue was used and a marked circle (area of 78.5 mm^2) was generated using Adobe Photoshop. Only when counts between the two researchers were the same, were the results considered valid and used further. The mean FPD for each individual was calculated from counts on the left and right side.

7.2.4 Sample characterization

7.2.4.1 Particle size characterization

The average particle size of cellulose particles was established using dynamic light scattering (Malvern MasterSizer X, Malvern, Instruments Ltd., Malvern, UK). Tests were conducted on both dry particles and particles submerged in water for different time periods (24, 96, and 120 hrs) to investigate the potential effect of water absorption over time on particle size. These results (not shown) indicate that particle sizes – expressed as $d_{3,2}$ – were very similar to values reported by the manufacturer (i.e. 50, 127, 263, 350, 500, 780 µm). In line with the results of Lopez et al. (2016), particle size was marginally influenced by water absorption, and the measured variation was <10%. Particle size provided by the manufacturer will be used for the remainder of the manuscript for convenience.

7.2.4.2 Rheological properties of quark and processed cheese

The apparent viscosity of quark was determined using a Physica MCR 501 Rheometer (Anton Paar GmbH). Flow curves of quark without microparticles were obtained at 4°C and 20°C at shear rates ranging from 1 to 1000 s^{-1} in a total time interval of 2.50 min with a concentric cylinder geometry (beaker diameter 18.08 mm; cylinder diameter 16.66 mm; height 24.94 mm). Before the measurements were performed, a waiting time of 2 min was used. Measurements were performed in triplicates. At 4°C and shear rates $\dot{y}$ (1/s) of 10, 50, and 100, the quark had an apparent viscosity η of 4.3 ±0.1, 2.7 ±0.1, and 2.2 ±0.1 Pa s, respectively. At the same shear rates of 10, 50, and 100 1/s at 20°C, the quark had a significantly lower ($p < 0.05$) apparent viscosity η with values of 2.8 ±0.1 , 1.8 ±0.1 , and 1.5 ±0.1 Pa s, respectively.

The mechanical properties of homogeneous processed cheeses (20x20x15 mm) and cheeses containing microparticles were characterized by penetration tests to determine the force needed (N) for 30% penetration. A Texture Analyser (TA.XT plus, Stable Micro Systems-SMS) equipped with a 5 kg load cell and a cylindrical flat probe (Ø: 4 mm) was used to perform this test. A crosshead velocity of 1 mm/s was used. Measurements were performed in triplicate. Homogeneous and heterogeneous processed cheeses had a maximum penetration force of approx. 0.58-0.66 N and no significant differences were found between cheeses ($p > 0.05$).

7.2.5 Data analysis

Data were analysed using IBM SPSS Statistics 23 (SPSS Inc., USA). Two-tailed independent sample t-tests were used to compare the two consumer groups on their familiarity with, and frequency of consumption of, the two products, and on their physiological variables (salivary flow rate, FP density, and tongue tactile sensitivity). A chi-square test was used to examine the proportions (%) of participants of each PROP status (NT, MT, ST) between Dutch and Chinese participants. Two-tailed independent sample t-tests were also used to examine the influence of participant group on perceived grittiness considering BET values as dependent variable for quark and processed cheese separately, and to compare BET values between the two matrices. To determine whether the considered psychological and physiological variables (across the two predefined groups) were related to detection threshold of grittiness, Pearson's correlation coefficients were calculated considering the whole panel (n=92).

7.3 Results and Discussion

7.3.1 Participant characteristics

Mean values of familiarity-related parameters for Dutch, Caucasian and Chinese, Asian participants are shown in **Table 7.1**.

Table 7.1. Mean values and standard deviations of product familiarity (1= unfamiliar; 5= very familiar) and frequency of consumption (1= never; 5= once or more per day) considering all participants, Dutch, Caucasian and Chinese, Asian participants.

		All (n=92)	Dutch Caucasian (n=47)	Chinese Asian (n=45)	p-value
Product familiarity	Quark	3.77 ± 1.19	4.45 ± 0.72	3.07 ± 1.18	< 0.001
	Processed cheese	3.57 ± 1.01	3.85 ± 0.83	3.29 ± 1.12	0.008
Frequency of consumption	Quark	2.80 ± 1.18	3.15 ± 1.20	2.44 ± 1.06	0.004
	Processed cheese	2.28 ± 1.03	2.53 ± 0.91	2.93 ± 1.12	0.061

As expected, Dutch, Caucasian participants were more familiar than Chinese, Asian participants with both products, and a larger difference in familiarity between groups was observed for the quark than for the processed cheese. This difference is also reflected in the frequency of product consumption: Chinese, Asian participants consumed quark less often than Dutch, Caucasian participants. Conversely, no differences in frequency of consumption between Chinese, Asian and Dutch, Caucasian were observed for processed cheese. The low consumption of processed cheese in both groups may be due to the fact that the specific processed cheese used in this study (Kiri) is a French product that is not traditionally part of the Dutch diet, and is not commercially available in most Dutch stores.

Across all participants, positive correlations were found between quark consumption frequency and familiarity ($r = 0.651$, $p < 0.01$), as well as between processed cheese consumption frequency and familiarity ($r = 0.529$, $p < 0.01$).

Unstimulated (USF) and stimulated (SSF) saliva flow rate did not differ significantly between the two groups, suggesting saliva flow was comparable between Dutch, Caucasian and Chinese, Asian participants (**Table 7.2**). Similar results were obtained also by Mosca et al. (2019) and Pedrotti et al. (2019) as no differences in saliva flow rate were observed between groups with the same ethnicity and nationality (i.e. Dutch, Caucasian and Chinese, Asian).

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Table 7.2. Summary of physiological parameters across all participants (n=92), as well as for Dutch, Caucasian (n=47) and Chinese, Asian (n=45) participants separately.

		All (n=92)	Dutch Caucasian (n=47)	Chinese Asian (n=45)	p-value
Saliva flow (g/min)	Unstimulated (USF)	0.51 ± 0.34	0.51 ± 0.34	0.51 ± 0.34	0.974
	Stimulated (SSF)	1.34 ± 0.80	1.37 ± 0.75	1.31 ± 0.86	0.728
PROP status (n participants)	Non taster (NT)	39 (42%)	24 (51%)	15 (33%)	0.087
	Medium taster (MT)	47 (51%)	22 (47%)	25 (56%)	
	Super taster (ST)	6 (7%)	1 (2%)	5 (11%)	
Tongue pressure detection thresholds (g/mm^2)	Averaged tongue	1.66 ± 0.12	1.68 ± 0.16	1.66 ± 0.06	0.393
	Right side tongue	1.66 ± 0.08	1.67 ± 0.11	1.64 ± 0.00	0.165
	Left side tongue	1.68 ± 0.23	1.69 ± 0.31	1.67 ± 0.11	0.675
Fungiform papillae density (count/cm^2)	Averaged tongue	16.7 ± 9.0	16.5 ± 9.2	17.0 ± 8.8	0.825
	Right side tongue	17.2 ± 9.4	16.9 ± 9.5	17.4 ± 9.5	0.780
	Left side tongue	16.3 ± 9.0	16.2 ± 9.3	16.5 ± 8.8	0.882

Overall, the group of Dutch, Caucasian participants presented a relatively high number of non-tasters (NT; 51%; mean intensity score ± SD: 7.56 ± 4.67), followed by 47% of medium tasters (MT; mean intensity score ± SD: 31.20 ± 11.69) and only one super taster (ST; 2%; mean intensity score: 57.00). Chinese, Asian participants showed a lower proportion of NT (33%; mean intensity score ± SD: 9.10 ± 4.67), but more MT (56%; mean intensity score ± SD: 30.50 ± 8.47) and 11% ST (mean intensity score ± SD: 65.55 ± 11.90). Differences in PROP status between groups (Dutch, Caucasian vs. Chinese, Asian) were not significant. Although some studies have found differences in PROP responses when comparing subjects belonging to different ethnic groups (Parr, 1934; Tepper, 2008), our results are in agreement with the more recent study of Genick et al. (2011) in which differences in PROP status between subjects varying in ethnicity were not observed. For both groups, the proportions of NT was unexpectedly higher than the common ratio in an average population (approx. 20-30%), although this could be a product of pure coincidence in the selected participants.

Using the Von Frey monofilaments, there was no evidence that tongue pressure detection thresholds differed between the Dutch, Caucasian and Chinese, Asian participants (**Table 7.2**). However, we should also note that we observed a floor effect using the Von Frey monofilaments, as most of our participants may have point pressure detection thresholds lower than 16.08 mN/mm^2. As shown in **Figure 7.2**, the average detection thresholds were relatively low as the majority of participants (>90%) could detect the smallest stress used (16.08 mN/mm^2). Among these high-sensitive participants, a large proportion (80%) reached the end of the test after six consecutive identifications of the weakest Von Frey monofilament (**Figure 7.2**), indicating that the individual threshold could not be quantified using a threshold definition based on five crossings (reversals) for a given monofilament. This suggests that these 74 participants (80%) would have likely required a lower amount of applied stress to estimate their thresholds. As filaments able to apply lower forces than 16.08 mN/mm^2 are not currently available, this suggests that more sensitive methods are needed to characterize tactile sensitivity of young healthy adults. We recommend that future research on the relation between tongue pressure sensitivity and texture perception should develop validated, standardized filaments able to apply lower forces than 16.08 mN/mm^2 or, alternatively, consider to use different techniques for characterization of tongue sensitivity (e.g. two point discrimination; letter identification task; grating test) (Essick et al.,1999; Van Boven & Johnson, 1994)

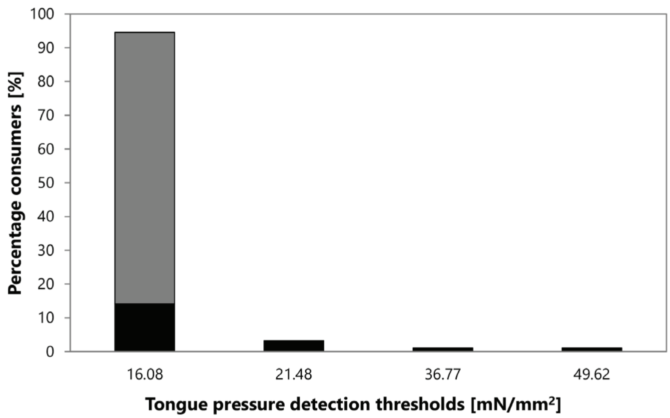

Figure 7.2. Individual mean tongue pressure detection thresholds tested on anterior left and right side of the tongue for Dutch, Caucasian and Chinese, Asian participants (n=92) obtained using Von Frey monofilaments. Bars indicate the percentages of participants for the respective pressure detection thresholds. The grey bar indicates the percentages of participants whose pressure detection thresholds are expected to be possibly below 16.08 mN/mm^2.

We conclude that further studies are warranted to confirm or disconfirm potential relationships between microparticle detection and tongue pressure detection thresholds or tongue threshold sensitivity.

We failed to observe any evidence of a difference in fungiform papillae density (FPD) between the two groups (**Table 7.2**); this is in line with previous studies comparing subject with different ethnicities (Miller, 1986; Pedrotti et al., 2019; Pritchard & Norgren, 2004). We conclude that physiological aspects as saliva production, PROP status, point pressure detection thresholds, and FPD did not differ significantly between the two consumer groups.

7.3.2 Particle size detection threshold in viscous and semi-solid foods

To quantify the effect of matrix type on detectability of microparticles, the percentages of correct answers obtained from the method of Constant Stimuli across participants (n=92) were compared. **Figure 7.3** shows the frequency of correct answers when assessing the presence of microparticles in the two matrices. As expected, an increase in particle size resulted in an increase of frequency of correct responses. **Figure 7.3** also shows that for the same particle size, the frequency of correct identifications was higher for the viscous quark than for the semi-solid processed cheese, meaning that particles were more perceptible in the softer, more liquid-like food. In the viscous quark, the smallest cellulose beads tested (50 μm) exceeded the a priori cutoff value of 75% correct answers. In semi-solid processed cheese, a minimum particle size of 127 μm was required before this cutoff value (75%) was reached. As smaller cellulose particles than 50 micron were not available, we are not able to precisely estimate a threshold based on the particle size for this concentration (1.5% w/w). Although feasibility tests completed before this study suggested that 1.5% w/w was an adequate concentration, a similar test with lower concentrations of particles would have provided better distinction.

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Generally, the data based on the frequency of correct answers are consistent with best estimated threshold (BET) analysis. For quark, the mean BET was 52 μm, versus 86 μm for the semi-solid processed cheese, and these values differed significantly ($t(156.73) = 3.48$; $p = 0.001$). Collectively, both individual estimates and BET values suggest that modification of matrix properties decreased perception of microparticles that may cause gritty sensations.

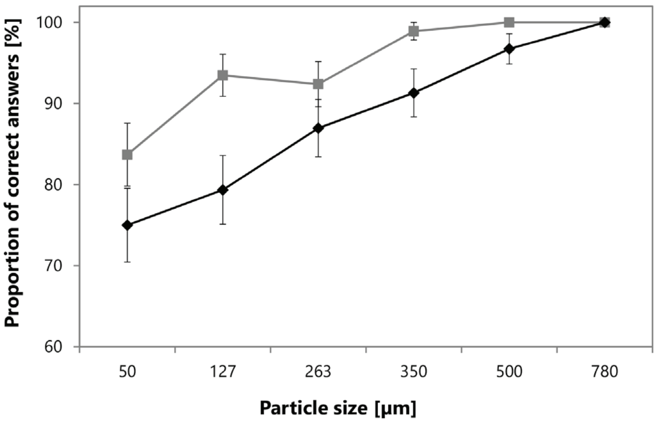

Figure 7.3. Perception of microparticles across all participants (n=92): cumulative frequency of correct answers as a function of difference in particle size. Quark samples are represented by squares (■); processed cheese samples by rhombus (♦). Error bars indicate standard error of the mean.

To test whether the detectability of microparticles differed between the two groups (Dutch, Caucasian and Chinese, Asian), BETs were compared between groups in separate t-tests for each matrix. As we could have expected already by inspecting **Table 7.2**, no group differences were observed for microparticle detectability in viscous quark ($t(90) = 0.24$; $p = 0.814$) or semi-solid processed cheese ($t(90) = 0.78$; $p = 0.437$), suggesting that particle detectability did not differ between these groups. Such results were also confirmed by a MANOVA test (data not shown) performed considering the individual particle size threshold for quark and processed cheese as depended variables and nationality/ethnicity as an independent variable. Thus, we conclude that microparticles detection increases with an increase of particle size, it is affected by matrix properties (e.g. consistency, fat content), but it does not depend on factors related to nationality and ethnicity.

7.3.3 Influence of individual product familiarity on particle size detection threshold

When all participants were considered (n=92), no significant correlations were found between product familiarity and individual BETs for either quark or processed cheese. Frequency of consumption of quark and processed cheese also did not influence detection of microparticles. This suggests that product familiarity and frequency of consumption do not affect ability to detect particles (i.e. larger BET) in the same product. This finding contradicts with our initial hypothesis, where we postulated that the degree of familiarity would be inversely related to individual BET – that is, we expected the ability to detect microparticles to increase with an increase in product familiarity. Given the absence of any significant correlations, we conclude that participant awareness towards product characteristics does not influence the ability of participants to detect the presence of microparticles in each of the matrices.

7.3.4 Influence of participant individual oral physiology on particle size detection threshold

7.3.4.1 Relation between individual saliva flow rate and particle size detection threshold

When all participants were considered (n=92), no relationship was found between the individual BET of particles in quark, and either unstimulated or stimulated salivary flow rate. Conversely, individual BETs for particle size in semi-solid processed cheese were negatively correlated with stimulated salivary flow ($r = -0.213$; $p = 0.041$). This weak correlation suggests salivation induced by mastication of a semi-solid matrix might enhance sensitivity to perceive microparticles. Generally, saliva can affect food texture perception due to either its dilution effect during oral food breakdown, or lubrication properties as its presence can facilitate oral manipulation of food and swallowing by lowering in-mouth friction (Engelen et al., 2005; Ranc et al., 2006). Considering this, higher salivary flows were expected to lower sensitivity (i.e. increase detection difficulty) towards microparticles present in food due to salivary lubrication. However, our results showed the opposite, as more saliva provided better detectability, suggesting that the saliva lubrication properties cannot explain the correlation between salivation and microparticles sensitivity. Such a weak correlation may be due to a dilution effect of saliva addition to the semi-solid food. That is, the incorporation of saliva into the semi-solid processed cheese may have diluted the continuous aqueous phase, and thus the processed cheese became more liquid-like during oral manipulation. As consistency plays a role in the detection (Engelen et al., 2005; Liu et al., 2016a), the decrease in viscosity may have resulted in a higher sensitivity towards the microparticles. Overall, we conclude that saliva flow is not related to particle size detection threshold in a viscous product, but it might enhance detection of particles during mastication of a semi-solid matrix.

7.3.4.2 Relation between individual PROP status and particle size detection threshold

Contrary to our hypothesis that PROP status would be positively related to detectability of microparticles, there was no evidence to support a relationship between PROP intensity scores and individual particle size detection thresholds, for either quark and processed cheese, when looking across all participants. These data suggest any individual variability in microparticles perception is unrelated to PROP phenotype, when PROP intensity was treated as a continuous measure (Hayes & Duffy, 2007). Likewise, no relationship was observed between PROP status group (NT, MT, ST) and particle size detection threshold. As sizes of the PROP groups were not equally balanced according to the categorization criterion used here, we also retested for a possible relationship using a tertile split (low sensitivity (33%), medium sensitivity (33%) and high sensitivity (33%) groups) in an exploratory analysis. We still failed to find any evidence of a relationship. Based on all three approaches, we cannot confirm the hypothesis that ability to perceive PROP is related to microparticle detection in the type of products used in our study.

7.3.4.3 Relation between individual tongue pressure detection thresholds and particle size detection threshold

Given the data summarized in section 7.3.2, the method used to determine tongue pressure sensitivity was clearly limited by a floor effect, and the point pressure detection thresholds of young healthy women likely fall below the lowest stress that can be applied with commercially available Von Frey monofilaments. Thus, we were unable to test the hypothesis that tongue pressure detection thresholds are related to perceived microparticles. In a recent study of Furukawa et al. (2019), no correlation was found between particle recognition thresholds and tactile threshold tested with a comparable methodology, suggesting that this characterization method is probably not suitable to evaluate the detection threshold of microparticles.

7.3.4.4 Relation between individual fungiform papillae density and particle size detection threshold

Across all participants, no significant correlations were found between fungiform papillae density (FPD) and BETs for particle size detection in either quark or processed cheese. We initially hypothesized that participants' fungiform papillae density would be positively correlated to perception of microparticles in food. Based on present data, we can reject this hypothesis, and conclude that participants' fungiform papillae density does not influence microparticle detection, at least for the viscous and semi-solid products tested here.

7.3.5 Discussion

This work explores the influence of participants' familiarity and physiological characteristics on oral detectability of microparticles in two foods. Our data show that product properties as particle size and matrix type played a key role in determining detection of microparticles. These findings are largely in agreement with other studies, where larger particle size and lower viscosity of the dispersing phase were positively associated with microparticle detection (Cayot et al., 2008; Engelen et al., 2005; Imai et al., 1998; Liu et al., 2016a; 2016; Petersson et al., 2013; Santagiuliana et al., 2018; Tyle, 1993). Here, we demonstrated that the particle size required to determine microparticle perception increases by roughly two thirds when the particles are embedded in a soft semi-solid food rather than a thick viscous product. This suggests that the detection of microparticles in commercial food products can potentially be reduced by embedding them in products with a higher viscosity/ consistency. We anticipate that even particles larger than 86 μm could be consumed without being detected when these are added into hard, solid foods like granola/ crunchy cereal or cookies.

