Bolus matters

Impact of food oral breakdown on dynamic texture perception

Marine Devezeaux de Lavergne

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« Les enfants, quelle que soit leur intelligence,
ne s’améliorent que par l’éducation et les exemples. »
Jean Dutourd (1970)

A mes parents et ma sœur

ABSTRACT

Background and aims:
Texture is an important, yet complex, quality attribute of food. Food structure and properties can be linked to texture perception during the first bite. However, the perception of attributes during chew down is more difficult to explain, as food requires to be broken down to be swallowed safely. Food oral processing, which is a recent discipline connecting food science to the physiology of the eating process, is considered to be the key for understanding dynamic food texture perception. The aim of this thesis is to understand the link between food properties and texture perception by investigating oral food breakdown in simple model foods.

Methods:
Gels were used as a model for soft solid foods. Several properties of the gels were controlled by modifying the composition of gels, including fracture stress and fracture strain, oil droplets binding to the gels matrix, melting, serum release and mechanical contrast. The texture perception of the gels was measured using several sensory methods. Qualitative descriptive analysis (QDA), progressive profiling and temporal dominance of sensations (TDS) were compared in the assessment of dynamic texture perception. In order to link gel properties to texture perception, the oral processing of gels was measured through analyses on the gel bolus and measurements of chewing behaviour. Gel boli were expectorated at various stages of oral processing and were analysed for gel fragments size and number, mechanical properties and saliva incorporation. These analyses were used to quantify the degree of breakdown of gels and to relate bolus properties to changes in texture perception. Chewing behaviour was measured using Electromyography (EMG) to understand the role of oral processing behaviour in bolus formation and dynamic texture perception.

Results:
Dynamic texture perception of gels could be measured by QDA, progressive profiling and TDS which were complementary methods. Fracture properties of gels could predict the perception of first bite texture attributes. Fracture stress and fracture strain were correlated to first bite firmness and brittleness respectively. During chew down, the link between gel properties and texture perception became less clear. Nonetheless, fracture properties and other gels properties, such as melting and serum release, related to chew down perception. Even though bolus properties depended on food properties, they correlated well to chew down texture perception. Mainly changes in mechanical properties and fragmentation of the bolus could explain the perception of complex texture attributes, such as creaminess and graininess respectively. Chewing behaviour depended on products properties. In addition, chewing behaviour impacted the formation

of the bolus and could result in differences in dynamic texture perception between groups of individuals.

Conclusions:

The oral breakdown of food is a valuable input to understand the perception of complex chew down texture attributes. Combining the three fields of sensory science, food science and oral processing is essential to unravel the mechanisms of texture perception. Such an input could be used to design foods with a desired texture sensory profile for reformulation of foods fitting in a healthier diet or foods for target consumer groups.

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CHAPTER 1

1

General introduction

Preface

The project "Dynamics of texture and taste perception" from TI Food and Nutrition aims to better understand the dynamic perception of food, by investigating oral processing. This project aims to do this by unravelling the mechanisms of sensorial perception. A better knowledge of food texture and taste perception would enable to design food products that fit in a healthier diet or that would be more liked by consumers. More especially, such knowledge can be used, at a later stage, to generate strategies for sugar, salt and fat reduction in foods. Four PhD projects were conducted in parallel to cover several areas of dynamic texture and taste perception. The first PhD project focused on the perception of fat related sensory attributes in semi-solid food and the use of fat replacers. The second PhD project focused on characterizing and quantifying food oral coatings, which are residues of food remaining in the mouth after swallowing. The third PhD project focused on chewing behaviour in relation to texture and taste perception. The fourth PhD project, described in this thesis, focused on the dynamic breakdown of food during oral processing and its relation to dynamic texture perception.

1.1. Introduction

Food texture perception is one of the key factors in determining the quality of a food product. The definition of texture itself is complex, as it is sometimes used to describe both the physical properties and the perception of texture of food. Additionally, the texture parameters used to describe perception of a food depend widely on the type of food itself. Therefore, a comprehensive definition of texture is essential. Texture has been defined by Szczesniak (2002) as "the sensory and functional manifestation of the structural, mechanical and surface properties of foods detected through the senses of vision, hearing, touch and kinaesthetic". Such a definition implies that only humans can assess texture, which is a sensory property of the food. The use of physical testing for quantifying texture perception is, therefore, limited. Even though texture is often taken for granted by consumers, they recognize poor food texture as a sign of spoilage or low quality (Bruhn et al. 1991; Cardello, 1996). Also, texture is required for the recognition of foods (Schiffman, 1977). More importantly, texture can determine the liking of foods and impact the consumer's decision to purchase a product (Guinard and Mazzucchelli, 1996). Companies that are able to modify and control effectively food texture perception are at a competitive advantage. Furthermore, the health properties of food are becoming more emphasized. Food industry is interested in lowering the fat, sugar and salt content in their products in answer to the consumers' wishes for healthier foods. However, such changes in composition often compromise the structure and hence the texture perception of the food (Wilkinson et al. 2000; Busch et al. 2013). In general, consumers do not accept a lower textural quality of food in spite of increased health benefits (Childs and Drake, 2009). In order to effectively improve health properties without compromising texture properties of food and to predict food acceptance in a more systematic way, a better understanding of texture perception is required (Szczesniak, 1990).

Due to the complexity of texture perception, a multidisciplinary approach is required to investigate the relationships between food properties and texture perception. The three main areas of research to be integrated are evaluation of texture by sensory research, research of food structure-texture relationship and study of food breakdown in relation to oral physiology (Wilkinson et al. 2000). This Chapter discusses the three areas involved in texture perception as described in Figure 1.1. First, the measurement of dynamic texture perception, from ingestion to swallow, by different sensory methods is explored (1). The first step to investigate texture perception is an effective sensorial methodology. Secondly, the impact of food properties on texture perception is explained (2). The technological resources to control texture perception require food structure design. Thirdly, the involvement of food oral processing in understanding texture perception is described (3). The changes in food structure during oral processing, or bolus properties, can be linked to changes in dynamic texture perception. Subsequently, an overview of research integrating these three areas is given, and, finally, the outline of the PhD thesis is explained.

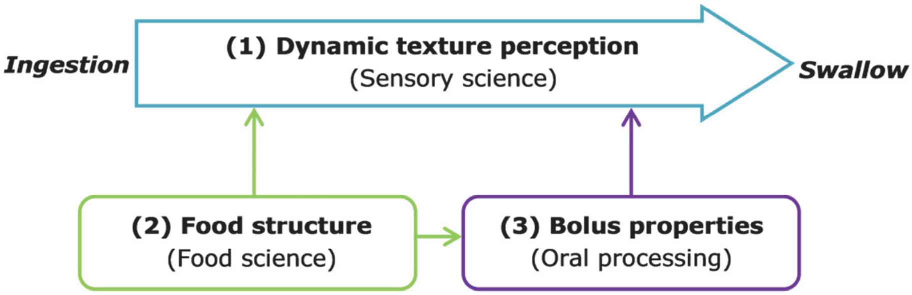

Figure 1.1 Relationship between dynamic texture perception, food structure and bolus properties, resulting in the integration of three fields of research: sensory science, food science and oral processing.

1.2. Assessment of sensory texture

As stated by Szczesniak (2002), texture is a sensory property. Therefore, the only way to measure food texture is by human assessment. Unlike for tastes and aromas, no specific receptors exist for texture perception. Texture perception is a multi-parameter attribute perceived by several senses. Textural parameters are mainly assessed by the sense of touch and kinaesthetic (sensation of movement in muscles) as a resistance to applied forces. These forces are first sensed by hand during manipulation of the food and later in the oral cavity by the teeth, the masticatory muscles, the tongue, the palate, the cheeks and the throat (Bourne, 2002; van Aken et al. 2007). Vision, hearing and thermal sensitivity are also involved in perception of texture attributes, such as rough surface, crunchy or irritation sensations, respectively (Vickers and Bourne, 1976; Green, 1991). As a result, texture is a multidimensional property of food that can be defined by many attributes. This thesis focuses on attributes perceived in the mouth by the senses of touch and kinaesthetic. A comprehensive description of sensory texture will also enable the design of desirable food texture and is discussed in this section.

1.2.1. Texture profiling

The classification of textural characteristics began with the developments of texture profiling (Szczesniak, 1963; Brandt et al. 1963). Texture profiling involves the use of standard scales for rating of sensory texture. Textural terms were grouped according to their common physical meaning in three groups: mechanical, geometrical and others (fat and moisture characteristics). The aim was to bring together the world of food technologists and sensory scientists by associating physical descriptors with sensorial descriptors of food. Out of the three, the group of mechanical properties was considered the most important (Szczesniak, 1998). In addition, texture profiling not only considers the degree in which each texture term is perceived, but also its order of appearance. This method recognizes the dynamic nature of texture perception due to food modifications in the mouth (Brandt et al. 1963; Szczesniak, 1963). In Table 1.1, the classification of texture terms from Brandt et al. (1963), together with their order of appearances is given. Table 1.1 also shows the common texture terms used in literature, which are in relation to textural characteristics. It can be seen that texture perception changes dramatically in time, with attributes being perceived at first bite, followed by early chew-down, late chew-down, swallow and after swallowing (residual) (Pascua et al. 2013; Foegeding et al. 2015). Specific texture attributes, such as firm or crunchy, are expected to be perceived at first bite, whereas completely different attributes, such as juicy or creamy, are expected to be perceived during late chew down.

The terms of texture profiling are still used with a recent emphasis on the use of a common texture terminology, in order to enable comparison between studies (Pascua et al. 2013). Texture profiling is the only method focusing solely on texture, however, other conventional sensory techniques such as Qualitative Descriptive Analysis (QDA) can be used to assess food texture by using texture profiling terms (Stone and Sidel, 1993; Wilkinson, 2002). Even though dynamic aspects of texture are acknowledged in these sensory methods, they require an integration of the perception of each attribute over time to a single intensity value. Such measurements do not describe the evolution of attributes over time which is known to occur (Cliff and Heymann, 1993; Dijksterhuis and Piggot, 2000; Lee and Pangborn, 1986).

Table 1.1 Sensory profiling scheme adapted from Brandt et al. (1963), supplemented by the classification of textural characteristics from Szczesniak (1963), in the white boxes, and additional sensory terms reviewed by Pascua et al. (2013), in the grey boxes.