We acknowledge, however, that the two matrices used in this study not only differed in consistency but also in fat content and microstructure. Quark did not contain fat (< 0.1%), while processed cheese had a fat content of ~20%. The presence of fat might also have contributed to a decrease in the detectability of microparticles by increasing the lubrication properties of the processed cheese (Imai et al., 1997; Liu et al., 2016b). Additional work is needed to decouple the specific contribution of fat content and consistency of the food on detectability of microparticles. Further, additional tests should be performed using microparticle concentrations below 1.5% (w/w), as the results on individual thresholds highlighted that such particle concentration did not allow a large distinction between participants' sensitivity towards microparticles present in both matrices. Alternatively, the concentration of microparticles could be based on their number rather than on weight concentration. The strategy used in this study (i.e. % w/w) lead to a higher number of microparticles for small sizes, contributing to enhancing their detectability.

Overall, only a weak correlation was found between detection thresholds of microparticles and the tested psychological or physiological characteristics of the participants. This suggests that the individual characteristics explored here explained to a very limited extent the inter-individual variability in detection thresholds of microparticles for the participant groups we tested. From a physiological perspective, the variability in detection of microparticles for young, healthy participants may be potentially explained by other factors that were not considered in this study (e.g. differences in oral processing behaviour, tongue-palate pressure, etc.). Nonetheless, the characterization methods applied in this study might still be able to explain variability in perceived texture when other groups of participants are considered, such as elderly or subjects with decreasing eating capabilities (Laguna et al., 2016a).

Considering that the two groups tested were homogeneous in their age and sex, this study focused on potential differences related to nationality and ethnicity. To the best of our knowledge, minimal research has been conducted to date addressing possible differences in oral physiology between participants of different ethnicities (Ketel et al., 2019; Mosca et al., 2019; Pedrotti et al., 2019; Xue & Hao, 2006). Similarly, a few studies have investigated whether possible cross-cultural differences influence food texture perception. When Vietnamese and French adults evaluated soy yoghurts and jellies, only small differences were found in the perceived textural profile between the two groups, although participants differed in their degrees of products familiarity (Kesteloot et al., 2006; Tu et al., 2010). Correspondingly, our results also suggest that young Caucasian women from the Netherlands and young Asian women from China present very comparable physiological characteristics, while they differ primarily in terms of product familiarity. These results are in agreement with the observations from other cross-cultural studies on basic taste thresholds which fail to find differences between groups (Blancher et al., 2008; Lundgren et al., 1998; Prescott & Bell, 1995). Thus, we conclude that the sensitivity towards oral texture appears to involve perceptual mechanisms that are unrelated to a participants' nationality and ethnicity.

Given present data, a relationship between product familiarity and particle size detection thresholds in either product could not be confirmed. However, care needs to be taken when generalizing such observation in real-life consumption conditions, as other factors could also affect the ability of participants to detect small variations in a familiar food. For instance, the discrimination ability of participants towards familiar product can be increased when subjects evaluate foods with affective (i.e. involving personal preference and emotions) rather than analytical (i.e. pure stimulus recognition) processes (Frandsen et al., 2003). We conclude that participant awareness of product characteristics was not affected by the presence of microparticles when tested in an analytically in a laboratory context. Additional work is needed to check how product familiarity might influence perception and liking of such attributes under real-life eating conditions.

The present results suggest saliva production might slightly increase perception of microparticles in a semi-solid matrix, consistent with the view that saliva influences perception of textural food properties (Chen, 2015; Engelen & Van Der Bilt, 2008; Nachtsheim & Schlich, 2013). We explain this weak relation mainly considering the dilution effect caused by the presence of saliva during mastication of soft semi-solid food. A higher amount of saliva is expected to decrease the bolus consistency (Drago et al., 2011; Saint-Eve et al., 2015), leading to a lower particle size required to trigger microparticle detection. For the quark product, no relation was observed between microparticle detection and saliva production, probably because salivation is induced mainly by mastication. The higher food consistency of the processed cheese might have had not only enhanced more saliva production, but also determined an increase in oral manipulation (Aguayo-Mendoza et al., 2019), enhancing the positive effect of saliva on the detection of microparticles. This suggests the influence of saliva on texture perception may be larger in solid foods requiring chewing versus easy-to-swallow liquid foods. To gain more insights on the role of saliva in the detection and perception of microparticles in foods, we recommend further research to investigate the incorporation of saliva into the food bolus and its influence on rheological characteristics of the bolus.

The link between the oral somatosensory system and perception of microparticles was investigated considering participants' tongue pressure detection thresholds, fungiform papillae density (FPD) and PROP status. As it is not possible to directly quantify mechanoreceptors density non-invasively, we measured FPD as a proxy instead. FPD provides a rough estimate of trigeminal fibres innervation and might be related to density of mechanoreceptors (i.e. the higher number papillae, the higher the innervation of trigeminal fibres, the higher the density of mechanoreceptors)(Bakke & Vickers, 2008; Foegeding et al., 2011). Correspondingly, point pressure detection thresholds were calculated using Von Frey monofilaments to indirectly evaluate consumer's mechano-sensitivity in the same areas where papillae were counted. Our data did not identify any relation between FPD and detectability of microparticles. These outcomes are in agreement with the findings of Bakke and Vickers (2008, 2011) where no correlation was found between FPD and roughness perception of staled bread. As FPD has been positively related with other textural sensations as creaminess (Hayes & Duffy, 2007, 2008) and fat perception (Nachtsheim & Schlich, 2013), we conclude that the link between textural sensations and FPD remains unclear, and further investigations are required to unravel the current inconsistent conclusions.

In this study, PROP status or scored PROP intensity were not related to individual variability in microparticle detection. Direct connections between enhanced texture discrimination (e.g. creaminess, heterogeneity, roughness) and PROP sensitivity was previously confirmed and disconfirmed by others (Bakke & Vickers, 2008; de Wijk et al., 2007; Essick et al., 2003; Nachtsheim & Schlich, 2013; Yackinous & Guinard, 2001). We conclude that the relation between PROP status and texture discriminability remains unclear and might depend on the specific textural attribute being considered. Further investigations are required to confirm any possible relationships, especially for texture.

7.4 Conclusions

The aim of this study was to test how product familiarity and physiological characteristics affect detectability of microparticles. Our results show that particle size detection thresholds differed significantly between viscous liquid and semi-solid dairy products, but did not differ between women who differed in nationality and ethnicity (Dutch, Caucasian and Chinese, Asian women). When all participants were considered, particle size detection threshold was 52 μm for quark and 86 μm for processed cheese. Particle size detection threshold was not correlated with participants' product familiarity for neither product; still, for processed cheese but not quark, there was a positive but weak correlation with stimulated salivary flow ($r = 0.21$, $p = 0.041$). This suggests detectability of microparticles might be slightly enhanced by salivation induced by mastication, at least for a semi-solid matrix. Particle size detection threshold in both matrices did not correlate with participants PROP status, point pressure thresholds on the tongue, or fungiform papillae density. Particle size detection threshold was also not influenced by nationality and ethnicity. We conclude that variations in particle size detection thresholds in semi-solid and viscous foods are mainly explained by the product properties, while further investigations are required to identify participant characteristics responsible for differences in detection of microparticles in food.

Chapter 8

DIRECTING ATTENTION

STRATEGIES TO COMPENSATE FOR UNDESIRED TEXTURE PERCEPTION IN FOODS

This chapter is submitted as:
Santagiuliana, M., Broers, L., Sampedro Marigómez, I., Stieger, M., Piqueras-Fiszman, B., Scholten, E., Strategies to compensate for undesired gritty sensations in foods.

Abstract

The addition of polysaccharide or protein microparticles to increase protein content in dairy products can lead to unpleasant gritty sensations. This study investigated whether the addition of macroparticles or fat can be used to compensate for negative texture sensations in quark. Cellulose beads were added as model microparticles (1.5% w/w; average size: 263 μm) to quark (0% fat) to induce unpleasant gritty sensations. The addition of microparticles to quark significantly increased grittiness and dryness, while creaminess and liking decreased. Three strategies were explored to reduce the impact of unpleasant gritty sensations on consumer perception: two strategies involved the addition of macroparticles (granola or peach gel pieces); the third one consisted of increasing the fat content of the quark (4.4 and 8.8% w/w). For all three strategies, grittiness caused by microparticles did not significantly decrease when macroparticles or fat were present. Addition of peach gel pieces to quark with microparticles did not increase liking. When granola pieces were added to quark containing microparticles, liking increased significantly despite that grittiness was still perceived. Temporal Dominance of Sensations (TDS) revealed that addition of granola pieces drew the attention of consumers away from negative gritty sensations and directed it towards positive, crunchy sensations. The addition of fat did not lead to a significant increase in liking of quark, although when a medium amount of fat was added (4.4%), it also did not decrease liking significantly. This was probably due to an effective hedonic compensation triggered by more positive sensations (i.e. sweetness). We conclude that addition of crunchy granola pieces or fat can be used as strategies to shift consumer attention towards positive and liked attributes, leading to an increase of overall liking, although negative sensations (grittiness) caused by microparticles are still perceived. This approach could be used to compensate for undesired texture sensations in different types of foods, such as high protein foods.

8.1 Introduction

Grittiness, graininess, and roughness are undesired textural sensations in food products which decrease overall food quality (Engelen et al., 2005; Krzeminski et al., 2013; Lopez et al., 2018). These sensations are usually caused by the presence of microscopic particles of different kinds and origins. Such microparticles can be either naturally present in food (e.g. protein aggregates in dairy products or in protein enriched liquid foods, fibres) or deliberately added to deliver pharmaceutical compounds upon oral consumption (e.g. multi-particulate formulations composed by cellulose beads; Lopez et al., 2016; Rohart et al., 2015).

Many studies investigated the effect of microparticle properties on detection thresholds and grittiness perception. Microparticle size, hardness, shape, and concentration have been reported to be key factors influencing texture perception of various foods such as custards and soups (Engelen et al., 2005; Petersson et al., 2013; Sainani et al., 2004; Santagiuliana et al., 2018b; Tyle, 1993). Gritty sensations increase with an increase in particle size, hardness, and surface roughness. A direct modification of these particle-related properties (e.g. reduction in particle size) remains the most effective strategy to decrease the undesired sensation of grittiness (Modler et al., 1989; Petersson et al., 2013). Nevertheless, such adjustments are not always possible to implement due to various technical limitations during processing or when microparticles are added after the production process. For instance, novel drug therapies require that patients add drug-loaded particulates to their food products. These forms of oral solid dosage do not allow product modifications that can prevent a gritty perception (Lopez et al., 2016, 2018; Marconati et al., 2018) and, therefore, other strategies have to be used to decrease undesired perceptions caused by the presence of microparticles.

When matrix modifications in foods are possible, a common strategy used to prevent microparticle detection consists of increasing the viscosity of the continuous phase. A higher matrix viscosity lowers consumers' ability to perceive microparticles suspended in it (Engelen et al., 2005; Liu et al., 2016; Lopez et al., 2016). Alternatively, there are indications that fat addition can also lower the detectability of microparticles (typically 25-150 μm), as fat provides lubrication to foods. De Wijk and Prinz (2005) demonstrated that higher fat contents in semi-solid foods can significantly decrease rough sensations and increase creaminess. This was attributed to the low friction coefficient of custards caused by the presence of dispersed fat droplets. Perception of microparticles (<200 μm) in foods can thus be modulated by modifying matrix consistency and/or adding fat. However, very little is known about the ability of fat to decrease perception of microparticles in the >200 μm size range. Additionally, since modifications of matrix consistency are not possible or desired in all food products, alternative solutions are required to reduce unpleasant gritty sensations.

With respect to the investigation of microparticle detection and gritty perception in foods, prior work focused on relatively simple foods in which participants might have focused their attention on a limited number of sensory attributes. Many foods, however, are characterized by the presence of multiple components (e.g. presence of chocolate chips in cookies or noodles in soups). For such heterogeneous foods, the perception of specific sensory characteristics becomes more complicated as the sensations provoked by the different components might direct consumers' attention unevenly. Possible novel strategies to prevent perception of undesired attributes might be developed by combining different components in a product. Consumers commonly add different types of particles to a variety of foods, for example, croutons or vegetable pieces to soups or granola and fruit pieces to dairy products such as yoghurt and quark. The presence of macroparticles not only provides contrasting textural and flavour sensations that contribute positively to product liking (Hyde & Witherly, 1993; **Chapters 4** and **5**; Szczesniak & Kahn, 1984), but also influences dynamic sensory perception and oral processing behaviour (Devezeaux de Lavergne et al., 2015; James, 2018; Larsenet al., 2016; Santagiuliana et al., 2018b; Tang et al., 2017; Tarrega et al., 2016; van Eck, et al., 2018; 2019). Multiple elements in foods can lead to differences in oral manipulation (Kim et al. 2015). When a combination of spherical particles varying in size (4 and 15 mm diameter) is present in foods, larger particles are chewed significantly more than smaller particles, and therefore oral processing was dominated by the larger particles. The authors suggested that an altered chewing behaviour by the presence of such particles varying in size, might be used to prevent undesired sensory effects caused by the presence of small particles.

To the best of our knowledge, it is not known how the addition of macroparticles or fat can alter the perception of foods containing microparticles (>200 μm), and whether such an addition has the potential to compensate for undesired texture sensations such as grittiness. We hypothesise that macroparticles direct the attention of consumers away from undesired gritty sensations towards desired positive texture sensations and thus prevent a decrease in liking. Addition of macroparticles with contrasting mechanical properties (i.e. soft or hard fruit pieces) or characterized by positive and dominant textural sensations (e.g. crunchy granola pieces) might alter the perception and hedonic response of the consumer in different directions. Furthermore, we hypothesise that presence of fat in foods containing microparticles might change the textural properties in the product matrix by providing extra lubrication and positive perception (i.e. creaminess) that could reduce perceived grittiness.

To test these hypotheses, we selected a common, commercially available dairy product (i.e. quark) in which not only the perception of microparticles is associated to a product defect, but also different macroparticles, such as fruit and granola, are usually added during consumption. Therefore, this study aimed to investigate whether the addition of macroscopic particles or fat to quark can be used to compensate for negative texture sensations (grittiness). Microscopic cellulose beads (263 μm) were added to quark to induce gritty sensations. The consumers' static and dynamic sensory perception and product liking of quarks containing added fat or macroparticles (peach gel pieces and granola pieces) varying in mechanical properties (soft, hard) were investigated.

8.2 Materials and Methods

8.2.1 Materials

Quark, a spoonable curd cheese ("Milde kwark naturel") with two different fat contents, was provided by FrieslandCampina (FrieslandCampina, Wageningen, The Netherlands) as a representative for a soft semi-solid dairy product for this study. Low-fat (0.1% fat, 10.3% protein, 2.8% sugars, 0.1% salt) and full-fat quark (8.8% fat, 8.8% protein, 2.7% sugars, 0.1% salt) were used. Both low-fat and full-fat commercially available quarks were chosen because of their smooth texture and homogeneous structure, as no particles or lumps are present in them. Microcrystalline cellulose particles (Cellets® 263) were kindly donated by Harke Pharma (Mülheim an der Ruhr, Germany). Granola honey/coconut with hazelnuts (pieces with an average diameter

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of ~6 mm) was kindly donated by Bio-familia AG (Sachseln, Switzerland). Canned peaches (PLUS, Utrecht, The Netherlands), strawberry flavoured yoghurt (Almhof®, Veenendaal, The Netherlands) and cornflakes (Jumbo, Veghel, The Netherlands) were purchased from a local supermarket. Agar was purchased from Caldic Ingredients B.V. (Rotterdam, The Netherlands). Holland Ingredients B.V. (Meppel, The Netherlands) kindly provided annatto (orange food colourant, WS 2.5%, E160b). Titanium dioxide (TiO_2, E171) and riboflavin (yellow food colourant, 10% PWS, E101) were provided by Pomona Aroma B.V. (Hedel, The Netherlands).

8.2.2 Sample preparation

8.2.2.1 Quark containing microparticles

Microcrystalline cellulose beads (average diameter: 263 μm; concentration: 1.5% w/w) were added to fat-free homogeneous quark to induce gritty sensations. Grittiness was ensured by the crystalline and not-deformable structure (i.e. hard beads) of the cellulose beads since particle hardness largely determines their detectability and perception (Chojnicka-Paszun et al., 2014; Santagiuliana et al., 2018b; Tyle, 1993). The size and concentration of added particles were chosen based on feasibility tests (data not shown) and available literature to ensure that consumers detect the particles and perceive them as gritty sensations. The microparticles and the continuous matrix were both white, and therefore the particles were not visually detectable. The microparticles were incorporated into the product by manually mixing them up to a max of 3 days before consumer evaluation; prior work indicated that water absorption of microcrystalline cellulose particles over this time period is negligible (Lopez et al., 2016; **Chapter 7**), so both particles and matrix properties are not affected.

8.2.2.2 Quark with added granola pieces

Granola pieces varying in hardness (soft/hard) were used as macroscopic particles and added to quark. Hard granola was the commercially available product. To obtain soft granola pieces, granola was moistened using an electric oven (Rational, Mod. SCC101, Barcelona, Spain) set at 40°C with 100% relative humidity for 1 h. Such a treatment provided the granola with a water absorption of 27±2% (w/w). Both soft and hard granola pieces were added (10% w/w) to low-fat quark and manually mixed just before providing each sample to the participants.

8.2.2.3 Quark with added peach gel pieces

The second macroparticle type used in this study was peach gel pieces varying in hardness (soft/hard). Peach juice was extracted from canned peaches using a hand blender (Braun MQ 745, Kronberg im Taunus, Germany) and centrifuged at 3900 g for 20 min (Beckman Coulter Allegra X-30R, Fullerton, USA). The obtained supernatant was combined with agar, TiO_2 (0.039% w/w), and the food colourants riboflavin and annatto. A 1.4% (w/w) and 3.6% (w/w) agar concentration was used to obtain soft and hard gels, respectively. The amount of colourants was also adjusted to ensure similar visual appearance independently from the amount of gelling agent used. Specifically, riboflavin and annatto were added in a concentration of 0.025% (w/w) and 0.024% (w/w) for soft gels, while concentrations of 0.024% (w/w) and 0.023% (w/w) were used for hard gels. Solutions were heated under continuous stirring in a water bath at 95ºC for 45 min, and subsequently poured in disposable plastic containers. After cooling on ice for 1 h, the obtained gels were cut in cubes of 7x7x7 mm using a mandolin (Michel BRAS, Laguiole, France). The resulting peach gel pieces resembled the appearance and shape of commercially available canned peach cubes, which are often added to dairy products. The peach gel pieces were stored at 4ºC for a maximum of one week. Similar to the granola pieces, peach gel pieces were combined (10% w/w) with quark and manually mixed at the moment of serving the samples.

8.2.2.4 Quark varying in fat content

Fat content in quark was varied from 0 to 4.4 and 8.8% w/w. For this purpose, commercially available low-fat quark (< 0.1% w/w) and full-fat quark (8.8% w/w) were used, and the mid-fat quark (4.4% w/w) was obtained by combining the low- and full-fat quark in a 50:50 ratio.