<table>
<tr><th colspan="8">FIRST BITE</th></tr>
<tr><td colspan="4">MECHANICAL</td><td colspan="4">GEOMETRICAL product dependant</td></tr>
<tr><td colspan="2">hardness
fracturability
viscosity</td><td colspan="2">soft, firm, hard
crumbly, crunchy, brittle
thin, thick</td><td colspan="2">particle shape and orientation</td><td colspan="2">fibrous, cellular, crystalline</td></tr>
<tr><th colspan="8">CHEW DOWN (early)</th></tr>
<tr><td colspan="4">MECHANICAL</td><td colspan="4">GEOMETRICAL product dependant</td></tr>
<tr><td colspan="2">hardness
fracturability
gumminess
chewiness
adhesiveness
springiness</td><td colspan="2">soft, firm, hard
crumbly, crunchy, brittle
short, mealy, pasty, gummy
tender, chewy, tough
sticky, tacky, gooey
plastic, elastic</td><td colspan="2">particle shape and orientation
particle size and shape</td><td colspan="2">fibrous, cellular, crystalline

gritty, grainy, coarse</td></tr>
<tr><th colspan="8">CHEW DOWN (late)</th></tr>
<tr><td colspan="2">BREAKDOWN</td><td colspan="2">MOISTURE</td><td colspan="2">FAT</td><td colspan="2">MOUTH-COATING</td></tr>
<tr><td>type
rate</td><td>rate/degree of breakdown</td><td>release

adsorption</td><td>moist, wet, juicy

dry</td><td>release mouth-coating</td><td>oiliness, greasiness, creaminess</td><td>amount
type</td><td>oil, particles, etc.</td></tr>
<tr><th colspan="8">RESIDUAL (after swallow)</th></tr>
<tr><td colspan="3">MOUTH-COATING</td><td colspan="2">THROAT-COATING</td><td colspan="3">GENERAL FEEL ON</td></tr>
<tr><td colspan="2">type
amount</td><td>oil, moisture, particles, etc.</td><td>type
amount</td><td></td><td>mouth
throat</td><td colspan="2">dry after-feel
slime producing</td></tr>
</table>

1.2.2. Time-intensity methods

In contrast to descriptive methods such as QDA that pre-determine the time of rating a texture attribute, time-intensity sensory methods allow continuous evaluation of a sensory attribute over eating time. Time intensity (TI) consists in continuous tracking of one or two attributes intensities over time (Cliff and Heymann, 1993). TI was first used to track a texture attribute in 1978, where hardness of gelatine gels was found to decrease with increasing eating time (Larson-Powers and Pangborn, 1978). Similarly to the concept of TI profiling, but using discrete instead of continuous time intervals, progressive profiling is another dynamic sensory method, which consists of rating an attribute on an intensity scale at different time points during oral processing (Jack et al. 1994). More recently, Temporal Dominance of Sensations (TDS) was developed as a time resolved method focusing on the determination of the most “dominant” sensation over time (Pineau et al. 2009). The dominant sensation is often defined as the sensation that catches the most attention at a time point during consumption (Pineau et al. 2009). TDS can rate up to 10 sensory attributes in one test and requires little training of panellist, which is a considerable advantage over TI, for rating the many texture related attributes. TDS is an effective method to demonstrate the sequence of sensations over time (Pineau et al. 2009). Often time-intensity methods are used to complement the descriptive methods, as they provide a different type of information (Lawless and Heymann, 2010; Labbe et al. 2009). Time resolved methods are becoming widely used for the evaluation of taste and flavour perception (Cliff and Heymann, 1993; Baek et al. 1999; Meillon et al. 2009; Ng et al. 2012). However, few studies focusing on texture perception have been conducted. Lenfant et al. (2009) used TDS on breakfast cereals with a focus on texture attributes. This study demonstrated the importance of dynamic sensory methods in texture perception that can be expressed as sensory trajectories. It was shown that some attributes were systematically perceived at the beginning, such as hardness and crunchiness, the middle, such as brittleness and lightness, and the end phase of mastication, such as stickiness. Other studies stressed the interest of TDS for evaluation of texture, as it can relate to modifications of food properties during mastication (Young et al. 2012; Saint-eve et al. 2015, Panouillé et al. 2014).

1.3. Designing food texture

Food structure is known to influence sensory perception greatly, including the visual appreciation, taste and flavour delivery, and the texture evaluation of a food product. Food structure can be defined as the way molecules interact with each other within a food product in three dimensions. Therefore, food structure can be characterised from the molecular level to the macroscopic level (van der Linden, 2012). Moreover, the structural organization of food determines the rheological properties of food. Understanding food structure-function relationship is necessary to design desirable food sensorial properties, including food texture (Aguilera and Lillford, 2008).

1.3.1. Food structure design using biopolymers

The most distinctive textures are perceived in natural foods, such as fruits or meat due to their complex structure. One major limitation of texture design is that a specific texture cannot simply be added to a food matrix like aromas or a tastants. Even the thickening of a liquid by addition of gums involves complex binding mechanisms between water and macromolecules (Szczesniak, 1990). Hence, the design of food structure by the use of proteins and polysaccharides is expected to be a major opportunity for controlling texture perception of processed foods (Tolstoguzov, 2008; Funami, 2011; van de Velde et al. 2015). These gel-forming biopolymers create a solid-like matrix. Such structures are already found in food products, such as cheese, yogurts, spreads, custards and processed meat, among others.

Extensive research is carried out on the structure formation of gel-forming biopolymers, mainly by investigating the effect of composition (type of polymers, concentrations, salts, and pH) and processing (temperature, shear, duration) on structure and rheological properties (Koç et al. 2013a). This enables the creation of model food gels with a relatively simple composition coupled with controlled rheological properties and structural features. These model foods can then be used to gain fundamental understanding of the relationship between food structure or rheology, and texture perception in solid and semi-solid foods (Foegeding, 2007; Pascua et al. 2013; Stieger and van de Velde. 2014). The most simple model foods used are gels containing a single biopolymer, such as agar gels (Foegeding, 2015) and gelatine gels (Muñoz et al. 1986a; Muñoz et al. 1986b), and gels containing a single polymer and cations, such as pectin gels, alginate gels or gellan gels. The mechanical and structural features of these gels are well investigated, which is not always the case for their sensorial properties (Pascua et al. 2013).

Mixtures of hydrocolloids allow the control of rheological properties of gels, for instance in mixed κ-carrageenan/locust bean gum (LBG) gels (Chen et al. 2001; Koç et al. 2013a) and mixed high acyl gellan/ low acyl gellan gels (Mao et al. 2000; Huang et al. 2003; Matsukawa and Watanabe, 2007). More complex model gels enable the manipulation of the rheology independently from the micro-structure. This is the case for phase-separated mixed gels of proteins and polysaccharides (Jong and van de Velde, 2007). As food contain often several type of ingredients, such as fats and sugars, emulsion-filled gels, which consist of a polymer solution mixed with a fat emulsion, can be used as another type of model gels (Dickinson, 2012). Interactions of oil droplets with the gel matrix can be controlled to obtain gels with oil droplets being bound or unbound to the gel matrix (Dickinson, 2012). Controlling the binding of oil droplets to the food matrix is difficult in common foods. Using emulsion-filled gel enables to investigate the perception of complex fat related sensations, such as creaminess (Sala et al. 2007b).

By using biopolymer gels as model foods, not only did the understanding of the relationship between food rheology and texture perception progressed, but also the importance of controlling food structure as well as rheological properties was determined.

1.3.2. Rheology-texture relationship in solid-like foods

Food rheology is a major factor in the evaluation of food by the sense of touch. Therefore, the focus of most research relating food properties to texture perception is on the rheological behaviour of food. In this thesis, only solid-like materials, that require chewing, are investigated as they provide a wider range of textural properties than liquid-like materials (see table 1.1).

Rheological properties of food can be measured either at small or large deformation. Small deformation rheology is often used to characterize food and provides mechanical properties independently from the food shape and size. During large deformation rheology, the food deforms widely and the measured parameters depend on the test conditions (van Vliet, 2014). In the study of deformation of food materials, the two units used are stress (σ) and strain (ε). Stress represents the force applied to unit area of food and strain represents the deformation per unit length of the food when subjected to a stress. Foods are subjected to large deformations during consumption; hence solid-like foods are expected to fracture after a certain deformation. Therefore, fracture properties, such as fracture stress and fracture strain, of food can be measured (Figure 1.2). Several types of tests can be used to apply large deformations on foods including puncture, cutting-shear, tension, torsion or compression tests depending on the type of food analysed. Food gels are generally analysed by plate to plate compression (Bourne, 2002; Chen et al. 2012). Before fracture occurs, other properties of food corresponding to elastic behaviour can be measured, such as Young's modulus (unit force per deformation) (see Figure 1.2). However, food often does not remain in the linear viscoelastic regime and either shows a strain hardening or a strain weakening behaviour (van Vliet, 2014). Therefore, measuring the area under the curve up to fracture (fracture energy) can be used to quantify this behaviour (Walstra, 2003). Another parameter obtained in the nonlinear regime is recoverable energy using compression-decompression testing, often used in gel systems (van den Berg et al. 2008; Çakır et al. 2012). Recoverable energy gives an indication of the ratio of energy dissipation and storage in the gel matrix during compression. After fracture, the shape of the curve can be qualitatively described to indicate fracture propagation and is hypothesized to impact perception as well (van den Berg et al. 2008). A limited number of rheological properties can be measured compared to the number of attributes used to assess sensory texture. Information of rheological properties at different levels of deformation should be considered when trying to explain texture perception (Koç et al. 2013a). As most food products and their corresponding model products are viscoelastic by nature, the rheological properties should also be tested at different deformation speeds (Sala et al. 2009).

In food, fracture properties have been related to texture perception. Hardness, which is an extensively studied texture attribute (Foegeding et al. 2015), was correlated to fracture stress of fruit and vegetables (Diehl and Hamann, 1980; Harker et al. 2002), cheeses (Xiong et al. 2002; Gwartney et al. 2002; Wium et al. 1997), biscuits (Kim, et al. 2012) and gels (Barrangou et al. 2006; Foegeding, et al. 2011; Gwartney, et al. 2004). Fracture strain was linked to perceived deformability at first bite (Barrangou et al. 2006) and fracturability (Gwartney et al. 2004). Often, rheological properties of gels are convoluted. For instance, Young's modulus and fracture energy can correlate to hardness or fracturability (Koç et al.

2013a) and recoverable energy of gels correlate to the perception of the attribute crumbly (van den Berg et al. 2008a and 2008b). Despite clear correlations at first bite, the relation between fracture properties of gels and attributes perceived during chew down remains unclear. Few studies relate the impact of fracture properties to texture attributes perceived during chew down. It is expected that fracture properties of food would influence breakdown of the food during eating and, subsequently, impact chew down texture perception (Lillford, 2011). In gels, fracture strain was found to be negatively correlated to particle breakdown rate, cohesiveness and adhesiveness (Gwartney et al. 2004; Çakır et al. 2012). Recoverable energy was also related to perception during chew down. According to Çakır, et al. (2012) recoverable energy was highly correlated to texture attributes, such as particle size distribution, cohesiveness, adhesiveness and moisture release. In emulsion-filled gels, fracture properties of gels were found to impact creaminess perception (Sala, 2007).