8.2.3 Sample characterization

8.2.3.1 Viscosity of quark

Viscosities of homogeneous quarks (low-fat, mid-fat, and full-fat) were determined using a rheometer (Anton Paar GmbH, MCR-302). Measurements were performed in triplicate at 4°C, using a shear rate ranging from 0 to 1000 s^{-1} in a total time interval of 2.5 min. The rheometer was operated in rotational mode with a C-CC17/T200/Ti cup (diameter of 18.08 mm) and a CC17/Ti inner cylinder (diameter 16.66 mm and length of 24.94 mm). A resting period of 5 min before each measurement was used to obtain equilibrium. Quarks varying in fat content showed no significant differences in viscosity at the same shear rate. All quarks were shear thinning as the apparent viscosity decreased significantly ($p < 0.05$) with increasing shear rate. At shear rates $\dot{y}$ of 10 1/s , the low-, mid- and full-fat quark had an apparent viscosity, η, of 4.1±0.1 Pa s, 4.6±1.0 Pa s, and 4.6±0.9 Pa s, respectively. When the shear rate, ẏ, was increased to 100 1/s, quarks presented an apparent viscosity, η, of 2.3±0.1 Pa s, 2.5±0.4 Pa s and 2.4±0.4 for low-, mid- and full-fat samples respectively. The variation in viscosity between quark samples was limited and was therefore assumed not to influence grittiness perception.

8.2.3.2 Mechanical properties of granola and peach gel pieces

Mechanical properties of granola and peach gel pieces were characterized by cutting tests. A Texture Analyser (TA.XT plus, Stable Micro Systems-SMS) equipped with a "Light Knife Blade" (20 mm height, 60 mm width, 3 mm max thickness, tip angle of 60°; Stable Micro Systems-SMS) and a 5 kg load cell was used. A crosshead velocity of 1 mm/s and a final strain of 90% was selected. From the force-distance curve, the max peak forces (N) at fracture were calculated. Average values were calculated based on a minimum of 10 measurements. The results of the cutting test on macroparticles highlighted that hard granola pieces had significantly higher ($p < 0.05$) max peak forces of 16±7 N than the soft pieces with 10±4 N. Similarly, hard peach gel pieces had significant higher ($p < 0.05$) mean peak force (0.45±0.07 N) than soft peach gel pieces (0.01±0.01 N). These results indicate that for both macroparticles, the soft and hard versions were different in mechanical properties. In addition, granola pieces required considerably more cutting force than the peach gel pieces, and can therefore be considered much harder.

8.2.4 Ranking test and hedonic evaluation

8.2.4.1 Participants

One hundred and fourteen untrained participants (n=114, 94 female, 20 male; average age: 22.3±2.3 yrs) completed the sensory evaluation (ranking test) and hedonic evaluation. Participants were screened based on several selection criteria age (between 18-35 years), health status (absence of recognized diseases), and BMI (18.5-26.5 kg/m^2). Exclusion criteria were allergies, pregnancy, smoking habit, missing teeth (except wisdom teeth), dental implants, or deficits in taste or smell. All participants gave written informed consent at the beginning of the sensory test and were requested to abstain from eating 1 h before each session.

8.2.4.2 Method

Participants attended one familiarization session of 30 min and two test sessions of 1 h each in 3 non-consecutive days. During the familiarization session, participants received an explanation on how to perform the sensory evaluation. During the first test session, 30 g of each of the eleven quark samples was delivered, as shown in **Table 8.1**, and they evaluated the samples on overall liking, flavour liking, and texture liking on a nine-hedonic point scale ranging from “Dislike extremely” (1) to “Like extremely” (9). Samples were presented in a monadic randomized counterbalanced sequence.

In the second test session, participants performed ranking tests on the three sets of products, namely the quarks containing granola, peach and fat (**Table 8.1**). Each set was composed of five samples: (1) a homogeneous plain quark (LF); (2) quark containing microparticles (LF|mp), which were used as reference samples; (3-4) two quarks containing microparticles and either fat, peach gels or granola varying in concentration or hardness; and (5) one quark with either fat (8.8% w/w), peach (soft) or granola (hard) without the presence of microparticles. Participants were asked to rank the five samples of each set on a line (100 mm VAS scale; verbal anchors: “not at all” and “very much”) with respect to different attributes (see **Table 8.2**).

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Table 8.1. Sample codes for homogeneous and heterogeneous quarks. Cellulose microparticles having an average size of 263 µm were added at 1.5% (w/w). Macroparticles having an average size of > 6mm (granola or peach gel pieces) were added at 10% (w/w).

Product code	Fat (% w/w)	Micro-particles	Macro-particles	Ranking product set			TDS
				Granola	Peach	Fat	
LF	<0.1	No	-	✓	✓	✓	✓
LF|mp	<0.1	Yes	-	✓	✓	✓	✓
LF|mp|SG	<0.1	Yes	Soft Granola	✓			✓
LF|mp|HG	<0.1	Yes	Hard Granola	✓			✓
LF|HG	<0.1	No	Hard Granola	✓			
LF|mp|SP	<0.1	Yes	Soft Peach		✓		✓
LF|mp|HP	<0.1	Yes	Hard Peach		✓		✓
LF|SP	<0.1	No	Soft Peach		✓		
MF|mp	4.4	Yes	-			✓	✓
FF|mp	8.8	Yes	-			✓	✓
FF	8.8	No	-			✓	

Rank intensity scores for each product were obtained (Kim & O'Mahony, 1997). Attributes and definitions were established and tested during previous feasibility tests. Due to a faulty set-up of the digital questionnaire, data for the attributes dryness and flavour intensity were not recorded for the quarks with fat, and are only available for the sets with granola and peach gel pieces. No ties were allowed and the order of attributes was randomized per participant. Serving order of each product set was counterbalanced. Sample evaluation was performed in sensory booths at 20 ºC and under normal light conditions. Quarks were served at 4 ºC in plastic cups coded with random 3-digit numbers and a spoon was provided with each cup. For the ranking test, the portion size was 50 g. Data was collected using EyeQuestion® software (V3.8.13, Logic 8, The Netherlands).

8.2.4.3 Data analysis

IBM SPSS Statistics 25 (SPSS Inc., USA) was used to analyse the data. Analysis of Variance (ANOVA) was performed on the data obtained instrumentally (viscosity and penetration tests). Liking scores were analysed using ANOVA with sample as fixed factor and panellist as random factor, and Tukey's HSD ($p<0.05$) was used as post-hoc test. Data obtained from the ranking test were initially analysed considering either rank positions (non-parametric test) or rank intensity scores (parametric test). Ranking positions for all attributes within each product set were analysed using a Friedman test and Wilcoxon signed rank test with Bonferroni adjustment. ANOVA was performed on the intensity scores obtained from the ranking on a line for each product set separately. Significant differences were further analysed using Tukey's HSD test ($p<0.05$) to specify the differences between samples. As both non-parametric and parametric analyses provided comparable outcomes and conclusions, only the rank intensity scores and related parametric analysis will be reported in the remainder of the manuscript.

Table 8.2. Sensory descriptors and definitions used for the ranking and TDS test. Check marks indicate that the term was used for the specific test type.

Descriptor	Ranking	TDS	Definition
Texture			
Creaminess	✓	✓	Sensation of a thick, smooth and velvety texture in the mouth.
Crunchiness	✓	✓	The sound of a low-pitched, longer sounding crushing noise during mastication.
Dryness	✓	✓	Perception of a dry feeling in the mouth.
Hardness	✓	✓	Force required to compress and/or break the sample (or its components) between the teeth.
Sandy/gritty	✓	✓	The perception of small (sand-like) particles in the mouth.
Flavour			
Overall flavour intensity	✓		Perception of product overall flavour.
Peach flavour		✓	Perception of peach aroma.
Dairy flavour		✓	Perception of milky aroma.
Wheat flavour		✓	Perception of wheat aroma.
Sourness	✓	✓	Perception of a sour flavour in the mouth.
Sweetness	✓	✓	Perception of a sweet flavour in the mouth (sugar like).

8.2.5 Temporal dominance of Sensation (TDS)

8.2.5.1 Participants

Fifty-one untrained participants (n=51, 38 female, 13 male; average age: 21.6 ±2.1 yrs) were recruited for this test. None of the participants performing the TDS evaluation performed the ranking evaluation. The same selection criteria as for the ranking test applied (section 8.2.4.1). Written informed consent was signed by all subjects at the beginning of the sensory test.

8.2.5.2 Method

During one session of 30 min, eight different quarks were tested (**Table 8.1**). As for the ranking test, homogeneous plain quark (LF) and quark containing microparticles (LF|mp) were used as reference quarks. The influence of macroparticle addition was investigated by adding soft and hard granola to low-fat quarks (LF|mp|SG, LF|mp|HG), and soft and hard peach gel pieces added to low-fat quarks (LF|mp|SP, LF|mp|HP). For samples containing macroparticles, low-fat quark was used to highlight the effect of macroparticle addition only on the perception of quarks, and not a combined effect of macroparticles and fat addition. The effect of fat concentration on dynamic perception of quarks was investigated by testing quark containing microparticles with mid- and full-fat (MF|mp, FF|mp). Before starting with the tasting session, participants received a short introduction on how to perform the TDS task and how to interpret the sensory attributes (**Table 8.2**). An extra practise sample (strawberry yoghurt mixed with cornflakes) was provided to the participants to get acquainted with the TDS task. The eight quarks were presented in a monadic counterbalanced sequence and the attributes order was randomized. Participants evaluated the samples over time as previously described (Lenfant et al., 2009; Pineau et al., 2009). Researchers clarified that the selection of the attributes should be based on the concept of dominance, defined as the sensation that is catching their attention the most at a given time. It was explained that the dominant attribute is not necessarily the one with the highest intensity. For this task, one spoon of quark (~15 g) was provided to the participants. The sensory evaluation took place in the Consumer Research Room (Department of Social Sciences, Wageningen University). Participants were instructed to cleanse their palate with unsalted crackers and rinsing with water between the evaluation of each sample. EyeQuestion® software (V3.8.13, Logic 8, The Netherlands) was used for data collection. Both sensory studies were conducted in accordance with the Declaration of Helsinki.

8.2.5.3 Data analysis

TimeSens software (version 1.1.601.0, ChemoSens, Dijon, France) was used to process the TDS data. Dominance curves representing the proportion (%) of participants who cited an attribute as dominant at that moment in time were obtained for each product as explained by Pineau et al. (2009).

8.3 Results and Discussion

8.3.1 Ranking test and hedonic evaluation

8.3.1.1 Effect of microparticles on sensory perception and liking of quark

As expected, the addition of hard cellulose microparticles (263 μm) to low-fat quark led to a significant decrease in perceived creaminess, while grittiness and dryness increased significantly in each of the product set tested (**Table 8.3**, **8.4**, and **8.5**).

The presence of microparticles in low-fat quark (LF|mp) resulted in significantly lower overall and texture liking scores than for homogeneous low-fat quark (LF; **Table 8.3**, **8.4** and **8.5**). We relate this decrease in liking to the relatively high grittiness and low creaminess perception of the quark with added microparticles in comparison to plain quark. No differences were observed in terms of flavour liking between LF and LF|mp quarks. This is in line with our expectations as the added microparticles did not contain any flavour. In general, these results confirm that perception of hard, microscopic particles as gritty and dry sensations in a product that is expected to be homogeneous, reduces liking.

8.3.1.2 Effect of granola pieces on sensory perception and liking of quarks containing microparticles

Addition of granola pieces and microparticles to quark affected sensory perception of all attributes significantly (**Table 8.3**). The addition of hard granola (LF|HG) to homogeneous low-fat quark (LF) increased significantly sweetness, crunchiness, grittiness, hardness, and flavour intensity, while it decreased sourness and creaminess. By comparing quarks containing microparticles (LF|mp, LF|mp|SG, LF|mp|HG), we observe that the addition of granola pieces (soft/hard) also contributed significantly to lowering creaminess and sourness perceptions, whereas crunchiness and overall flavour intensity increased significantly (**Table 8.3**). However, no differences in grittiness were observed between quarks containing microparticles (LF|mp) and the ones with granola (LF|mp|SG, LF|mp|HG), suggesting that consumers still perceived microparticles even when granola pieces were present. The granola was not able to change the detectability of the particles, and therefore the quarks were still perceived as gritty. However, considering that homogeneous quarks containing hard granola pieces (LF|HG) were perceived significantly grittier than the homogeneous quark (LF), we conclude that granola pieces also contributed to consumers' grittiness perception. As the quarks with both microparticles and granola (LF|mp|SG, LF|mp|HG) are grittier than the quarks with only granola (LF|HG), grittiness scores are not dominated by the granola but are a cumulative effect of granola and microparticles.

Table 8.3. Mean attribute rank intensity and liking scores (±standard deviation) of the quarks belonging to the granola set. Different superscript letters across columns indicate significant differences among samples (p<0.05) per attribute obtained from Tukey's HSD.

	LF	LF|mp	LF|mp|SG	LF|mp|HG	LF|HG
Ranking scores					
Sweet	18 ± 15^{a}	15 ± 14^{a}	58 ± 21^{b}	61 ± 19^{b}	57 ± 23^{b}
Sour	62 ± 23^{b}	67 ± 19^{b}	34 ± 19^{a}	32 ± 19^{a}	38 ± 23^{a}
Creamy	74 ± 21^{d}	58 ± 26^{c}	46 ± 19^{ab}	41 ± 21^{a}	49 ± 22^{b}
Crunchy	6 ± 6^{a}	11 ± 14^{a}	49 ± 24^{b}	81 ± 15^{d}	76 ± 18^{c}
Gritty	11 ± 16^{a}	54 ± 30^{c}	49 ± 24^{c}	53 ± 26^{c}	34 ± 26^{b}
Hard	8 ± 13^{a}	11 ± 13^{a}	52 ± 21^{b}	62 ± 20^{c}	58 ± 21^{c}
Dry	31 ± 27^{a}	42 ± 28^{b}	45 ± 22^{b}	44 ± 24^{b}	44 ± 23^{b}
Flavour intensity	35 ± 25^{a}	36 ± 25^{a}	50 ± 22^{b}	64 ± 7^{c}	63 ± 18^{c}
Liking scores					
Overall liking	5.7 ± 1.7^{b}	4.5 ± 1.6^{a}	5.4 ± 1.7^{b}	6.9 ± 1.4^{c}	6.8 ± 1.3^{c}
Texture liking	6.4 ± 1.7^{b}	4.3 ± 1.8^{a}	5.3 ± 2.1^{a}	6.8 ± 1.6^{bc}	6.5 ± 1.9^{c}
Flavour liking	5.3 ± 1.7^{a}	4.8 ± 1.7^{a}	6.4 ± 1.4^{b}	6.7 ± 1.4^{c}	6.3 ± 1.7^{bc}

As expected, quarks containing hard granola (LF|mp|HG) were perceived as significantly crunchier, harder, and with overall higher flavour intensity than quarks with added soft granola (LF|mp|SG). Variations in granola hardness, however, did not affect grittiness perception. We conclude that addition of granola pieces to quark containing microparticles can significantly boost positive sensory perceptions as sweetness, crunchiness and overall flavour intensity, but these positive perceptions do not influence the scores of the negative gritty sensation.

Incorporation of hard granola pieces to homogeneous quark (LF|HG, LF) provided significant higher scores for overall, texture, and flavour liking (**Table 8.3**). Such a positive effect of granola on hedonic responses was observed also for quarks containing microparticles (LF|mp|SG, LF|mp|HG) as these were significantly

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more liked than quark containing microparticles only (LF|mp) and even than the homogeneous quark (LF). Considering both ranking and liking outcomes, the results indicate that granola pieces can effectively improve consumer hedonic responses of quark containing microparticles, although gritty sensations were still perceived by participants. We suggest that such an increase in liking of quarks with microparticles by the addition of granola pieces is caused by a possible shift in attention of consumers to positive, more dominant sensations (i.e. crunchiness, sweetness, overall flavour intensity). This will be discussed further in section 8.3.2. This effect was larger for quark containing hard granola pieces (LF|mp|HG) than for quark containing soft granola pieces (LF|mp|SG) probably because consumers preferred products with crunchy pieces over quark containing soft granola pieces. We conclude that addition of granola pieces to quark can not only prevent a decrease in liking when microparticles are present, but can even increase liking of a quark with microparticles in comparison to the respective homogeneous version.

8.3.1.3 Effect of peach gel pieces on sensory perception and liking of quark containing microparticles

All quark sensory attributes were found to be significantly affected by the addition of microparticles and/or peach gel pieces (**Table 8.4**). Quark containing soft peach gel pieces (LF|SP) were perceived significantly sweeter, crunchier, harder and with a higher flavour intensity than homogeneous low-fat quark (LF). Similar to the effects observed for quark containing hard granola, the addition of soft peach gel pieces to homogeneous quark decreased sourness and creaminess significantly. Quarks containing microparticles (LF|mp, LF|mp|SP, LF|mp|HP) scored equally in grittiness and creaminess, signifying that addition of peach gel pieces (soft/hard) did not prevent microparticles detection, and accompanying gritty perception. The presence of peach gel pieces in quark with microparticles led to higher crunchiness, hardness, and overall flavour intensity perception than in quarks containing only microparticles (LF|mp). Variations in mechanical properties between soft and hard peach gel pieces resulted only in a higher sweetness when the particles were soft and higher hardness when the particles were hard. We conclude that incorporation of peach gel pieces to quark containing undesired microparticles cannot prevent negative gritty perceptions or decrease in perceived creaminess, although their addition can boost positive sensory perception, such as sweetness, crunchiness, and overall flavour intensity.

Table 8.4. Mean attribute rank intensity and liking scores (±standard deviation) of the quarks belonging to the peach set. Different superscript letters across columns indicate significant differences among samples (p<0.05) per attribute obtained from Tukey's HSD.

	LF	LF|mp	LF|mp|SP	LF|mp|HP	LF|SP
Ranking scores					
Sweet	18 ± 14 ^{a}	18 ± 14 ^{a}	53 ± 21 ^{c}	43 ± 19 ^{b}	53 ± 21 ^{c}
Sour	58 ± 21 ^{b}	63 ± 21 ^{b}	37 ± 18 ^{a}	42 ± 19 ^{a}	35 ± 20 ^{a}
Creamy	71 ± 23 ^{c}	50 ± 25 ^{a}	43 ± 21 ^{a}	43 ± 21 ^{a}	62 ± 20 ^{b}
Crunchy	8 ± 12 ^{a}	19 ± 20 ^{b}	36 ± 23 ^{d}	42 ± 26 ^{d}	28 ± 21 ^{c}
Gritty	12 ± 17 ^{a}	63 ± 25 ^{b}	57 ± 25 ^{b}	57 ± 24 ^{b}	18 ± 18 ^{a}
Hard	10 ± 15 ^{a}	20 ± 20 ^{b}	36 ± 20 ^{c}	50 ± 26 ^{d}	29 ± 21 ^{c}
Dry	32 ± 25 ^{ab}	44 ± 27 ^{c}	36 ± 24 ^{bc}	40 ± 26 ^{bc}	24 ± 18 ^{a}
Flavour intensity	39 ± 28 ^{a}	36 ± 25 ^{a}	51 ± 20 ^{b}	49 ± 21 ^{b}	54 ± 22 ^{b}
Liking scores					
Overall liking	5.7 ± 1.7 ^{c}	4.5 ± 1.6 ^{a}	4.9 ± 1.7 ^{ab}	4.3 ± 1.6 ^{a}	5.4 ± 1.6 ^{bc}
Texture liking	6.4 ± 1.7 ^{c}	4.3 ± 1.8 ^{a}	4.4 ± 2.0 ^{a}	4.2 ± 1.7 ^{a}	5.3 ± 1.8 ^{b}
Flavour liking	5.3 ± 1.7 ^{a}	4.8 ± 1.7 ^{a}	5.2 ± 1.6 ^{a}	4.9 ± 1.6 ^{a}	5.4 ± 1.7 ^{a}

The addition of soft peach gel pieces to low-fat quark (LF|SP, LF) did not result in a change in overall liking scores, but decreased texture liking significantly (**Table 8.4**). When comparing the overall liking and texture liking scores of quarks containing microparticles (LF|mp) with those with added peach gel pieces (LF|mp|SP, LF|mp|HP), no significant differences were observed. Addition of peach gel pieces did not prevent a decrease in hedonic responses caused by microparticle addition. This is probably related to the fact that the peach gel pieces were themselves not very well liked, possibly as a result of disconfirmation of expectations due to the unfamiliar texture of the gel (**Chapters 4** and **6**). The variation in their hardness did not affect liking scores. In contrast to the addition of fat and granola, the positive sensations (e.g. sweetness and flavour intensity) induced by addition of peach gel pieces did not inhibit the decline in product liking of quarks with microparticles. We conclude that a possible hedonic compensation or shift in consumers' attention towards positive sensation in quark containing microparticles depends on the properties of the added macroparticles and their ability to positively contribute to liking.