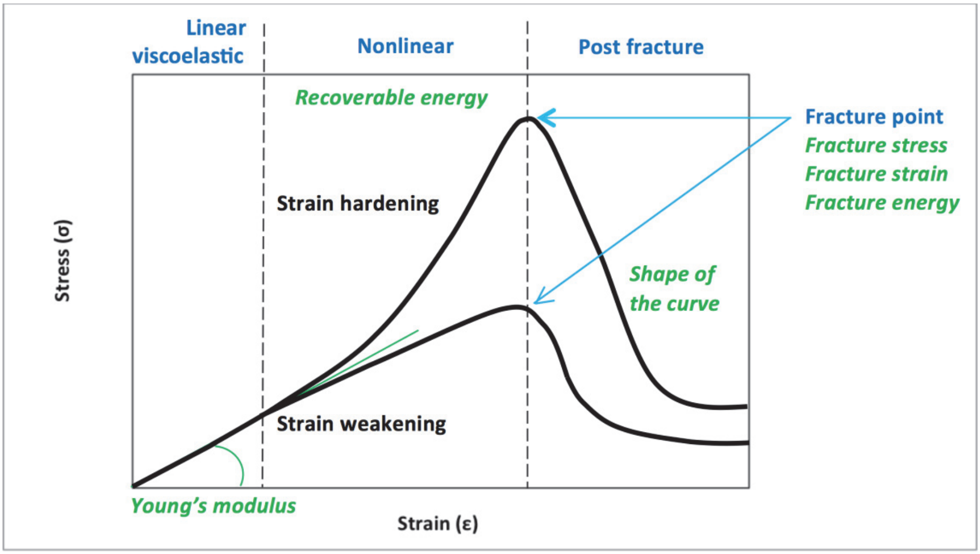

Figure 1.2 Illustration of strain hardening, strain weakening and fracture behaviour of solid materials under large deformation. The different regimes are indicated in blue and measured parameters in green. Inspired by Koç et al. (2013a).

1.3.3. Other structure-texture relationships

Often, food rheology is directly dependent on food structure. Therefore, changes in rheological properties are coupled to changes in structure. For example, microstructure of gels impacts fracture properties in protein-polysaccharide gels or in emulsion-filled gels (Sala et al. 2007a; Çakır et al. 2011). Microstructure, when uncoupled from fracture properties, was found to have an impact on texture perception in mixed protein-polysaccharide gels (Çakır et al. 2011; van den Berg et al. 2007a and 2007b) Differences in gel microstructure, such as pore size and micro-phase separation impact serum release from gels (Urbonaite et al. 2014). Serum release is a high determinant of moisture related sensory attributes with first chew (Gwartney et al. 2004; van den Berg, 2008a; Çakır et al. 2012) and during chew-down, such as juiciness (van den Berg et al. 2007b). In emulsion-filled gels, a higher fat content and smaller fat droplets enhance creaminess perception (Sala, 2007). In addition, oil droplet binding is related to creaminess and fattiness perception, however, this effect is not always found (Sala et al. 2007b; Liu et al. 2015). In addition to microstructure, the choice of biopolymers influences texture perception. In a study by Sala et al. (2008) it was found that texture attributes, such as crumbly, slippery and melting differ between different gelling agent systems. They found that melting of the emulsion-filled gel at human body temperature leads to a more creamy perception and concluded that the melting behaviour of gels dominated sensory perception compared to fracture properties. Therefore, several properties of food have to be taken into account to predict texture perception. Sensory melting can result from the physical melting of for example gelatine, but also from liquefaction of starch upon hydrolysis by the amylase present in the saliva (Janssen et al. 2007).

Due to the complexity of texture perception, large deformation measurements, which are simple to perform, are often difficult to correlate with texture perception after first bite. Moreover, they are time-rate dependent and vary with test conditions used (Koç et al. 2013a). The development of more imitative tests, mimicking deformation condition of the food in the mouth, is expected to give better results (Wilkinson, 2002). A drawback of these imitative methods is the focus on one or two sensory attributes, which could evolve in developing empirical methods. An example of a physical test mimicking mouth conditions is food tribology. The tribological regime is supposed to govern food perception in the later stage of mastication and includes the impact of surface properties of food, as opposite to the rheological regime (Stokes, 2012; Chen and Stokes 2012). Tribological measurements could be related to perception of fat related attributes (Prakash et al. 2013; Liu et al. 2015). However, this approach is limited to investigation of late chew down texture attributes, as the technique requires a liquid or apparent liquid product, such as the bolus after being broken down. As revealed by the development of mouth mimicking evaluation techniques, food texture perception remains difficult to explain based solely on food structure and rheological properties. In addition to the complexity of the food structure itself, the other main obstacle is a poor knowledge of oral processing.

1.4. Role of oral processing in texture perception

Understanding texture perception requires considering the constant modification of food structure during oral processing. Such modification is especially relevant in solid and semi-solid foods, which require mastication, and are responsible for dynamic changes in texture perception. Oral processing consists of all the processes occurring in the oral cavity, from the food entering the mouth until swallowing. The functions of oral processing are to recognise the food as being edible and to process it into a swallowable mass referred to as food bolus (Hiiemae, 2004). The food bolus has to be adjusted to body temperature, comminuted and lubricated enough to be safely swallowed. In addition, particle size reduction improves the speed of further digestion and release of tastants and flavours during chewing increase the intensity of the sensory stimulus. The modifications of food during oral processing depend on both oral physiology and how the food material responds to oral manipulations.

1.4.1. Physiology of mastication

As texture is perceived during mastication, it is important to know how the human body interacts with food to understand texture perception. Two types of approaches can be employed to relate oral physiology to perception. The first approach investigates on the micro-level how the receptors integrate the texture signals while the second approach describes the oral processes on the macro-level (Wilkinson et al. 2000). As changes of food structure depend on oral processes taking place on the macro-level, this thesis follows the second approach.