8.3.1.4 Effect of fat on sensory perception and liking of quarks containing microparticles

Sensory perception of quark differed considerably between samples varying in fat content as significant differences were found between samples for all attributes (**Table 8.5**). Considering the similarity in composition reported in section 8.2.1, we expected that these changes were primarily related to differences in fat content. However, we cannot exclude that small differences in the composition or production process might have been present between the two commercially available LF and FF quark.

An increase in fat content from 0 to 8.8% (LF, FF) in homogeneous quarks significantly increased sweetness, whereas sourness and hardness decreased. These effects were also observed when quarks differing in fat content containing microparticles were compared (LF|mp, MF|mp, FF|mp), suggesting that the presence of fat in quark can significantly influence perceived sweetness, sourness, and hardness even when microparticles are present and perceived. Conversely, the results show that fat addition had no significant effect on perceived grittiness, creaminess, and crunchiness for quark containing microparticles.

The results indicate the creaminess did not significantly differ between low-fat quark (LF) with a score of 66 and full-fat quark (FF) with a score of 55. This was not expected as full-fat quark should be perceived considerably creamier than low-fat quark due to the lubrication abilities of the dispersed fat droplets. Potential reasons could be related to the properties of the continuous protein phase (i.e. fine vs course protein network) or a different production process (e.g. homogenization) between the two commercial quark types. The low-fat quark has apparently been successfully modified in such a way that the creaminess is the same as the one of the full-fat quark. Therefore, although the results showed that higher fat content in quark containing microparticles did not reduce grittiness (**Table 8.5**), we cannot yet conclude from this study that lubrication cannot be used as an effective strategy to reduce detectability of microparticles (>200 µm) and therefore reduce perceived gritty sensation. To verify such strategy, quarks with the same properties in the continuous phase and an obvious effect of fat addition on the attribute creaminess would be required.

Table 8.5. Mean attribute intensity and liking scores (±standard deviation) of the quarks belonging to the fat set. Different superscript letters across columns indicate significant differences among samples (p<0.05) per attribute obtained from Tukey's HSD. Due to a faulty set-up of the digital questionnaire, data for the attributes dryness and flavour intensity were not recorded.

	LF	LF|mp	MF|mp	FF|mp	FF
Ranking scores					
Sweet	22 ± 20^{a}	20 ± 19^{a}	35 ± 19^{b}	43 ± 22^{c}	47 ± 25^{c}
Sour	62 ± 23^{c}	64 ± 22^{c}	47 ± 22^{b}	31 ± 20^{a}	29 ± 23^{a}
Creamy	67 ± 22^{b}	50 ± 25^{a}	49 ± 24^{a}	49 ± 24^{a}	55 ± 26^{b}
Crunchy	13 ± 17^{a}	31 ± 27^{b}	30 ± 26^{b}	25 ± 24^{b}	8 ± 10^{a}
Gritty	14 ± 13^{a}	63 ± 23^{b}	57 ± 25^{b}	55 ± 27^{b}	8 ± 12^{a}
Hard	17 ± 20^{b}	30 ± 24^{d}	26 ± 22^{cd}	22 ± 21^{bc}	7 ± 8^{a}
Liking scores					
Overall liking	5.7 ± 1.7^{c}	4.5 ± 1.6^{a}	5.3 ± 1.8^{bc}	5.0 ± 2.0^{ab}	6.4 ± 1.6^{d}
Texture liking	6.4 ± 1.7^{c}	4.3 ± 1.8^{a}	4.9 ± 2.1^{b}	5.6 ± 2.1^{ab}	6.9 ± 1.3^{c}
Flavour liking	5.3 ± 1.7^{ab}	4.8 ± 1.7^{a}	5.5 ± 2.1^{bc}	5.6 ± 2.1^{ab}	6.3 ± 1.7^{c}

An increase in fat content from 0 to 8.8% in homogeneous quarks (LF, FF) provided a significant increase in overall liking and flavour liking, but no differences were observed between the two samples in terms of texture liking (**Table 8.5**). With the addition of microparticles, significant lower overall and texture liking scores were recorded for all quarks (LF|mp, MF|mp, FF|mp) regardless of the fat content. This shows that quarks with microparticles were less liked than the respective smooth products. Quark with mid-fat content and microparticles (MF|mp) were significantly more liked than quark with microparticles and no fat (LF|mp). Therefore, it seems that fat can increase liking of the product, although the particles could still be perceived. However, when the fat content was increased further (FF|mp), no further increase in overall liking was observed, and no differences between mid-fat (MF|mp) and full-fat (FF|mp) quarks containing microparticles were shown. Although fat seems to increase liking, the quarks with microparticles and fat are still much less liked than quarks without microparticles. As no differences were observed in grittiness between quarks with microparticles varying in fat content, we relate the increased liking of quarks with fat more to their higher ratings in sweetness and lower sourness (**Table 8.5**) than to differences in creaminess. We conclude that although the presence of fat in quark did not decrease perception of grittiness, it marginally positively affects the liking scores of quark.

8.3.2 TDS

8.3.2.1 Effect of addition of microparticles on dynamic sensory perception of quarks

To further investigate the perception of homogeneous and heterogeneous quarks and to identify possible explanations for the hedonic responses previously reported, Temporal Dominance of Sensations (TDS) was used. **Figures 8.1A** and **8.1B** show the temporal profiles of consumers (n=51) for low-fat quarks without and with microparticles, respectively. The dynamic profile of homogeneous quarks was characterized by an alternate dominance of the attributes creaminess, dairy flavour, and sourness. Dryness dominance increased towards the end of consumption without reaching significance level, whereas the remaining attributes did not overcome chance level. Upon addition of microparticles (**Figure 8.1B**), creaminess remained the most dominant attribute, but grittiness dominance rates also presented high values at the beginning of consumption. Grittiness dominance decreased progressively reaching non-significance level at approximately one-third of the total time. Such a high dominance rate of gritty sensations over time led to overall lower dominance rates of dairy flavour and sourness in the first half of consumption time in comparison to homogeneous quark. The presence of microparticles also increased dominance of dryness, which became significant at the end of consumption. Therefore, microparticle addition mainly determined modifications of the dynamic sensory profile of quarks during the first and last part of sensory evaluation.

In conclusion, presence of microparticles in quark increases dominance of gritty and dry sensations at the beginning and end of consumption, while dominance of flavour attributes (i.e. sourness and dairy flavour) in the first part of oral manipulation is reduced.

8.3.2.2 Effect of granola pieces on dynamic sensory perception of quarks containing microparticles

The effect of granola pieces added to quarks containing microparticles is shown in **Figures 8.1C** and **8.1D**. As observed in the ranking outcomes (**Table 8.3**), the incorporation of granola pieces (soft/hard) strongly changed the perceived product profile of quarks with a shift from quark-related to granola-related dominant

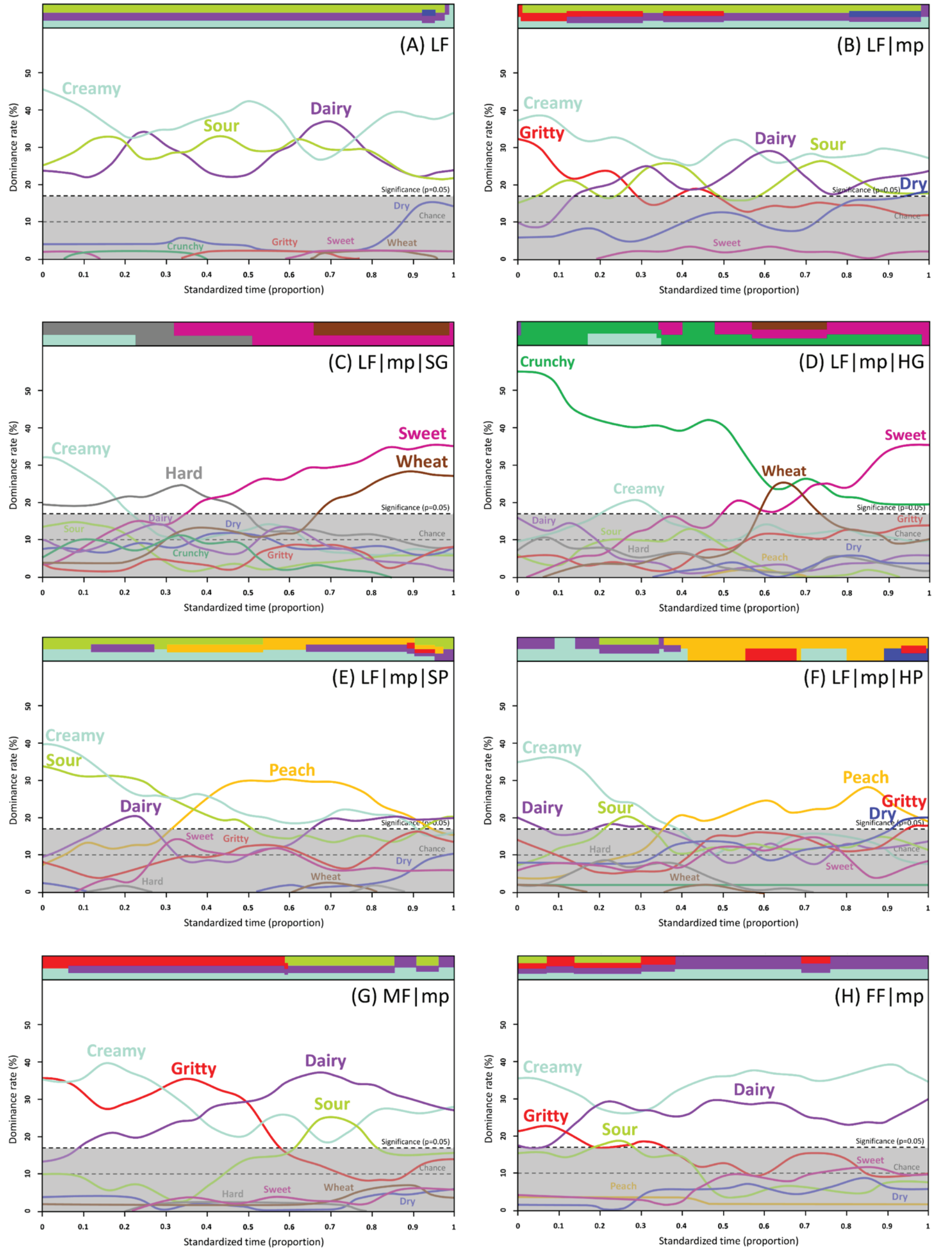

Figure 8.1. Band plots and TDS curves of homogeneous quark (A), quark with added microparticles (B), quark containing microparticles with added soft and hard granola pieces (C, D), quark containing microparticles with added soft and hard peach gel pieces (E, F) and quark containing microparticles with mid and high fat content (G, H) over standardized eating time. The abbreviations are explained in Table 8.1.

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attributes. For quarks containing soft granola pieces (**Figures 8.1C**), the first half of the dynamic sensory profile was characterized by creamy and hard sensations, leading to progressively higher dominance of sweet and wheat-flavour perception. For this type of granola, crunchiness was not perceived as a dominant sensation. For quarks containing hard granola pieces (**Figures 8.1D**), the first two-thirds of consumption was dominated by crunchiness perception followed by wheat and sweet sensations. The increase in hardness of the granola induced a shift from hard to crunchy. As a consequence of these dominant perceptions, hard and crunchy, lower dominance rates of sourness and dairy flavour were observed in quarks containing either of the granola pieces. Similarly, grittiness perception never reached significance level for both products, supporting the hypothesis that the positive, more dominant sensations have caused a shift in attention of consumers away from unpleasant perception, such as grittiness. This positive effect of added granola on dynamic sensory profile was also observed as the dominance ratings for dryness decreased, which did not reach significance level at the end of consumption. We conclude that addition of granola pieces providing positive dominant perceptions (i.e. crunchiness) to quarks can effectively direct away consumers' attention from the undesired gritty, sour, and dry sensations.

8.3.2.3 Effect of peach gel pieces addition on dynamic sensory perception of quarks containing microparticles

The temporal profiles of quarks containing peach gel pieces and microparticles are illustrated in **Figures 8.1E** and **8.1F**. The results show that addition of peach gel pieces to quarks containing microparticles determined significant changes especially in the second part of the product oral consumption. For both quarks containing soft and hard peach gel pieces, the dominance of dairy flavour observed for quark containing microparticles (**Figure 8.1B**) was replaced by relatively high dominance rates of peach flavour. For both peach types, creamy and sour perception dominated the first half of product evaluation. Soft peach gel pieces were more effective in preventing dominance of grittiness and dryness than the respective hard version as the dominance rate for these attributes progressively increased, reaching significance level in the second half of consumption when hard peach gel pieces were present.

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These results indicate that optimization of dynamic sensory perception of quarks containing microparticles depends on the properties (i.e. hardness) of added peach gel pieces. The low dominance of grittiness, however, did not improve liking for quarks containing microparticles and peach gel pieces (**Table 8.4**). We conclude that a shift in consumers' attention away from gritty sensations might not have been large enough for such relatively soft macroparticles (approx. 35-100 times softer than the granola) or, alternatively, that the change in attention might not be the only mechanism able to explain the differences in dominance rates observed upon addition of other macroparticles.

8.3.2.4 Effect of fat addition on dynamic sensory perception of quarks containing microparticles

Variations in fat content caused significant modifications in dynamic sensory perception in quarks containing microparticles (**Figures 8.1G** and **8.1H**). When 4.4% fat was added to quark containing microparticles (**Figure 8.1G**), the temporal perception was largely dominated by creamy and gritty sensations during the first half of consumption time. For this product, dairy flavour and sourness dominance rates increased progressively over time, reaching their maximum value towards three-fourths of total oral evaluation time. A further increase in fat content to 8.8% (**Figures 8.1H**) resulted in an increase of creaminess dominance throughout the entire sample evaluation, while grittiness and sourness dominance decreased considerably in comparison with the mid-fat quark with added microparticles. For both MF|mp (4.4% fat) and FF|mp (8.8% fat) quarks, dryness dominance did not reach significance level, indicating that presence of fat at both 4.4 and 8.8% in quark can reduce the dominance of such a negative sensation.

When comparing the dynamic perception with the static scores obtained during the ranking test, both similarities and differences can be observed across quarks with different fat content. For instance, the progressively lower sourness sensation observed during dynamic evaluation for the mid-fat and full-fat quark is in agreement with the results of the static evaluation in which fat-containing quarks presented significantly lower scores than the low-fat quark containing microparticles. Conversely, when microparticles were present, the ranking outcomes did not highlight any significant difference in the effect on creaminess and grittiness of the quark containing a high fat content (8.8%; FF|mp) in comparison to the scores for quark with a lower fat content (4.4%; MF|mp). This could possibly suggest that the presence of fat in quark did play a minor role in perception of creamy and gritty sensations over time, although such effects could not be observed in the static evaluation by the ranking test.

When the dynamic sensory profiles of quarks with added microparticles varying in fat are compared to low-fat quarks containing microparticles (**Figures 8.1B**, **8.1G**, **8.1H**), it can be seen that grittiness dominance rates were considerably higher in quarks containing 4.4% fat than in low-fat and full-fat quarks. We explain this non-linear effect of fat addition on dominance of grittiness by the fact that the present fat not only affects the attribute creaminess, but also modifies the matrix sensory profile with respect to attributes as sourness and dryness. For sample LF|mp, the perception of multiple negative sensations as high grittiness, high sourness, and high dryness determined an increased difficulty for the participants to determine the most dominant attribute during the first part of consumption. As a result, there was little consensus between the participants, and scores did not reach significant levels. Conversely, for sample MF|mp, apparently the lower sourness and expected lower dryness did not draw the attention as a negative attribute (**Table 8.3**), and therefore grittiness was perceived dominant by many participants. Finally, for sample FF|mp, the even lower sourness and dryness as a negative contribution in combination with a possible positive effect of the lubrication properties of fat resulted in a low dominance of gritty sensation over time. We conclude that high fat content in quark can decrease dominance of negative sensation as grittiness and sourness over time, while it increases positive dominance sensations as creaminess.

8.3.3 General discussion

This study aimed to examine whether the addition of macroparticles or fat to quark can be used to perceptually compensate for undesired gritty sensations caused by hard microparticles. None of the tested strategies allowed to decrease gritty sensations, and therefore were not able to mask grittiness. Nonetheless, addition of fat or granola pieces to quarks containing microscopic cellulose beads increased liking. So even though grittiness was still perceived, the different strategies affected perception and appreciation. We suggest that the observed effects are caused by (i) a shift in consumers' attention induced by perceptions of more dominant sensations (cognitive attention-driven mechanism), and (ii) compensation of the gritty negative perceptions by more positive ones (hedonic compensation effect).

The attention-driven mechanism is supported by the findings obtained during the dynamic sensory evaluation of quark as the presence of macroparticles could draw the attention of consumers away from microparticle-related perceptions by providing more dominant sensations (i.e. crunchiness). Such an effect was also observed when in an additional, explorative study (data not shown) other macroparticles (i.e. chocolate chunks, canned peach cubes) were used and evaluated for their sensory profile and liking. For instance, when chocolate chunks were added to quark containing microparticles, the high dominance of perceived crunchiness and chocolate flavour led to a shift in attention away from gritty sensations. This suggests that the dominance of sensations in foods can be influenced by a combination of different components providing contrasting texture and flavours and this is in line with previous work on heterogeneous products (Tang et al., 2017). It also suggests that a variety of macroparticles such as granola, chocolate chunks and canned peach cubes can be used to direct attention and possibly to increase liking of foods with undesired texture sensations.

The addition of granola pieces was demonstrated to be the most effective strategy to prevent a decrease in liking of quarks with added microparticles, while addition of peach gel pieces showed to be considerably less effective in such a task. Both macroparticles (peach and granola) provided positive and more dominant sensations during consumption and, therefore, we suggest that consumers' expectations might have also played a role during the evaluation of quarks as the importance of expectations on product acceptance is already known (Costell et al., 2010; Deliza, 1995; Deliza & Macfie, 1996; Higgs, 2015; Tarancón et al., 2014). We hypothesize that during the chewing process of granola pieces, the consumers expect the formation and presence of particles of different sizes as a result of product breakdown and related reduction in size of the macroparticles. On the contrary, consumers do not expect the perception of small gritty particles as a result of oral breakdown of peach gel pieces. Consequently, the type of stimulus triggered by the presence of microparticles in the two products did not change, but consumers textural expectations did. This suggests that to efficiently compensate for undesired textural sensations caused by microparticles, the selection of the type of macroparticles should be based on the presence of attributes that are relatively similar to those of the microparticles. We conclude that the recognition of the origins of gritty sensations (i.e. from which food component the microparticles originate) in a product is a crucial factor in determining consumers' hedonic response.

However, the attention-driven mechanism is not sufficient to explain differences in liking between the different quarks with added granola, peach gel pieces, or fat. For instance, the TDS outcomes highlighted that mid-fat quarks with particles (MF|mp) presented higher rates of grittiness dominance over time than the respective low-fat quarks (LF|mp), although the mid-fat gritty quarks were more liked. For such fat-containing samples, we explain this effect mainly by considering that modifications of other sensations besides grittiness can also contribute to an effective hedonic compensation of the negative perceptions. For example, a reduction of product sourness or increase in sweetness might help the consumer to compensate for the negative sensation of grittiness. To test this, we performed additional, exploratory tests (data not shown) by adding sugar (2.3% w/w) to quark containing microparticles and evaluated the dynamic perception and liking. Dominance of sweet sensations was increased, while sourness dominance was reduced. Although addition of sugar could not decrease grittiness dominance, liking of the sweetened quark was higher than the respective unsweetened quark. This confirms indeed that positive sensations (i.e. sweetness) can determine an effective hedonic compensation of the negative gritty sensations.

The hedonic compensation effect can also be explained by the intrinsic palatability of the particles. In fact, considering the hedonic scores of the quark without microparticles, the presence of hard granola pieces provided the largest increase in overall liking (+1.1 based on average score), followed by full-fat quark (+0.7 based on average score), while no differences were found for quark with added soft peach gel pieces (LF|SP). These results coincide with the effectiveness of the tested strategies and we therefore suggest that liking of added particles itself is a critical factor that determines the hedonic compensation of negative sensations. Further investigation is required to establish whether the attention-driven mechanism or hedonic compensation (either perception-driven or liking-driven) or a combination of the two are mainly responsible for the for the perceptual compensation effect of microparticles observed in this study.

The present findings have significant implications for the design of both pharmaceutical delivery systems and food products. Patient rejection of particulate formulations could be limited or prevented if the drug carriers are provided in a food matrix in combination with other macroparticles. From a food development perspective, addition of macroparticles providing positive sensory sensations into a food product can possibly counteract negative product textural defects, so the strategy could be used to compensate for undesired texture sensations in foods. Gritty, rough and dry feelings originated from presence of protein aggregates in protein-enriched liquid foods, or fibres in foods could be mitigated by such textural combination. For instance, addition of particles (e.g. addition of coconut flakes, chocolate sprinkles, or granola pieces to quark/yoghurt) could allow better acceptability of products containing microparticles, such as high-protein dairy products.

8.4 Conclusions

This study aimed to investigate whether the addition of macroparticles or fat to quark could be used to perceptually compensate for negative gritty sensations caused by microparticles. The addition of granola pieces to quark containing microparticles prevented the decrease in liking, even though grittiness was still perceived. The TDS profiles of quarks containing microparticles indicated that the presence of granola pieces changed the focus of attention of consumers towards more positive and dominant sensations (i.e. crunchiness), preventing a decrease in hedonic responses. Conversely, the incorporation of peach gel pieces to quark containing microparticles did not prevent gritty sensations nor avoid a decline in liking. We related the different effects of the two macroparticles on liking of quarks with gritty sensation to the different expectations of the consumers, as participants did not expect the presence of small hard particles when peach gel pieces were present, whereas the presence of small particles is not uncommon for granola. This suggested that consumers' expectations determine the interpretation of the stimulus triggered by the presence of microparticles and its effect on the product hedonic response. When a medium amount of fat was added (4.4%), liking did not decrease, which is probably due to an effective hedonic compensation triggered by more positive sensations (i.e. sweetness). Higher level of fat (8.8%) in quark did not significantly improve liking nor reduced perceived grittiness. Overall, these results show that incorporation of well-liked macroparticles (i.e. crunchy granola pieces) or fat can be used as strategies to shift consumers' attention towards positive sensations leading to an increase of liking while negative sensations (grittiness) caused by structural heterogeneities (cellulose beads) are still sensed. These findings could help to prevent patient rejection of particulate formulations and food companies to optimize food products presenting textural defects.

Chapter 9

GENERAL DISCUSSION

9.1 Introduction

The perception and appreciation of food depends on a variety of factors related to both the product properties and consumer physiological and cognitive characteristics. The interpretation of food stimuli that are established by physical and chemical properties involves processes that largely depends on individual physiological sensitivity and previous experiences with the food. Therefore, to design foods that are appreciated during consumption, there are several variables that should be taken into consideration.

The aim of this thesis was to unveil the effect of structural heterogeneity on expected and perceived sensory properties and liking of foods in different consumer groups using a multidisciplinary approach. The effect of physical and physicochemical properties of heterogeneous food matrices on sensory perception and liking in relation to consumer physiological and cognitive characteristics were investigated. The main findings of the thesis are summarized in **Table 9.1** and **Figure 9.1**.

9.2 Discussion and interpretation of the results

9.2.1 Influence of food properties on perceived heterogeneity

In this Thesis, food structural heterogeneities at different length scales were used to investigate how products physical and physicochemical characteristics affect sensory perception and liking of consumers. Heterogeneity was created by either combining different layers varying in mechanical properties (**Chapter 2**) or adding particles varying mainly in hardness (i.e. fracture stress), size, and flavour concentration (**Chapters 3** to **8**) into matrices with different consistencies (**Figure 9.2**).

9.2.1.1 Mechanical contrast as a means to influence perception of heterogeneous foods

The key factor determining perception of heterogeneity in both layered and dispersed foods with added particle was found to be a difference in mechanical properties between structural components. Incrementing the mechanical contrast by modifying fracture stress between layers (**Chapter 2**) or between particle and surrounding matrix (**Chapter 3**) resulted in an enhanced perception of texture contrast (heterogeneity) and mouthfeel heterogeneity, independent of the matrix

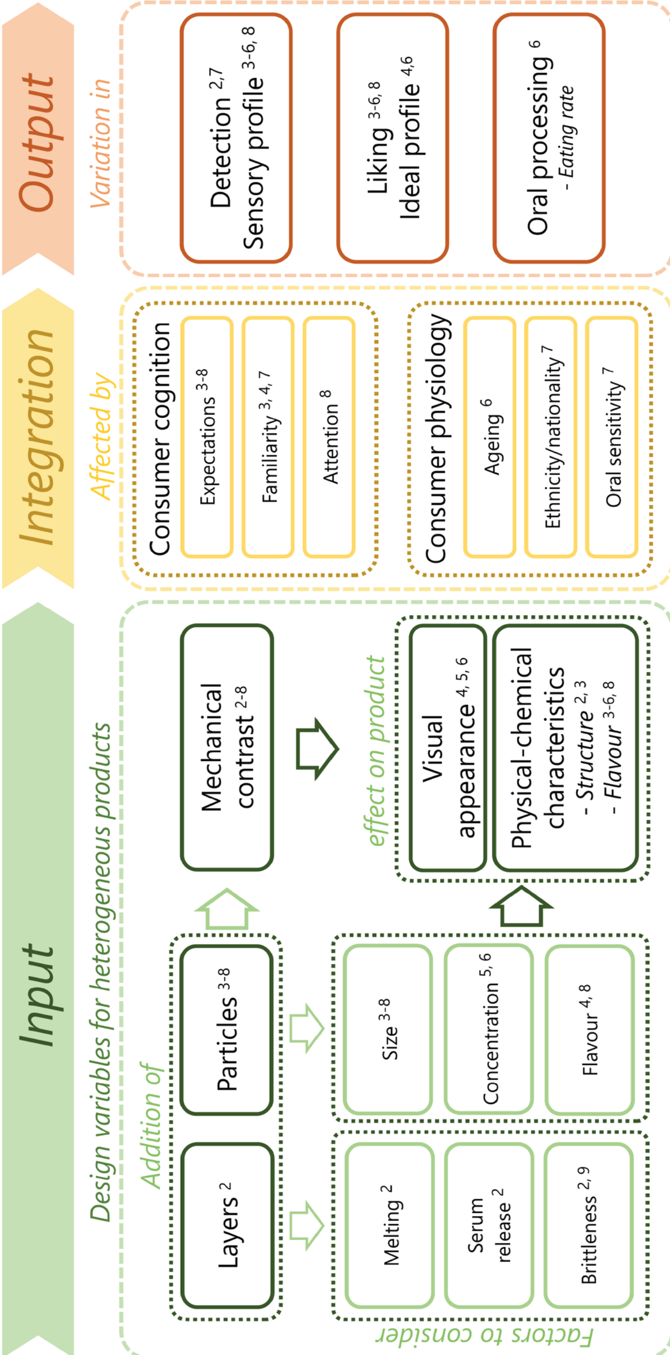

Figure 9.1. Schematic overview of the integrated approach and key variables evaluated in this thesis. Superscript numbers indicate chapters in this thesis.

Table 9.1. Summary of the main findings of the studies described in this thesis.

Chapter	Aim	Key factors investigated	Measured response	Main findings
2	To determine the influence of mechanical and physicochemical properties of bi-layer model foods on the detection of perceived texture contrast.	Fracture stress Fracture strain Melting properties Serum release	Detection threshold Time-intensity profiling	Texture contrast perception thresholds varied between brittle ($\Delta\sigma_F$ =5 kPa) and elastic soft gels ($\Delta\sigma_F$ =16 kPa) and between soft (low σ_F) and hard (high σ_F) gels ($\Delta\sigma_F$ soft gels < $\Delta\sigma_F$ hard gels). A combination of mechanical and physicochemical properties influences the dynamic perception of heterogeneity over time.
3	To investigate the combined effects of particle size, particle hardness, and matrix type of dispersed model foods on sensory perception and liking.	Particle size Particle hardness Matrix consistency	Perceived sensory profile (Rate-All-That-Apply) Liking	Particle size determines the type of sensory descriptors selected, while particle hardness (fracture stress) establishes the intensity of selected sensory attributes. Mere mechanical contrast does not enhance liking of model soups and gels
4	To examine the effect of mechanical contrast and flavour concentration of carrot particles added to soups on expected and perceived sensations and liking.	Particle size Particle hardness Particle flavour intensity	Expected and perceived sensory profile Liking Ideal profile	Particle size mainly influences expected textural attributes (chewiness, crunchiness and hardness) and perceived flavour sensations (carrot flavour). Flavour concentration in model carrot particles added to soups marginally influences liking. Addition of congruent and familiar particles that match consumer' expectations changes positively the sensory product profile of a common product towards higher liking.

5	To determine the influence of visual and oral sensorial cues on consumer preferences and sensory perception of novel, heterogeneous cheeses.	Particle size Particle hardness Particle concentration Visual and oral cues	Expected and perceived sensory profile Liking	Both visual (recognition of particles) and oral sensory cues (size, hardness, concentration of particles) can influence significantly texture and flavour perception of heterogeneous cheeses. Liking of heterogeneous cheeses is determined by somatosensory and gustatory cues, whereas visual appearance and product description do not contribute to the consumer's hedonic response during consumption.
6	To study the effect of particle addition - varying in size, hardness and concentration - into yoghurt on oral processing behaviour, expectations and sensory perception of consumer groups differing in age	Particle size Particle hardness Particle concentration Ageing	Oral processing behaviour Expected and perceived sensory profile Liking Ideal profile	Addition of particles to yoghurt increases number of chews, consumption time, and decreased eating rate up to 60% for both consumer groups. Although the oral processing time of elderly is longer than young subjects, ageing of healthy participants marginally affect texture perception of heterogeneous products.
7	To explore the influence of consumer familiarity and physiological characteristics of participants on oral detectability of microscopic particles in foods.	Matrix type Nationality and ethnicity	Detection threshold Oral physiological characteristics Familiarity	Microparticle detection depends on matrix properties (i.e. easier to detect particles in a viscous low-fat product than in solid high-fat one), but not on factors linked to participants' nationality and ethnicity or product familiarity. Particle size detection thresholds were not influenced by participants PROP status, tongue pressure detection thresholds, and papillae density.
8	To investigate the possible compensating effect of macroparticles or fat addition to quark on the perception of negative texture sensations (grittiness).	Particle type Particle hardness	Perceived sensory profile Dynamic sensory profile (TDS) Liking	Incorporation of well-liked macroparticles (i.e. crunchy granola pieces) or fat can be used as strategies to shift consumers' attention towards positive sensations leading to an increase of liking while negative sensations (grittiness) caused by structural heterogeneities are still sensed.

consistency (**Chapters 4** and **5**). The addition of particles varying in fracture stress also influenced the perception of other textural attributes such as hardness, chewiness, and crunchiness of the overall product. This modification of the product sensory profile is in line with the results of Tang and co-workers (2017), where it was shown that addition of hard components (i.e. poppy seeds, sunflower seeds and gluten-based hard disc) into gelatine-agar gels established an increase of perceived firmness/hardness of the overall product. The authors showed that with larger variations between the mechanical properties of the components of a heterogeneous food, there was a higher number of different textural attributes provoked by the food during mastication and, as defined by Larsen et al. (2015), there was therefore a higher textural complexity of the product.

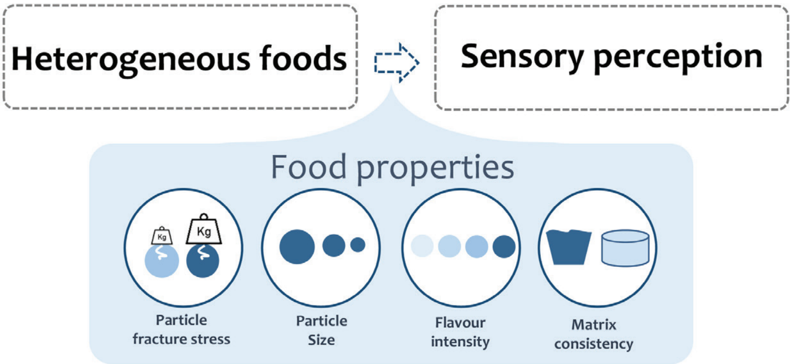

Figure 9.2. Connecting food heterogeneity to consumer perception by food properties.

Variation in fracture strain between components of a heterogeneous food had a significant role in affecting the detection of heterogeneity in bi-layer gels (**Chapter 2**). The results showed that the detection of mechanical contrast as perceived texture contrast was inversely correlated with the brittleness (fracture strain) of soft gels; smaller differences in mechanical contrast were required to trigger perception of heterogeneity in brittle model foods than elastic ones. When comparing the results of **Chapters 3**, **4** and **5**, a limited effect of fracture strain was observed in particles-filled systems. In fact, particles with comparable fracture stress but different fracture strain were used. In these studies, a progressively lower fracture strain was obtained by changing gelling agent required for the different model particles, obtaining values ranging from 0.64-1.32, 0.39-0.45, and 0.21-0.31 for κ-carrageenan, agar, and low acyl gellan gum respectively.

As the effects of particle addition into a homogeneous food on perceived texture were comparable between the three chapters, we conclude that the effect of variation in fracture stress overrules the possible consequences on sensory perception related to variation in fracture strain of the added particles. Apparently the degree of elasticity of different components within a single bite can significantly influence perception and oral processing in layered foods (Devezeaux de Lavergne et al., 2015), but for heterogeneous food with added particles, the fracture stress (i.e. hardness) of embedded components is the key factor that determines noticeable differences in consumer perception.

Since the evaluation of brittleness/elasticity occurs during the breaking-down of the product throughout mastication, we speculate that the effects of such a variable on the consumer perception are larger for heterogeneous products that need active destruction before swallowing (i.e. layered foods) than products that require a limited chewing process (i.e. particles dispersed in food products). In conclusion, the results of this Thesis suggest that the detectability and perception of heterogeneity is mainly determined by variation in fracture stress (i.e. mechanical contrast) in particles-filled foods, while variations in fracture strain between food components might also influence such a perception in layered heterogeneous food products.

9.2.1.2 Relating particle size with perception of heterogeneous foods

The size of added particles in different matrices tested in this Thesis was systematically varied (see **Figure 9.3**) to determine the contribution of such product variable on the oral perception of heterogeneous foods. In general, the presence of small particles with an averaged diameter of ≥0.8 mm (**Chapters 3**, **7** and **8**) or cubes with a side length of 2 mm (**Chapter 5**) was associated with the perception of gritty sensations. Increasing the size of spherical particles above 4 mm in diameter, or to 6-7 mm for cubed particles, determined an increase in perception of sensory attributes as chewiness, lumpiness, and mouthfeel heterogeneity, while grittiness decreased (**Chapters 4** and **5**). In agreement with our results, an increased perception of sandy sensations was also observed when pineapple puree containing particles smaller than 1.5 mm was added to yoghurt (Tarrega et al., 2016). The results of that study showed that when pineapples was added in the form of cubes (8 × 8 mm), the perception of sandy sensations in yoghurt could be prevented. Consequently, particle size is a key variable to determine the texture profile of different heterogeneous food products, even though the intensity of the specific attributes is affected by the particle fracture stress (i.e. fracture stress; **Chapter 3**). We conclude that the perception of food products containing particles depends on the interaction between the size of the particles and their mechanical properties (i.e. fracture stress).

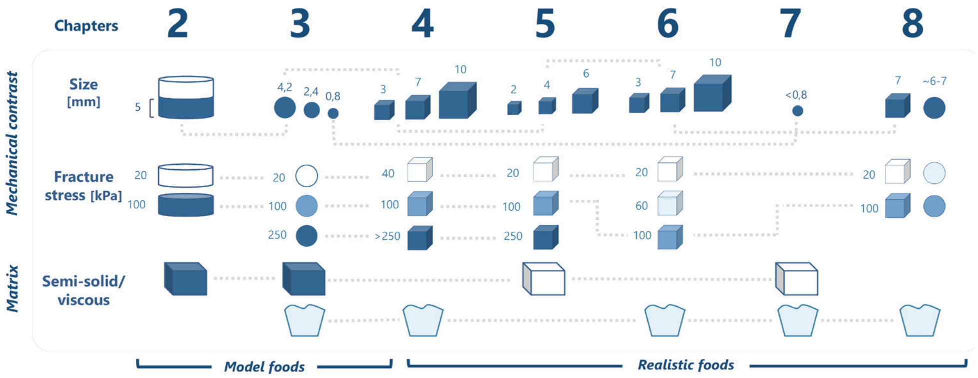

Figure 9.3. Connecting food heterogeneity to consumer perception by food properties.

9.2.1.3 The link between flavour and heterogeneity

The addition of particles to a homogeneous food is often associated not only with the introduction of diverse textures in the product, but also with the combination of different flavours. The analysis of flavour attributes showed that addition of particles having a flavour profile that differs from the surrounding matrix results in an obvious perception of the added flavour(s). For instance, the incorporation of carrot pieces into soup (**Chapter 4**) or bell pepper cubes into processed cheese (**Chapter 5**) caused the predictable perception of carrot and bell pepper flavours respectively. Such an effect was not only explained by the presence of aroma compounds in the particles, but could also be related to a multimodal perception effect caused by the visual appearance of particles. In fact, the result of **Chapter 4** showed that when the flavour concentration of model carrot cubes was varied (0 to 100%) while keeping the appearance of the particles constant (i.e. orange colour), a limited variation in perceived carrot flavour intensity between soups was observed (4.07–5.59 out of 9). It was concluded that the association between the orange colour and flavour of carrots led the participants to perceive the carrot flavour, even when this was not present. When transparent particles were added to tomato soup (**Chapters 2**), however, almost all flavour attributes of the product were not affected by the presence of particles. Together these results indicate that in heterogeneous foods with added particles, the colour and visibility of added heterogeneities can affect the flavour perception of the product more than the actual flavour content.