The mastication and salivation patterns largely depend on food properties, including its physical and chemical properties (Kapur et al. 1966). The mastication sequence is regulated by a sensory feedback system as the food properties are modified and dynamically perceived (van der Bilt, 1995). Therefore, oral movements are tightly linked to perception of food texture. Measurement of oral movements or muscle activity can be done using different methods such as electromyography (EMG), jaw-tracking, video recording, radiography, electromagnetic articulography (EMA) or videofluography. It was observed that, next to differences in food properties, differences between individuals impact oral processes (Woda et al 2006). Differences between individuals can be due to several factors, such as physiological or behavioural differences, and are expected to impact texture perception (Szczesniak, 2002; Wilkinson et al. 2000). However, Engelen et al. (2005) suggested that differences between individuals explain less of the variations in oral processes than rheology of food. It was observed that chewing cycles and duration varied greatly between foods (Hiiemae et al. 1996; Wilson and Brown, 1997; Fontijn-Tekamp et al. 2004). Harder foods lead to higher muscle activity, duration of mastication and number of chewing cycles (Peyron et al. 2002 and 2004; Mioche, 2004; Foster et al. 2006). Other properties of foods, such as shape and size, lubrication, adhesiveness and heterogeneity also were found to influence oral processing parameters (van der Blit et al. 1991; Engelen et al. 2005; Çakır et al. 2012; Hutchings et al. 2011). It was demonstrated that oral processing parameters could be related to perception. For instance, sensory hardness was correlated to muscle activity at first bite, chew down sensory attributes were related to jaw opening velocity and cycle duration of the first five chewing cycles and after-feel sensory attributes were related to jaw movement amplitudes of the later chewing cycles (Çakır et al. 2012). However, while monitoring oral movement or muscle activity can relate to attributes assessed during a bite, such as hardness, it cannot relate to attributes assessed by the tongue, such as oiliness (Wilkinson et al. 2000; de Wijk et al. 2011). Moreover, changes in food properties might not be reflected in these types of measurements (Brown and Baxton, 2000). These observations put in evidence the need to study food breakdown in parallel to oral physiological parameters.

1.4.2. Food breakdown

The dynamic modification of food properties during eating was explicitly introduced by Hutchings and Lillford (1988) by stating that “texture” depends on oral processing. Indeed, the physical properties of the food are modified during oral processing to transform the food into a bolus that can be swallowed safely. They described a different breakdown pathway for different food products where, for all foods, a safe swallow requires to be below a maximum degree of structure and above a minimum degree of lubrication. Together with oral processing time, the degree of structure and degree of lubrication were described by Hutchings and Lillford as the main parameters of bolus formation, as shown in figure 1.3. The breakdown of structure is reached by comminution by the teeth and the tongue, but also dissolution in saliva and, in the case of starchy products, enzymatic breakdown by amylases. Increase of lubrication is reached by addition of saliva, release of fluids from the food matrix and phase transition of fat or other components by changes of temperature (Chen, 2009; Foegeding et al. 2010). Those modifications influence the physical properties of the mass of food and thus its perception over oral processing time (Wilkinson, 2000).

Sampling methods, which consist of collecting and characterizing the broken down foods, can be used to directly observe changes in food properties during mastication. Several methodologies have been developed to characterise the breakdown and lubrication properties of food boli. The wide range of methods used, demonstrates the need to adapt the characterization method to the specific properties of the bolus, which can differ considerably between foods depending on degree of breakdown. Structure reduction is mainly related to particle size analysis measured by sieving or image analysis (Peyron et al. 2011; Guo et al. 2013; Hutchings et al. 2011; Mosca et al. 2012; Chen, 2013). The study of particle agglomeration, which is relevant to bolus cohesiveness and swallowing, was done by image analysis and microscopy (Rodrigues et al. 2014). Mixing of bread boli was analysed by photographing the boli and performing texture image analysis (Tournier et al.

2012). Lubrication of the bolus can be considered through several aspects including saliva and dry matter content of boli (Loret et al. 2011), release of oil from the food matrix during mastication (Guo et al. 2013) or tribological properties of boli from custard desserts (de Wijk et al. 2006a and 2006b). Rheological properties of boli change as well with the decrease of structure and increase of lubrication. Different methods can be used to measure rheological properties of boli that vary between food products, including modified Texture Profile Analysis (TPA) of cereal boli (Peyron et al. 2011), oscillatory small deformation rheology of bread and cheese boli (Le Bleis et al. 2013; Saint-Eve et al. 2015), force-displacement mechanical testing of model cheese boli (Drago et al. 2011) and shear rheology of meat boli (Yven et al. 2005).

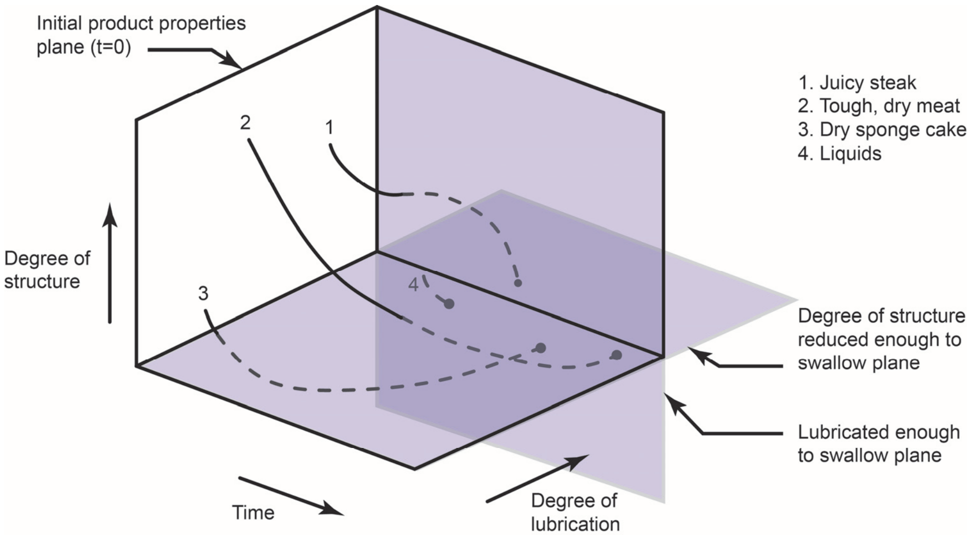

Figure 1.3 Hutchings and Lillford's philosophy of the breakdown path (Hutchings and Lillford, 1988).