In addition, the results of this Thesis highlighted other two important and interconnected flavour-related advantages of particle addition to a homogeneous food. The first one being the compensation ability of particles towards matrix negative flavour attributes (**Chapter 8**), while the second one is related to the opportunity of decreasing concentration of taste compounds (e.g. salt) without reducing perception of the respective attribute (i.e. saltiness). In fact, the results of **Chapter 4** showed that the addition of unsalted carrot particles to a chicken soup did not significantly influence perceived product saltiness although the effective concentration was lower (~15%) than the homogeneous soup. There, we concluded that the perception of saltiness could be controlled by combining different food components varying in their flavour content. Such a conclusion is consistent with the results of previous studies on the inhomogeneous distribution of tastants or aroma compounds (Emorine et al., 2015; Mosca et al., 2010; Nakao et al., 2013). For instance, in layered cream-based snack foods that varied in salt distribution, Emorine and co-workers (2013) demonstrated that salt perception was mostly dependent on the salt concentration in the saltier layer. In that study, a 20% salt reduction in the product without affecting perceived saltiness was made possible by a heterogeneous spatial distribution of salt. Similarly, a heterogeneous distribution in aroma compound in model gels obtained by adding small gel cubes varying in their aroma content was shown to enhance perceived intensity during consumption (Nakao et al., 2013). Therefore, the addition of particles could be used as strategy to possibly counteract less desired flavour sensations of the matrix in which particles are embedded or to induce an inhomogeneous distribution of tastants or aroma. Such inhomogeneous distribution has been proven to increase perception of flavour compounds thanks to a discontinuous stimulation of taste/aroma receptor that prevents their stimulus adaptation (Mosca et al., 2012; 2010).

9.2.1.4 The role of matrix consistency on the perception of heterogeneous foods

Matrix consistency was found to influence perception of heterogeneity at both macroscopic and microscopic scale lengths as described in **Chapters 2**, **3** and **7**. For gel macroparticles, the addition of particles in a viscous, spoonable matrix (i.e. model soup) had a greater effect on the sensory profile compared to the addition of particles to a solid, chewable matrix (i.e. model dessert) (**Chapter 3**). It was demonstrated that a high consistency of the continuous phase has the ability to reduce perception of large macroparticles (gel beads having an average diameter of 2-4 mm), suggesting that larger differences in mechanical contrast are required to determine variations in sensory response of participants in a chewable food in comparison to a spoonable one. Correspondingly, when layered gels were tested in **Chapter 2**, the participants' discrimination ability to detect mechanical contrast decreased considerably in harder gels ($\Delta\sigma_F$=14-26 kPa) in comparison to softer gels ($\Delta\sigma_F$=5-16 kPa). At a microscopic length of scale, similar conclusions were obtained considering that the particle size required to determine grittiness perception rises by roughly two thirds when the particles are embedded in a chewable processed cheese rather than a spoonable quark (**Chapter 7**).

The general agreement between these results suggests that perception of heterogeneity in foods might follow a defined relationship between the sensorial stimulus and its perceived intensity known as Weber's law (Lawless & Heymann, 2010). According to this theory, the degree of a noticeable difference of a sensory characteristic is proportional to its own intensity. This means that when the intensity of the stimulus is low, the difference required to determine variations in sensory response is also little. On the contrary, a high intensity of the sensorial stimulus requires large divergence to trigger the response of the sensory system. Such power-law relation has been found for many food properties such as perception of food firmness and spreadability, creaminess, and viscosity (Camacho et al., 2015). Although this Thesis did not directly investigate the explained relation, we speculate that the detection and perception of oral heterogeneity within a single bite follows a relationship similar to those of other oral mechanical stimuli. When the consistency of the matrix that contains contrasting components (harder than the surrounding matrix) increases, the difference in mechanical contrast (see section 9.2.1.1) between the components of a heterogeneous food decreases (i.e. lower stimulus intensity). This smaller difference causes a lower ability to perceive the mechanical stimulus. On the other hand, a low consistency of the matrix will determine larger levels of stimulus intensity (i.e. mechanical contrast) that will result in enhanced responses in the consumers. Differently from the other oral textural sensations (e.g. thickness), however, the perception of heterogeneity is affected also by the size of the present components determining the sensory perception. In fact, as seen in **Chapter 7**, the presence of hard microparticles with a diameter smaller than 50 μm did not result in detection by the participants in the semi-solid matrix. This was due to the fact that the intensity of the stimulus was too small to be perceived. In conclusion, the consistency of the matrix in a heterogeneous food has the potential to alter the level of stimulus intensity that influences perception of heterogeneity, although this is in direct relation with the size and hardness (i.e. fracture stress) of the embedded or combined elements of the food product.

9.2.2 Consumer clustering: a "sensitive" topic

The determination of consumers' physiological characteristics shaping the perception and appreciation of any food remains a challenge. There are several possible sources of variation in consumer perception that are attributable to differences related to factors such as oral sensitivity, age, and ethnicity. The investigation of such causes of differences in perception is further complicated by the dynamic process of food processing during mastication. Within the research project presented in this Thesis, key possible variables which were expected to affect the perception and appreciation of heterogeneous foods were investigated (see **Figure 9.4**).

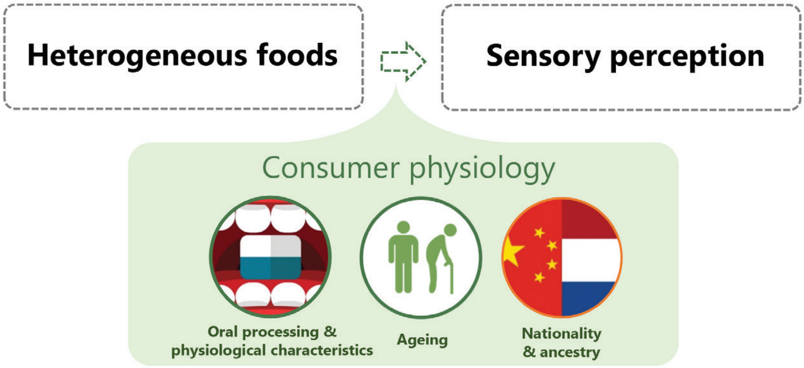

Figure 9.4. Connecting food heterogeneity to consumer perception by subject' physiological characteristics.

In **Chapter 6**, when healthy participants presenting good dental status but varying in age (young, age 21±2 years; elderly, age 70±5 years) were compared in their oral processing behaviour and perception, differences were mainly found between their chewing patterns. An increase in the age of participants determined a significant increase in consumption time and number of chews of heterogeneous yoghurts with added peach gel particles. Comparable results were obtained in the study of Ketel et al. (2019) in which macroscopically homogeneous food products with different consistencies (e.g. yoghurt, soup, cheese, carrots) were tested. In that study, elderly participants required a significantly longer consumption time and higher number of chews for solid products than young participants. In both cases, these variations caused by ageing can be explained by a decrease in bite force due to the reduction of density of the mastication muscles and related chewing compensation to obtain a bolus consistency that is safe to swallow (Field & Duizer, 2016; Mishellany-Dutour et al., 2008).

Even though the oral processing between the two consumer groups differed, variance in perception of heterogeneous yoghurts between young and elderly consumers was marginal. Differences were observed mainly for flavour attributes (e.g. lower perceived sweetness for elderly), while textural sensations varied only minimally. These observations seem somewhat in disagreement with the results of Laguna et al. (2016a), in which it was shown that progressive deterioration of tactile sensitivity was positively correlated to the ageing of consumers (average age 79±9 years). Similarly, the work of Forde & Delahunty (2002) demonstrated that old subjects (74±5 years) were less able to discriminate between small texture variations in yoghurts than younger subjects (27±4 years), although this did not result in large differences in terms of preferences between the two groups. On the other hand, as reported by Calhoun and co-workers (1992), the effects of subjects ageing on oral tactile sensations appear to determine considerable changes on perception only after 80 years. As a confirmation of this, no differences were found when young and elderly participants (age 65-82) were tested in their ability to discriminate sugar crystal sizes (Kälviäinen et al., 2003). Significant impairments in sensory performance in subjects over 80 years old were observed also for taste and smell (Arganini & Sinesio, 2015). Overall, these results suggest that, although ageing of subjects determines a progressive deterioration of their oral sensitivity, the perception of heterogeneity in food products is only minimally influenced by the ageing of healthy subjects being less than 80 years old. The effects of ageing on food texture perception are expected to become progressively more significant after 80 years in the average population, even though such a conclusion is strictly dependent on the subject’s health status (e.g. dental status, diseases of the central nervous system, skeletal diseases, and dysphagia). We expect that with a decline in health status, oral sensitivity might change more upon ageing, leading to larger differences in perception in comparison to younger adults. We conclude that, even though ageing leads to an inevitable decrease in muscle strength and coordination that affect the oral manipulation of food, the subject’s health status plays a main role in determining whether such changes affect perception of food or not.

Differences in oral processing behaviour between consumer groups were also found between young Dutch, Caucasian and Chinese, Asian participants in the study of Ketel et al. (2019). The authors found that Chinese, Asian consumers presented averaged lower eating rate (g/s) with smaller bite size (g) and consumption time than Dutch, Caucasian consumers for foods varying in consistency. However, that study did not investigate whether such changes in oral processing determined a variation in perceived texture of food. Therefore, to further verify whether differences in oral processing behaviour can affect texture perception and to identify possible differences in food perception among different consumer groups, the same target groups of the study of Ketel et al. (2019) were selected in the research project presented in **Chapter 7**. The results reported there showed that the detection limit of microparticles embedded in different foods was comparable between young Dutch, Caucasian and Chinese, Asian participants. Therefore, no differences in texture perception between two consumer groups were observed when participants were differing in their nationality and ethnicity, although these groups presented differences in oral processing behaviour. Thus, these results suggest that variation in oral behaviour of consumers do not necessarily result in differences in perceived texture of food. Nevertheless, differences in oral processing behaviour among consumers have been shown to influence dynamic perception of custards (De Wijk et al., 2003), sausages (Devezeaux de Lavergne et al., 2015) and ice-creams (Doyenette et al., 2019). We conclude that the influence of oral processing behaviour on food sensory perception depends on both the product and the specific texture attribute considered. We expect that the effect of different oral strategies is large in products that are affected by the in-mouth conditions (e.g. melting ice or fat in ice-cream; enzymatic digestion of starch in custard), while possible differences in oral behaviour have a relative small impact on perception for textural stimuli that are little/not affected by oral transit (i.e. perception of insoluble cellulose particles in food).

The comparable perception between consumer groups observed in **Chapter 7** agrees with the available literature on cross-cultural studies as the perception of appearance, basic taste and texture of food have been found to be similar between groups of several nationalities (Blancher et al., 2008; Laing et al., 1993; Lundgren et al., 1998; Pagès et al., 2007; Prescott & Bell, 1995; Tu et al., 2010). For instance, Laing et al. (1993) showed that the discrimination ability of tastants in solutions (e.g. sucrose, sodium chloride, citric acid and caffeine) did not differ significantly between Australians and Japanese subjects. Correspondingly, when subjects of ten countries were tested in their ability to differentiate between differences in perceived oral firmness of pectin gels, no differences were found across the results of the different labs (Lundgren et al., 1998). Such similar perception of food stimuli among groups varying in nationality was also observed not only for model foods but also for real products as apples (Andani et al., 2001) and cookies (Pagès et al., 2007). Altogether these results indicate that genetically-based influences originating from different nationalities and ethnicity have little effect on the perception of chemosensory and tactile stimuli. We conclude that for healthy participants, perception of (heterogeneous) food products is very similar, independently from age, nationality and ethnicity.

The comparison between the two consumer groups of **Chapter 7** was further extended considering several oral physiological features (i.e. PROP status, FPD, saliva flow, point oral touch sensitivity) that are known sources of possible variation in perception between consumers. The results highlighted a considerable similarity between Dutch, Caucasian and Chinese, Asian consumers on the characterized physiological aspects, suggesting that the equal perception of heterogeneity in food between groups was probably determined by the overall biological similarities. A relatively large individual variation in phenotype markers (e.g. PROP status, FPD) was observed considering all the participants recruited for the test, independently from the consumer group considered. Such a large variation in physiological traits among individuals has been previously reported by several other studies (Dinnella et al., 2018; Masi et al., 2015; Piochi et al., 2018) and supported by genetic studies comparing different populations. In fact, as variations in phenotype markers emerge from differences in the individual's genetics, a large intra-population variance and a fundamental similarity of all people around the world have been shown when thousands of alleles (i.e. variant form of a gene) were compared across major geographical regions (Romualdi et al., 2002; Rosenberg et al., 2002). Apparently, only a minor part of alleles (7.4%) were found to be specific of one geographical region and, due to the high variation within different population, a clear subdivision of humans into biologically defined groups appeared impossible to achieve. Thus, considering both the large intra-population variance in physiological traits and the fact that separate ethnic groups actually never existed, we conclude that the physiological mechanisms of food perception are not influenced by the geographical/ancestral origins of the subjects. We believe, however, that differences in learned behaviour and culture might determine large variations during the interpretation of the sensorial stimulus.

The results of this Thesis did not find any significant correlation between phenotype markers as PROP status and FPD and the detection of microparticles in food products. Currently, there are a few studies which (dis)confirm our missing relation between perceived texture and such participants' phenotype markers. Nevertheless, the number of studies that no longer support a direct relation between PROP status or FPD and responses to oral stimulation is increasing even for simple taste stimuli. In fact, thanks to the contradicting results of large scale studies, a general re-discussion of consumer phenotyping is currently undergoing in the field and there are many rising doubts about the associations between PROP taste status, FPD, and responses to oral stimulation (Dinnella et al., 2018; Garneau et al., 2014; Webb et al., 2015). Briefly, these recent studies put forward a much more complex relationship between the factors determining oral responsiveness and, in general, they all agree that the understanding of food oral perception cannot rely on a few biological characteristics. Therefore, we suggest that future studies should consider the characterization of more than a single texture stimulation. We advise that further research should involve different methodologies for texture sensitivity determination (e.g. combination of tasks as detectability of microparticles in food or fine surface roughness; two-point discrimination or oral stereognosis test; edge sharpness discrimination; ability to detect changes in viscosity/firmness) and the quantification of other forms of papillae (e.g. filiform papillae via image analysis software).

In summary, we conclude that for the investigation of textural properties of foods, a priori segmentation based on age (young vs elderly) or nationality/ethnicity (Dutch, Caucasian vs Chinese, Asian) in healthy consumers is not recommended since difference in perception between these groups are small. By the same token, a priori segmentation of participants based on single phenotype markers (i.e. PROP status, FPD) is also not advised. On the other hand, considering the high variability in subject texture sensitivity within the same population, we advise that the selection of panellists for quality control should include screening tasks for texture sensitivity (e.g. microparticle detection; detection in changes of viscosity or hardness). This would ensure the recruitment of highly sensitive subjects and would possibly guarantee the detection of small (textural) product variations.

9.2.3 Influence of expectations on perceived heterogeneity

The results presented in this Thesis underline that consumer's expectations are of primary importance to establish both perception and hedonic response of heterogeneous foods. The presence of heterogeneities in food trigger in the mind of the consumers a series of conscious and unconscious reactions, which proved to greatly influence the interpretation of sensorial stimulus. In this subchapter, the specific contribution of these cognitive factors on participant perception as illustrated in **Figure 9.5**, will be discussed.

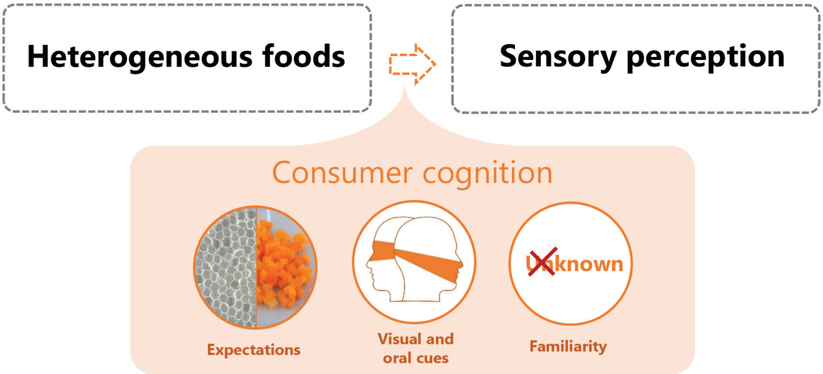

Figure 9.5. Connecting food heterogeneity to consumer perception by subject' cognitive characteristics.

9.2.3.1 Heterogeneous foods: when appearance matters

The expected perception of heterogeneous food products containing particles appears to be affected by several visual factors that can be categorized into two main categories: (1) Visual recognition of particles' presence and appearance; (2) Visual recognition of size and concentration of particles.

Firstly, the visual recognition of particles into a product can significantly change the perception of food and this effect was observed to be consistent with the different model and real foods tested in **Chapters 3**, **4**, **5** and **6**. Overall, the visual recognition of particles in the products leads to an increase in the expected perception of several particle-related textural (e.g. lumpiness, grittiness, mouthfeel heterogeneity) and flavour attributes (e.g. carrot, bell pepper and peach flavour) (**Chapter 4**, **5** and **6**). Such modulation of consumer expectancy by particle addition was also observed by Marcano et al., (2015). The authors added different types of visible particles (e.g. wheat bran, ground coconut) to cheese pies and reported an increase in perceived product complexity and selection of more attributes (e.g. lumpy, hard, grainy). The visual recognition of particles is also affected by the appearance of particles observed and the expectations that such visual cues provoke in the mind of the consumer. In fact, although consumer's expectations were not directly investigated in **Chapter 3**, we speculated that expectations generated by the visual recognition of transparent model gel particles used to introduce mechanical contrast highly determined the consumer response to the product. Specifically, we concluded that the presence of such visible particles in model foods was perceived as a product defect of the food by the participants, which ultimately influenced negatively the participants' hedonic response. Considering that the model gel particles used in **Chapter 3** presented comparable mechanical properties of model gel particles added to soups in **Chapter 4** and differed mainly in their appearance (i.e. carrot-like), this suggests that both visual appearance of particles and the match between the appearance and the consumer's expectations are important factors for consumers that can be considered to establish their product perception.

Secondly, for foods containing visible particles that distinguished themselves from the surrounding matrix thanks to a different colour, variations in their size and concentration led to changes in the expected profile of the heterogeneous foods tested in this Thesis (**Chapters 4**, **5** and **6**). For instance, when the size of model peach cubes was augmented from small/medium (3x3x3; 7x7x7 mm) to large (10x10x10 mm), the expected chewiness and hardness of yoghurt increased significantly (**Chapter 6**). Similarly, an equal increase in the size of added carrots to a chicken soup determined significantly higher expected scores of particle size, visual thickness, chewiness, crunchiness, and hardness (**Chapter 4**). Such effects were not limited to viscous, spoonable products, as the results of **Chapter 5** showed that increasing size of bell pepper pieces embedded in processed cheese from small (2x2x2 mm) to large (6x6x6 mm) caused significantly higher ratings of expected chewiness, crunchiness, hardness, lumpiness, particle size, mouthfeel heterogeneity, and bell pepper flavour. These results indicate that, independently from the matrix type and its consistency, the expected food perceptions of the participants can be manipulated by varying the size of the visible particles added to it.

Chapters 4 and **6** reported the effect of variation in particle concentration on the expected perception of processed cheese and yoghurt. An increase in concentration from 7.5% to 30% in cheeses containing bell pepper pieces induced an increase in many heterogeneity-related attributes (e.g. chewiness, crumbliness, crunchiness, hardness, lumpiness etc.), while it decreased homogeneity-related sensations (e.g. creaminess, smoothness, melting). A smaller variation in particle concentration in yoghurt (from 10 to 20%) resulted in fewer differences in the expected profile (**Chapter 6**), determining mainly higher intensities of peach flavour and sweetness, and lower sourness intensity. Therefore, the outcomes suggest that expected product perception of the product can be altered not only by variation in particle size, but also in their concentration.