The effect of rheological properties of solid-like food on breakdown has been studied by sampling boli. Lillford (2011) observed that fracture properties were the most relevant rheological property of food during oral breakdown. Gels with high fracture strain were found to breakdown in large pieces at a slow rate (Gwartney et al. 2004; Çakır et al. 2011). Harder food resulted in boli with smaller particles than softer foods (Chen et al. 2013). A low initial dry matter was associated with a higher saliva incorporation in cheeses (Tarrega et al. 2011; Saint-Eve et al. 2015) and a low fat content with a higher particle size compared to full fat cheeses (Çakır et al. 2011; Saint-Eve et al. 2015). Few studies start to relate bolus properties to texture perception. Slipperiness and compliance of the food bolus are two sensory properties that correlate to bolus rheology during swallowing (Seo et al. 2007). Hardness, stickiness and dryness of cereals were evaluated and hardness was found to decrease together with mechanical hardness of the boli (Peyron et al. 2011). A few studies, which used TDS in parallel with bolus analysis, found that bolus properties could be related to differences in perception between biscuits, bread and cheeses (Young et al. 2013; Panouillé et al. 2014; Saint-Eve et al. 2015).

1.5. Integration of texture perception, food structure and oral processing

On the one hand, food scientists investigate structural and rheological properties of food in relation to texture perception and often disregard measurements of oral processing. On the other hand, dentists and biologists investigate the physiology of eating by measuring oral physiological parameters as it is relevant for dental health (Foegeding et al. 2015). The integration of all disciplines is seldom found in literature. Moreover, most texture investigation focus on one or two texture attributes. Some studies relate food properties to oral processing parameters and texture perception (Çakır et al. 2012; Rodrigues et al. 2013; Panouillé et al. 2014; Saint-Eve et al. 2015) and are partly discussed in previous sections. These studies demonstrate the complexity of texture and the importance of a multidisciplinary approach to understand texture perception.

In bread, density and Young's modulus were found to impact bolus properties and dynamic texture perception. Using TDS sensory trajectories, it could be seen that the dense bread was perceived differently over time than other breads (Panouillé et al. 2014). Saint-Eve et al. (2015) found that bolus properties of cheeses related to cheese mechanical properties and that differences in bolus properties could explain differences in texture perception between cheeses. They highlighted the interest of measuring dynamic bolus formation for a better understanding of texture perception. Using TDS, Young et al. (2013) found that fracture-related sensory attributes, such as hardness and crumbliness, dominated perception of biscuits in early stages of mastication whereas chew down texture attributes may relate better to bolus properties. Using the same biscuits, Rodrigues et al. (2014) found that changes in biscuits boli coincided with changes in perception. The boli were perceived as dry during early chew down and sticky when they were lubricated and agglomerated enough to be swallowed. These studies helped understanding dynamic texture perception in breads, cheeses and biscuits. However, the use of model gels has been widely recommended for such studies, as it could enable a better control of rheological properties and microstructure than using complex food products (Pascua et al. 2013; Foegeding et al. 2015). In gels, first chew and tongue palate compression can relate to mechanical properties. Çakır et al. (2012) did not measure gels oral breakdown, but they successfully linked oral movement to rheology of gels and texture perception. However complex chew down attributes remain unclear (Koç et al. 2014). Moreover, emulsion-filled gels have not yet been used in multidisciplinary studies, which could enable to understand the perception of creaminess, which is a complex chew down texture attribute of high relevance for food reformulation aiming at fat reduction, in simple models of solid-like foods.

1.6. Rationale and thesis outline

There is a need for better understanding of how complex texture attributes are perceived and which factors determine the perception of specific texture attributes. To investigate texture perception, a multidisciplinary approach is recommended combining food rheology and structure, human physiology and behaviour, and sensory perception (Dijksterhuis and Piggott, 2000; Wilkinson et al. 2000; Foegeding et al. 2015). Dynamic food breakdown, depending on both food properties and human physiology might be the key to understand dynamic texture perception. The effect of oral processing on food breakdown has been investigated in the past decades. However, little is known on which properties of the bolus determine perception of texture attributes (Koç et al. 2013a).
As shown in Figure 1.4, foods can be designed with controlled properties as an input to texture perception. The effect of these properties on dynamic texture perception can then be measured as output. The aim of this thesis is to fill and understand the link between the designed food properties and measured texture perception, in simple model foods. To do so, food oral breakdown and oral processing behaviour are monitored and linked to both food properties and texture perception.