9.2.3.2. Stimulus recognition and the effect of consumer's familiarity on the perception of heterogeneous foods

In this Thesis, the effect of product and stimulus familiarity was investigated to understand the relation between textural properties of heterogeneous foods, their sensory perception and liking. As suggested by Prescott (1998), in fact, the level of familiarity that the consumer possesses for a product offers a cognitive context for interpretation of the signals delivered by the food. The consumption of food provides exposure to different sensorial stimuli that, once stored in the memory of the consumers, offer a base for the generation of expectations which are likely to influence the consumer response (Zajonc 1968; Berlyne 1970; Methven et al. 2012). The findings of **Chapter 3** demonstrated that the consumer response towards heterogeneous foods was negatively impacted by the presence of unfamiliar particles in the tested foods. To prevent the negative effects on product appreciation and distinguish possible consequences of particle familiarity on consumer perception, **Chapters 4**, **5** and **6** used model particles that resembled real vegetable or fruit pieces in their appearance, texture, and flavour. Overall small differences were observed on textural perception between products with familiar and unfamiliar particles. Therefore, the combined results of this Thesis show that the degree of participant' familiarity with the particles present in the product has little or no effect on the perception of textural stimuli. The limited effect of consumer familiarity toward food stimuli perception was further confirmed by the results described in **Chapter 7** in which no relation was found between the participants' familiarity and the product characteristics and their ability to detect the presence of microparticles in either a spoonable or chewable dairy food. Therefore, the combined results of this Thesis show that the degree of participant' familiarity with the particles present in the product has little or no effect on the sensory recognition of textural stimuli.

9.2.4 Food heterogeneity to enhance liking: an integrated approach

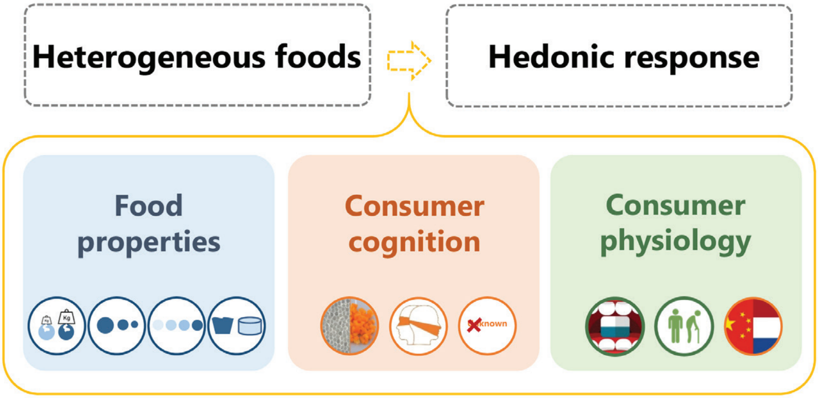

Figure 9.6. Connecting food heterogeneity to consumer hedonic response using an integrated approach.

The results of this Thesis demonstrated that the response towards heterogeneous food products of the consumer depends on both food properties and consumer characteristics, and such interdependency is even more relevant to explain their appreciation. As illustrated in **Figure 9.6**, an integrated approach that considers all the variables previously discussed is required to understand liking of such products presenting a heterogeneous texture.

9

Throughout the chapters of this Thesis, several textural and flavour properties of heterogeneous products were related to the participants' product liking. In **Chapters**

3, **4**, **5** and **6**, the addition of hard (fracture stress >100 kPa) particles to either solid or viscous food products always decreased their appreciation. For instance, participants preferred soft carrot or soft peach gel particles over hard ones in soups and yoghurts respectively (**Chapters 4** and **6**). Similarly, soft bell pepper pieces providing no mechanical contrast in processed cheeses were the most preferred by participants (**Chapter 5**). These results suggest that large variations in mechanical contrast between the components of a single bite can possibly diminish the hedonic scores of the product. When the outcomes of **Chapter 8** are examined, however, the addition of hard granola pieces to homogeneous quark determined a significant increase in product liking. This apparent contradiction reveals a much more complex picture for the understanding of consumers' hedonic response of heterogeneous foods. Hardness of the particles, in fact, does not explain consumers' appreciation of the product per se, but it should be considered together with other product texture properties and consumer expectations. In terms of texture properties, it is known that for macroscopically homogeneous food products, perceived hardness of the product has a negative effect on liking for a variety of products such as cereal snack bars, gluten-free bars and biscuits (Bower & Whitten, 2000; Morais et al., 2015). For instance, the work of Tarancón et al. (2015) demonstrated that for fat-reformulated biscuits, "easy to chew" was a driver of liking for consumers, whereas "hard to chew" was a driver of disliking. Considering this, we speculate that the presence of hard gel particles used in **Chapters 3**, **4**, **5** and **6**, presented an increased difficulty of product manipulation required to ensure safe swallowing of the product for the participants. Therefore, the hard gel pieces were probably related to unwanted textures (possible cause of gagging or choking), which ultimately determined a decrease in liking of the product. On the contrary, when product physical properties are only considered, the high fracturability and ability to absorb water during mastication of granola pieces did not determine the same negative arousals, but provided variations in texture that were appreciated by the participants. We conclude that by combining different food elements (e.g. layers or particles) that facilitate the oral processing of the product by either reducing the product overall hardness during mastication or assisting in the formation of a ready-to-swallow bolus (e.g. combining soft cheese on hard crunchy bread) can possibly increase liking of the product.

In terms of consumer expectations, the outcomes of **Chapter 3** strongly demonstrated that the presence of unfamiliar gel particles in foods determined a decrease in product liking. In **Chapter 4**, the addition of chicken soup-based gel particles described as "chicken pieces" to soup established a large discrepancy between expected and actual perceived texture sensations that negatively impacted the overall liking of the product. Such particles presented mechanical properties that were comparable to those of carrot gel particles for which liking did not decrease, suggesting that matching of consumer's expectation in terms of flavour and texture largely determine the palatability of heterogeneous foods. The fact that consumer's expectations control palatability of the food product was further confirmed in **Chapter 8**, in which it was suggested that the hedonic masking effect of microparticles in quark by addition of granola pieces was likely linked to the recognition of the origins of gritty sensations by the consumers. Specifically, in that chapter, it was concluded that the interpretation of the stimulus triggered by the presence of particles (i.e. cellulose microparticles or granola pieces) was largely influenced by whether the consumers expected to perceive such a textural sensation during the consumption of the product. Therefore, these results indicate that the expectations the consumer has towards a product will determine whether the perception of textural heterogeneity is considered acceptable or linked to a product defect. We conclude that palatability of heterogeneous products could be possibly steered by influencing expectations of the consumers thanks to the provision of information (e.g. visual recognition, packaging information).

Altogether, these results confirm that food texture is a sensory property that is learned by consumers. As the learning process can be influenced by a variety of factors that are only marginally affected by the product properties, finding a general and straightforward guideline for the development of heterogeneous foods remains very challenging. Nevertheless, the results of this Thesis suggest that the consumer will appreciate combinations of textures that are more familiar (e.g. crunchy cereal in yoghurt; soft vegetable pieces in soup) and will dislike addition of components providing texture that might be source of potential harm (e.g. hard particles that are difficult to chew) or unexpected sensations in a product that might be an indication of a product defect (e.g. gritty sensation in a smooth and creamy food). As such, these conclusions do not preclude the opportunity of optimization of products by addition of particles. In fact, this Thesis demonstrated that the presence of particles in foods was generally appreciated by the consumers not only in products that are known to possibly contain particles (i.e. soups and yoghurts in **Chapters 4** and **6**), but also in foods that are primarily known for their homogeneous texture (processed cheeses in **Chapter 5**).

Overall, the link between textural heterogeneity and product liking tested in this Thesis shares many concepts with the idea of sensory complexity (Palczak et al., 2019). Sensory complexity in foods has been defined in a variety of ways, but it is generally directly related to the number of sensations observed visually or perceived in the mouth during product consumption (Larsen et al., 2016; Mielby et al., 2013; Pierguidi et al., 2019). The visual, physical or perceived sensorial complexity is suggested to increase palatability of food product (Giacalone et al., 2014; Meillon et al., 2010; Pierguidi et al., 2019; Stolzenbach et al., 2016). According to Berlyne's Theory, an increased complexity of a stimulus determine higher hedonic responses until the subject reaches his/her optimal level (Berlyne, 1971). Nevertheless, the validity of this theory has not always been confirmed as other studies have found no relation between complexity of the stimulus and hedonic response (Jellinek & Köster, 1983; Porcherot & Issanchou, 1998). The recent study of Pierguidi et al. (2019) proposed that the perceived complexity of food products is a multi-dimensional construct that is affected not only by the complexity of the stimulus but also by the familiarity of the consumer with the product category. Therefore, as previously suggested by Hong et al. (2014) and Pagès et al. (2007), also in this instance the relation between sensorial stimulation and hedonic response appears to be influenced by the familiarity and related expectations that the consumer possesses about the product. We conclude that the addition of heterogeneity remains a potential strategy to increase visual, physical/structural, and oral sensorial complexity that might have arousal-inducing properties.

9.2.5 Methodological considerations

The physical properties of food products used in this Thesis were characterized using instrumental techniques in order to find a possible correlation with the sensory data. The majority of assessments were done using uniaxial compression tests in which the homogeneous products (i.e. particles or solid matrix) were compressed to determine their fracture behaviour. This approach, however, was centred on the characterization of the individual properties on the components in a heterogeneous product. From an instrumental point of view, one of the biggest challenges that was faced within this research project was the characterization of the mechanical properties of the composite material. Very little research is present on the influence of multiple components in the fracture behaviour of a food product and related texture perception. In **Chapter 2**, a wedge test was performed to assess the composite fracture behaviour of bi-layer gels as it was expected that the fracture properties of the top layer could influence the fracture properties of the bottom layer. The results showed that the fracture behaviour of heterogeneous bi-layer gels was affected by both fracture properties of the layers and their position (top/bottom) and was positively related with the perception of texture contrast in such a system. This first indication - that the measured composite fracture behaviour could be used to predict the perception of heterogeneous foods - was also confirmed in **Chapter 3**. In fact, the results of the puncture tests highlighted positive correlations between AUC values and sensory parameter as hardness and chewiness of a solid matrix containing relatively large particles. For these methods, however, we found severe limitations when the size of added particles was small (i.e. < 1mm) and when the particles were added into a liquid, viscous matrix since no puncture/penetration test can be applied for liquids containing particles. Thus, further investigations and methods development are required to characterize the composite mechanical behaviour of such heterogeneous products. Specifically, for the dynamic mechanical product characterization, we recommend the use of either more empirical methods simulating the oral conditions (i.e. in-vitro mouth) of heterogeneous, liquid products containing particles (i.e. > 1mm) or tribological tests for products containing small particle (i.e. < 1mm). Additionally, different technologies (e.g. ultrasounds or tomography) could be coupled to such instrumental methods in order to obtain a visual representation of the heterogeneous structure during deformation.

Within this Thesis, the in-vivo texture evaluation was carried out through consumer tests. The use of consumer tests is relatively novel in the field of sensory science as the majority of prior work was done using descriptive analysis techniques as QDA®. In these classical approaches, a pool of assessors is trained with the ultimate goal of obtaining reproducible results which are comparable across studies and over time (Varela & Ares, 2014). Such classic methods allowed having a precise and defined quantification of sensorial characteristics, although they did not provide information regarding the future response in terms of liking by the final consumer. The solution adopted was to combine sensorial data obtained from a trained panel with the data separately obtained from a hedonic evaluation by consumers. The use of a trained panel is, however, costly and demands a high amount of time and for these reasons, new methods based on untrained or semi-trained consumers have been proposed recently for both research-related and product development purposes. These methods allow to ask the consumer directly both hedonic evaluation and perceived intensity of sensory attributes, making the data collection process faster and the comparison between sensory and hedonic perception more direct.

This Thesis based its research on novel consumer methodologies as RATA (Rate-All-That-Applies), TDS (Temporal Dominance of Sensations), Constant Stimuli, Ranking and Ideal Profile methods (IPM). The use of untrained consumers increased variability in the data as no clear consensus can be reached a priory of the test on attribute definition and scored intensity of perceived stimuli. To prevent such negative drawbacks, several solutions have been applied in this thesis. Firstly, for all the tests reported, pilot tests were performed to verify the applicability of the selected attribute and the degree of difficulty of their definitions for the consumer. Secondly, a higher number of participants was required for the studies in order to stabilize the average value scores caused by a possible diverse use of the rating scale (Moskowitz, 1997). Thirdly, the definition of attributes was always provided to the participants in order to limit misinterpretation and ensure a more uniform understanding of the task. The use of these consumers tests was required not only for the investigation of consumer textural sensitivity (**Chapters 2** and **7**) in a specific population, but also gave the opportunity to have an evaluation that was closer to the one that a consumer might have (i.e. not too analytical).

9.3 Practical implications of the current findings

From the results of this Thesis and the currently available literature, several concrete implications can be formulated for the development and optimization of heterogeneous food products.

Firstly, to design heterogeneous foods with texture contrast, differences in hardness (i.e. fracture stress) between the components should be mainly considered, since hardness/fracture stress seems to drive perception of texture contrast. In liquid and semi-solid foods with dispersed particles, the size of particles mainly affects the type of sensory descriptors perceived. The presence of small spherical particles with averaged diameter <0.8 mm or cubes with a side length of 2 mm is associated with the perception of undesired gritty sensations. Increasing the size of spherical particles (>4 mm) or the diameter of cubed particles (>6 mm) increases the perception of sensory attributes as chewiness, lumpiness, and mouthfeel heterogeneity. The intensity of these descriptors can be determined by the hardness of the particles; the harder the particles, the higher the perceived intensities. These findings can be directly applied to design novel heterogeneous food products with specific sensory properties or to manipulate the consumer oral perception of already existing heterogeneous foods.

Secondly, when designing heterogeneous food products, it should be considered that the addition of particles to a product provides visual cues that can change the expectations that consumers have towards a certain product, generating potentially positive arousal; by tuning the size and concentration of added particles it is possible to increase expected liking and, therefore, possibly affect consumers' attractiveness to the product. For instance, for the development of novel, heterogeneous processed cheeses, small-medium sized (2-4 mm) bell pepper particles could be used to increase willingness to try the new product. Actual product liking is determined by particle texture and matching of consumers' expectation. Consumers tend to prefer congruent and familiar particles (e.g. soft vegetable pieces in soups or crunchy granola pieces in yoghurts) as large and discrepant variations from the expected texture profile result in consumers' rejection due to the association of the perceived stimulus with a possible product defect. Therefore, it is more important that the properties of the novel food match the expectations of the consumer, rather than providing a new, unfamiliar perception.

Thirdly, ageing of healthy consumers appears to affect marginally texture perception of heterogeneous products. Therefore, foods should not be changed with respect to texture for healthy elderly (<80 years), while product textural modifications might be required for consumers presenting impaired dental status or decreased eating capabilities (Laguna et al., 2016a; 2016b). Similarly, perception of food seems not to be influenced by participants' nationality and ethnicity. A priori segmentation based on age (young vs elderly) or nationality/ethnicity (Dutch vs Chinese) in healthy consumers is therefore not recommended for characterization of perceived product profile since differences are small. Conversely, a priori segmentation of consumer based on the same criteria (i.e. age, ethnicity) is suggested for the hedonic evaluation of food products, as different degrees of familiarity with the product across such consumer groups can determine large differences in perceived liking (Hong et al., 2014; Kremer et al., 2014; Pagès et al., 2007).

Fourthly, the addition of macroparticles to a homogeneous food can be used to prolong oral processing behaviour of consumer and decrease eating rate. In fact, considering that several studies have proven that oral exposure time influences eating rate which strongly impacts food intake (Kokkinos et al., 2010; Viskaal-van Dongen et al., 2011; Zijlstra et al., 2009; McCrickerd et al., 2017; Robinson et al., 2014), these results suggest that particle addition could be used to decrease food intake and induce an earlier satiation. By modifying the size, concentration, number and mechanical properties of particles added to foods, oral processing behaviour can be influenced and this can be used to moderate food intake within a meal. Recent studies have shown a positive relation between physical textural complexity and satiation, which appears to be independent of oral processing time (Larsen et al., 2016; Marcano et al., 2015; Tang et al., 2016; Tarrega et al., 2016). Since the presence of multiple components in a food product is expected to postpone sensory-specific satiety (SSS) (González et al., 2018; Guinard & Brun, 1998; Weijzen et al., 2008; Wilkinson & Brunstrom, 2016) by combining textural and flavour complexity (Kremer et al., 2014), food intake and satiation of consumers could be controlled, while ensuring an equal or enhanced palatability of the product.

Finally, product rejection caused by undesired texture perceptions (e.g. rough/gritty sensations in high protein foods) can be prevented by the addition of well-liked macroparticles (i.e. granola pieces) to a homogeneous product thanks to a hedonic compensation and re-direction of consumer attention. Such strategies associated with the combination of different macro components might also enhance liking of other products that have textural defects (i.e. dry mouthfeel in beverages) or do not fully satisfy the consumer textural demands (e.g. meat replacers).

9.4 Directions for future studies

The results described in this Thesis contributed to shine more light on the relation between food heterogeneity and consumer response using a multidisciplinary approach. Physical, cognitive and physiological variables have been taken into consideration to unravel the link between food heterogeneity and consumer perception. However, there are several open questions that still remain to be answered.

Overall, the findings of this Thesis demonstrated that the expectations that consumers possess towards a certain food product can be manipulated in a desirable way using different strategies (e.g. visual cues). It is therefore worth investigating to what extent the generation of (textural) expectations can be influenced by providing the consumer with different visual or descriptive information. Similarly, the strategies proposed in terms of compensation effects of textural properties by either hedonic compensation or redirection of consumer attention could be validated and extended to other food types and consistencies. Such additional studies are encouraged to consider multiple exposures to the product and cues to understand whether the positive effects of the manipulation on the perception are maintained over time.

Far from being complete is also our understanding of the underlying physiological mechanism of perceived texture of either homogeneous or heterogeneous food products. Additional research should be conducted to understand and predict what characteristics of the oral somatosensory system are responsible for the perceptual recognition of textural stimulus and what features might explain variability in perception among individuals. Especially to understand the perception of microscopic heterogeneities, such a physiological characterization could be coupled with instrumental characterization (e.g. tribological properties) of the processed bolus as this would allow a direct quantification of the physical food properties during consumption.

Finally, although little/no differences in perception were observed among healthy individuals, different results are expected for consumers presenting decreased eating capabilities (e.g. dysphagia patients, elderly >80 years). Further investigations are required to assess whether the combination of textures within a single bite could be used as a possible strategy to facilitate oral manipulation of foods while ensuring product palatability for such sensitive target groups.

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SUMMARY

Summary

In many modern societies, the importance of food enjoyment has overruled that of the basic nutritional need. Therefore, understanding the factors influencing the perception and appreciation of food has become of utmost importance to design foods that satisfy the consumer' requests. Such requests can be fulfilled through modification of food properties which depend on several consumer characteristics. Consumers, in fact, can not only differ in their physiological characteristics, but also in their familiarity and expectations with the product. Such a complex scenario is further magnified by the heterogeneous nature of many foods. As a matter of fact, most of the foods consumed daily are characterized by the presence of multiple components, which can differ in their structure, flavour, and appearance. The combination of different food textures in such heterogeneous products has the potential to enhance palatability. Nevertheless, an understanding of how food properties in heterogeneous products could be manipulated to influence perception and liking for different consumers groups is still lacking evidence. This thesis aimed to better understand the effect of the combination of different food textures on expected and perceived sensory properties and liking in different consumer groups. The effect of physical and physicochemical properties of complex, heterogeneous food matrices on sensory perception and liking were investigated in relation to consumer physiological and psychological characteristics.

After providing a brief introduction to the fundamental aspects of the relationship between product characteristics and consumer perception (**Chapter 1**), the physical properties of heterogeneous products were first investigated in this Thesis. Specifically, **Chapter 2** explored the effect of mechanical and physicochemical properties of semi-solid model foods on the detection and temporal perception of perceived heterogeneity. The role of fracture stress (σ_F), fracture strain, syneresis, and melting behaviour on perceived texture contrast was unravelled with the use of bi-layer gel-based model foods. It was found that the participants' oral ability to detect differences in textures between components varied between brittle and elastic gels and between soft (low σ_F) and hard (high σ_F) gels. Heterogeneity was perceived when

the difference in fracture stress between layers was small (σ_F = ≥ 5 kPa) in soft and brittle agar gels. However, a larger difference in fracture stress between the layers (σ_F = ≥ 12 kPa) was required to determine the perception of texture contrast in soft and elastic gels and hard gel. The results also showed that the temporal perception differed as a function of mechanical properties of the gel, as heterogeneity intensity was perceived for a longer period of time for gelatine gels. The results of Chapter 2 demonstrated that the detectability of mechanical contrast as perceived texture contrast (heterogeneity) is mainly determined by the mechanical properties of gels.

Considering that an effective strategy to combine textures in different food products consists on the addition of particles, **Chapter 3** investigated the combined effect of size and fracture stress of added particles in food on sensory perception and hedonic response. K-carrageenan gel particles varying in their size (0.8, 2.4, 4.2 mm) and fracture stress (σ_F: 25, 100, 250 kPa) were added to liquid model soups and semi-solid model gels. Results indicated that the size of particle added to both matrices mainly affected the type of descriptors selected (e.g. lumpy, gritty), while the hardness of the particles determined the intensity of the selected descriptors. Upon addition of the model particles, however, liking of the product decreased probably due to the fact that the added heterogeneities were perceived as flavourless and artificial, even though they provided texture contrast. Therefore, it was concluded that the mere mechanical contrast between components of a heterogeneous is not sufficient to enhance food appreciation. It was hypothesised that both consumer's expectations engendered by visual and oral sensorial cues and flavour of the added particles are of great relevance for the perception and liking of heterogeneous food.

Such hypotheses were examined in **Chapter 4**, in which real and model carrot particles were added to chicken soups. Real carrot particles varied in fracture stress (σ_F: 40, 100, 300 kPa) and size (cubes with a side length of 3, 7, 10 mm), while model carrot particles were made from agar gels and differed in carrot flavour concentration (0, 33, 66, 100%) and fracture stress (σ_F: 40, 100 kPa). Both expected (i.e. visual evaluation) and perceived liking and sensory properties of the heterogeneous soups were assessed. The results showed that expected sensory properties were affected by the size of particles: the larger the particles, the higher were the expected intensities for hardness, chewiness, and crunchiness. Size and fracture stress of carrot particles both significantly influenced perceived sensory properties of soups. The congruent and familiar appearance of the model carrots did not result in a decrease in liking, nor did an increase in their flavour concentration. Relative small differences between expected and perceived sensory profile of model carrots resulted in decreased liking. This suggested that the expectation generated by the appearance and texture of the added particles had a larger role in determining the liking of soup than flavour concentration in particles. It was concluded that addition of congruent and familiar particles matching consumer' expectations has the potential to improve the sensory product profile of common products such as soups.

To precisely decouple how visual and oral cues influence sensory perception and liking of heterogeneous foods, the following experiment - summarized in **Chapter 5** - was performed. Twelve heterogeneous processed cheeses were prepared by adding bell pepper pieces to homogeneous processed cheese matrices. While homogeneous processed cheeses are well-known products, consumers are not familiar with processed cheeses with added vegetable pieces. Bell pepper pieces differed in size, fracture stress, and concentration. The novel heterogeneous cheeses were evaluated perceptually in three conditions. In the first condition, participants tasted cheeses and rated sensory properties and liking while being blindfolded (only oral cues). In the second condition, participants evaluated expected sensory properties and liking of cheeses presented as pictures together with product descriptions (only visual cues). In the third condition, consumers tasted and evaluated cheeses while visual cues and product descriptions were provided (both visual and oral cues). It was shown that bell pepper size or concentration influenced expected sensory properties in the exteroceptive condition the most, while fracture stress and concentration of bell pepper pieces mostly influenced changes in sensory perception. Although visual cues influenced texture and flavour perception of heterogeneous cheeses, liking was not influenced by the visual cues during the combined condition. On the contrary, consumer's hedonic responses were mainly influenced by the texture of the added particles. It was concluded that the size of added pieces mainly determined the expected liking and possibly affect consumers' attractiveness to the novel product, although actual product liking was determined by particle texture and matching of consumers' expectation for the specific product type.

Throughout Chapter 3-5, the addition of particles in foods was expected to influence oral processing behaviour of the participants, although limited information for such heterogeneous products was available. **Chapter 6** aimed to quantify the mastication changes related to the addition of particles in food. A spoonable yoghurt with added peach gel particles varying in size, fracture stress and concentration was taken as an example. Considering that both expectation and perception for such a product were estimated to be influenced by the age of the consumers evaluating the products, consumer groups differing in age were used in this experiment (i.e. healthy young adults vs. healthy elderly). It was shown that the addition of particle varying in hardness and concentration prolonged significantly the participants' oral consumption time, whereas particle size did not affect the tested oral processing parameters. Irrespective of particles characteristics, the presence of peach gel particles in yoghurt resulted in a decrease of eating rate up to 60% in both participant groups. From the sensory comparison of the two consumer groups (i.e. young vs. elderly), it was concluded that age of healthy subjects marginally affect texture perception of semi-solid heterogeneous food, whereas a larger effect was observed on flavour perception. The two consumer groups also differed in their ideal product properties as elderly consumers preferred yoghurts containing soft and medium hard peach gel particles, while young adult consumers did not have a defined ideal profile for yoghurt.

Similarities in perceived texture were also observed between consumers with different nationalities and ethnicities in **Chapter 7**. Such a chapter investigated how product familiarity and physiological characteristics of consumers affect detectability of microparticles (50-780 μm) comparing Dutch, Caucasian and Chinese, Asian healthy women. Participants were characterized for product familiarity, salivary flow rates, propylthiouracil (PROP) status, point pressure thresholds measured with Von Frey filaments, and fungiform papillae density. It was found that detectability of microparticles did not significantly differ between the two ethnicities, although differed significantly between the two products tested (i.e. viscous quark and semi-solid processed cheese). No relationship between product familiarity and particle size detection thresholds in either product could be found. Among all the tested physiological characteristics, only a positive and weak correlation was found between stimulated saliva flow and particle size detection threshold in semi-solid processed cheese ($r = 0.21$, $p = 0.041$). It was suggested that active salivation might enhance sensitivity for microparticle detection in semi-solid foods. Results from chapter 7 suggested that modification of product characteristics is probably the key strategy that should be considered to prevent gritty sensations in foods.

Based on the conclusions of Chapter 7, different product modifications were tested with the goal of perceptually compensate for negative texture perceptions in **Chapter 8**. Specifically, the addition of macroparticles or fat to common food was investigated as strategies to prevent perception of cellulose beads (1.5% w/w; average size: 263 μm) in quark. Two macroparticle types were used: granola pieces and peach gel pieces. Fat concentration of quark was also varied (0, 4.4, 8.8% w/w). The results indicated that the presence of macroparticles or fat did not significantly decrease grittiness intensity caused by microparticles. Despite the fact that grittiness was still perceived, the addition of granola pieces to quark containing microparticles increased liking. From the Temporal Dominance of Sensations (TDS) outcomes, it was shown that such an addition drew the attention of consumers away from negative, dominant gritty sensations and directed it towards positive, dominant crunchy sensations. On the other hand, although the consumer attention was shifted away from gritty sensations also by the addition of peach gel pieces, their presence did not avoid a decline in liking likely because participants did not expect the presence of small hard particles when peach gel pieces were present. Liking did not decrease upon presence of microparticles when a medium amount of fat was added (4.4%), which was probably due to an effective hedonic compensation caused by more positive sensations (i.e. sweetness). The results of Chapter 8 demonstrated that incorporation of well-liked macroparticles or fat can be used as strategies to steer consumers' attention towards positive sensations leading to an increase of liking while negative textural sensations caused by structural heterogeneities are still perceived.

Chapter 9 summarizes the findings presented in the different chapters and provides an integrated discussion on the relationship between characteristics of heterogeneous foods and the consumer response. From the comparison of all the chapters, it was concluded that to design heterogeneous foods with texture contrast, differences in hardness (i.e. fracture stress) between the components should be mainly considered. For foods with added particles, the size of particles mainly affects the type of sensory descriptors perceived during consumption, while the intensity is determined by the hardness of the added particles. The presence of particles product provides visual cues that can change the expectations that consumers have towards a certain product, generating potentially positive arousal. Confirmation or disconfirmation of visual and textural expectations together with the level of familiarity the consumer has towards a product establish whether the perception of textural heterogeneity is considered acceptable or linked to a product defect. A comparable perception of food heterogeneity in healthy consumers was observed in the tested groups varying in age (young vs elderly) or nationality/ethnicity (Dutch, Caucasian vs Chinese, Asian). Finally, it was concluded that addition of macroparticles to a homogeneous food can be used as a strategy to steer oral processing behaviour and dynamic perception, with the advantage of either reducing eating rate or prevent a decrease in palatability when other textural defects are present.

Acknowledgements

A group of 80 subjects (n=80) contributed to different degrees in determining the content of this thesis. The group was composed of supervisors, students, colleagues and friends (age range of 0-80 years) belonging to 20 different nationalities. A few of the subjects have been of particular support from both a scientific and personal perspective. Others spent their precious time to evaluate the content of this thesis. A couple provided the author with a new incredible family. The majority of the subjects were and will remain naïve about the experimental procedures, content and purpose of this thesis. Nevertheless, they all helped the author in having a great four-year experience. They accomplished tasks of utmost importance, such as inspiring, mentoring, leading, teasing, tasting, chatting, training and, of course, playing ping-pong. The author prefers to thank them all individually, and leave their names to remain part of this thesis in Figure below.

N	L	X	E	W	C	I	G	U	I	D	O	A	M	E	L	I	K	A	B	D	B	R	E	M	T	Q	V	X	J
V	W	I	I	K	E	E	S	E	R	B	V	A	G	S	S	O	G	P	S	A	V	J	X	U	K	G	X	A	R
B	J	P	V	A	H	V	X	H	L	I	C	U	E	D	Z	V	B	Z	N	R	E	E	I	Z	I	K	N	C	E
L	E	U	A	I	N	M	E	N	A	I	A	K	H	T	Y	M	N	N	R	I	R	S	P	X	Y	O	T	A	P
T	I	L	L	U	A	O	D	R	I	P	S	E	I	X	D	A	N	I	O	A	I	S	A	E	L	K	E	M	C
T	I	A	I	I	L	D	I	K	O	N	A	A	X	I	Y	Y	L	R	R	N	K	E	U	J	F	Y	G	I	M
N	B	J	O	N	E	I	A	P	Y	N	N	S	A	Q	G	W	I	K	Y	N	A	O	L	H	A	R	O	L	D
R	C	E	S	G	D	C	N	N	R	R	I	A	J	A	I	K	B	D	B	E	L	R	X	V	B	G	V	L	R
O	U	V	T	D	Q	A	L	E	A	U	U	C	G	V	U	N	H	R	P	E	E	P	E	J	A	T	Z	A	O
S	G	L	P	I	U	M	V	A	A	S	L	A	A	B	S	E	A	X	M	E	I	R	L	F	O	L	H	Q	L
A	P	E	I	S	N	O	L	J	U	W	E	G	P	K	E	K	R	O	N	I	I	A	N	F	D	H	Y	H	I
P	W	A	R	P	Z	A	J	F	H	D	C	V	A	B	P	G	R	P	R	C	R	Q	N	K	W	A	N	X	E
G	D	S	S	A	F	X	V	P	E	J	I	W	E	X	P	J	Y	E	E	Z	B	A	I	J	F	Z	U	N	N
N	Z	Z	T	C	R	T	M	A	N	H	Y	N	U	L	E	Q	A	D	S	C	M	A	N	D	I	M	O	S	G
E	I	S	J	J	A	D	A	R	N	V	G	M	E	E	I	B	O	C	A	A	T	B	P	D	R	E	M	K	O
E	X	E	I	I	R	L	R	I	Y	V	E	S	B	L	Q	N	I	P	K	V	M	W	O	V	A	Y	C	Q	Z
I	N	V	E	N	V	E	I	S	M	T	Q	W	E	N	J	I	E	E	I	X	H	P	E	J	C	F	O	F	L
V	N	F	A	F	E	M	A	A	P	M	X	K	E	H	Z	V	B	V	N	I	L	A	A	L	A	Y	L	A	B
A	H	E	E	E	V	A	N	Y	M	M	J	I	G	X	C	H	I	A	R	A	R	E	M	R	A	I	S	A	O
D	X	T	S	N	A	R	N	V	E	F	V	A	L	E	X	A	N	D	E	R	O	E	N	B	O	B	O	B	S
R	I	O	L	G	P	C	A	B	L	J	V	L	T	O	K	J	O	E	D	B	K	M	N	K	B	E	R	L	K
O	L	U	K	A	V	E	Q	G	V	I	O	A	I	S	N	Z	H	I	H	O	N	G	I	E	A	N	E	E	U
H	K	Y	R	O	E	L	B	R	I	U	S	Q	N	E	U	G	Q	E	W	Z	H	L	C	H	I	O	M	O	N
I	U	M	C	J	X	S	R	D	N	Z	J	T	F	I	H	R	T	U	A	O	T	K	Q	A	L	I	C	N	U
T	K	L	A	U	G	M	Y	C	G	K	R	G	E	M	O	U	A	E	M	E	Y	R	E	Q	I	T	O	A	W
Q	A	E	R	Z	K	B	O	P	C	H	R	I	S	F	O	F	H	J	E	V	M	E	D	H	I	D	H	R	G
T	C	L	L	S	L	B	N	D	S	K	O	S	P	W	A	N	K	M	L	I	D	W	D	U	B	T	I	D	C
G	E	S	O	Q	R	Q	Y	F	V	A	N	I	K	A	N	N	I	X	I	W	K	G	K	J	O	R	I	S	M
E	V	E	L	I	N	E	H	B	W	I	J	C	V	L	O	J	I	C	E	Y	T	G	D	A	N	I	M	F	T
H	N	Q	G	E	Z	W	H	Y	F	E	D	E	O	V	P	U	Z	A	A	S	M	J	M	A	R	K	U	S	F

About the author

Marco Santagiuliana was born on the 11th of June 1991 in the North-east of Italy. With the aspiration of becoming a professional cook, he started his studies at the School for Culinary Arts & Hotel Management in Recoaro Terme in 2005.

After receiving his diploma as 'chef enogastronomo' in 2010, he continued his education with the BSc program in Science and Culture of Gastronomy and Catering at Padua University, Italy. As a part of his training, he carried out an internship at the Centre of Rural Culture and Civilization - The international library "La Vigna" in Vicenza, Italy. Parallel to his studies, he worked as a cook and had the opportunity to join several prestigious restaurants.

In 2013, he completed his BSc studies *cum laude* and started the MSc program Food Science and Technology at Padua University. During his master, he followed an Erasmus semester and performed part of his thesis at Wageningen University, The Netherlands. He obtained his degree of Master *cum laude* in 2015. At the beginning of 2016, he was appointed as a PhD candidate at TIFN and within the group of Physics and Physical Chemistry of Food at Wageningen University. His work, whose results are presented in this thesis, was part of the public-private project "Smooth bite for all".

He can be contacted by email: **marco.santagiuliana@gmail.com**.

List of publications

Peer reviewed publications

Santagiuliana, M., Piqueras-Fiszman, B., van der Linden, E., Stieger, M., & Scholten, E. (2018). Mechanical properties affect detectability of perceived texture contrast in heterogeneous food gels. *Food Hydrocolloids*, 80, 254-263.

Santagiuliana, M., Christaki, M., Piqueras-Fiszman, B., Scholten, E., & Stieger, M. (2018). Effect of mechanical contrast on sensory perception of heterogeneous liquid and semi-solid foods. *Food Hydrocolloids*, 83, 202–212.

Santagiuliana, M., van den Hoek, I. A. F., Stieger, M., Scholten, E., & Piqueras-Fiszman, B. (2019). As good as expected? How consumer expectations and addition of vegetable pieces to soups influence sensory perception and liking. *Food & Function*, 10, 665–680.

Santagiuliana, M., Bhaskaran, V., Scholten, E., Piqueras-Fiszman, B., & Stieger, M. (2019). Don't judge new foods by their appearance! How visual and oral sensory cues affect sensory perception and liking of novel, heterogeneous foods. *Food Quality and Preferences*, 77, 64-77.

Aguayo-Mendoza, M. [1], **Santagiuliana, M.** [1], Ong, X., Piqueras-Fiszman, B., Scholten, E., & Stieger, M. (Submitted, 2019). How addition of peach gel particles to yoghurt affects expectations, sensory perception and oral behavior of consumers differing in age.

Santagiuliana, M., Sampedro Marigómez, I., Broers, L., Hayes, J. E., Piqueras-Fiszman, B., Scholten, E., Stieger, M. (Accepted, 2019). Exploring variability in detection thresholds of microparticles through participant characteristics. *Food & Function*.

Santagiuliana, M., Broers, L., Sampedro Marigómez, I., Stieger, M., Piqueras-Fiszman, B., Scholten, E., (Submitted, 2019). Strategies to compensate for undesired gritty sensations in foods.

Overview of completed training activities

Discipline specific courses

6th Sensory Perception and Food Preference, 2016, WGS, Wageningen, NL

Multivariate analysis for food data/sciences, 2016, VLAG, Wageningen, NL

Understanding consumers. Preferences, emotions, expectations, contexts and sensory characterisation, 2017, SISS, Florence, IT

16th European school on rheology, 2017, Leuven University, Leuven, BE

Conferences

16th Food Colloids Conference, 2016, Wageningen, NL

7th International Symposium on Delivery of Functionality in Complex Food Systems, 2017, Auckland, NZ *

4th International Conference on Food Oral Processing, 2018, Nottingham, UK *

8th European Conference on Sensory and Consumer Research, 2018, Verona, IT *

8th International Symposium on Delivery of Functionality in Complex Food Systems, 2019, Porto, PT *

13th Pangborn Sensory Science Symposium, 2019, Edimburgh, UK *

33rd EFFoST International Conference, 2019, Rotterdam, NL

** Oral presentation*

General courses

VLAG PhD week, 2016, Baarlo, NL

Applied statistics, 2016, VLAG, Wageningen, NL

PhD Workshop Carousel, 2016, WGS, Wageningen, NL

PhD Peer Consultation - a powerful tool to tackle PhD challenges, 2017, WGS, Wageningen, NL

Scientific Writing, 2017, WGS, Wageningen, NL

The Essentials of Scientific Writing & Presenting, 2018, WGS, Wageningen, NL

Research Data Management, 2018, WGS, Wageningen, NL

Interpersonal Communication for PhD candidates, 2018, WGS, Wageningen, NL

Career Perspectives, 2018, WGS, Wageningen, NL

Optional courses and activities

Preparation of research proposal, 2016, Wageningen, NL

Participated and organized the PhD study tour to Singapore and Indonesia, 2018

Project meetings TIFN "Smooth Bite for All", Wageningen, NL

Project partners visits (Unilever, FrieslandCampina, Bel group)

Weekly group meetings Physical and Physical Chemistry of Foods, Wageningen, NL

Colophon

The studies presented in this Thesis were performed within the framework of TiFN.

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