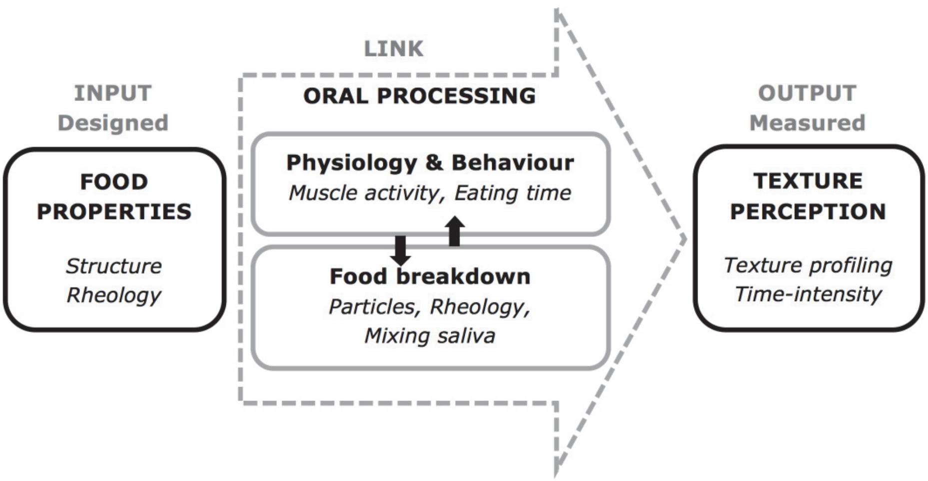

Figure 1.4 Scope of this thesis

In **Chapter 2**, the use of three sensory methods in the dynamic assessment of texture is compared. A set of emulsion-filled gels were assessed by QDA, progressive profiling and TDS to identify the strengths and weaknesses of each method in the dynamic assessment of texture. Properties of the model emulsion-filled gels used in the study were designed and varied in a full factorial design varying in fracture stress (high/low), fracture strain (high/low) and binding of oil droplets to the gel matrix (bound/unbound). The aim of **Chapter 2** was to compare the three sensory methods in the evaluation of dynamic texture perception and to investigate the effect of gels rheology on dynamic gels texture perception.

The emulsion-filled gels described in chapter 2 were used in **Chapter 3** to explain the impact of bolus properties of the gels on texture perception. Texture attributes were divided in three categories depending on which stage of oral processing they were perceived. Relevant bolus properties were discussed in relation to the texture attributes. The properties of gels were used to explain differences in breakdown and bolus formation between gels. The aim of **Chapter 3** was to gain a comprehensive understanding on how gels properties impact oral processing and texture perception.

It was found in chapter 3 that modifying composition of emulsion-filled gels was required to modify fracture properties. Such modification of composition influences other gel properties relevant for texture perception. In order to uncouple the effect of fracture properties and other properties linked to gel composition (ingredients), emulsion-filled gels differing in ingredient composition but with similar fracture properties were designed and characterized in **Chapter 4**. Variation in the gelling agent matrix (agar/gelatine, k-carrageenan/Locust beam gum and high/low acyl gellan) allowed the design of three matrices with similar fracture stress (high/low) and fracture strain (high/low). The gels were characterised for properties linked to composition, such as water holding capacity or melting at mouth temperature. Oral breakdown of gels was characterised and texture perception of gels was determined using QDA. The aim of this chapter was to identify which chew down attributes were explained by fracture properties of gels, or by other gelling agent specific properties.

Model gels with homogeneous texture were used in the studies described in chapters 2, 3 and 4. To add a level of complexity to the model gels, gels with inhomogeneous texture (gels composed of layers displaying mechanical contrast) were used in **Chapter 5**. It is known from literature that compartmented foods break down differently than homogeneous foods, which then could influence texture perception (Hutchings, 2011). In this chapter, the impact of inhomogeneity of mechanical properties on dynamic texture perception was studied by characterising bolus properties, monitoring muscle activity and dynamic texture perception. This chapter aimed at a better characterisation of oral processing of homogeneous gels and a first step in understanding dynamic texture perception of inhomogeneous gels.

Chapters 2, 3, 4 and 5 focus mainly on controlling and linking food properties to breakdown and dynamic texture perception. It is known that other factors related to eating behaviour such as eating duration, chewing frequency and muscle activity also impact food oral processing and consequently sensory perception (Brown et al. 1994). These factors could explain inter-individual differences in texture perception. In **Chapter 6** subjects differing considerably in their natural eating time of a piece of sausage were studied. Oral processing and texture perception were monitored by EMG, bolus analyses and TDS. The aim of chapter 6 was to identify differences in texture perception between subjects varying in naturally preferred eating duration, and to explain these differences by the subjects' chewing behaviour and bolus properties.

Chapter 7 summarises and integrates the findings of the different chapters of the thesis and discusses the significance of the results and possible applications.

2

CHAPTER 2

2

Dynamic texture perception and oral processing of semi-solid food gels:

Part 1: Comparison between QDA, progressive profiling and TDS

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Abstract

Texture perception of food is a dynamic phenomenon depending on food properties and oral processing. Several sensory techniques enable to measure texture perception over time. The aim of this study was to compare quantitative descriptive analysis (QDA), temporal dominance of sensation (TDS) and progressive profiling in the assessment of dynamic texture of emulsion-filled gels varying in fracture stress (low/high), fracture strain (low/high) and oil release (oil droplets bound/unbound to the gel matrix).

The QDA results revealed that the variation of mechanical properties led to significant differences in texture properties perceived at first bite (firmness and brittleness). Texture attributes perceived at later stages of mastication showed significant differences between gels depending on the first bite properties e.g. soft gels were perceived as more melting. Progressive profiling showed that creaminess increased over eating time while firmness decreased. TDS results were in agreement with the other methods and additionally conveyed information on the succession of perceived attributes over time. The TDS sensory trajectories demonstrated that for all gels dynamic perception evolved in a similar fashion but samples with a high or low fracture strain differed at the end of oral processing.

We conclude that texture perception of semi-solid gels is dynamic and can be measured by any of the three sensory methods. The mechanical properties of the gels influence the perception of texture attributes at first bite and at later stages of mastication. QDA, TDS and progressive profiling gave matching and complementary results in the assessment of dynamic sensory texture.

2.1. Introduction

Hutchings and Lillford introduced the notion that texture perception is a dynamic phenomenon depending on oral processing (Hutching and Lillford, 1988). Indeed, the physical properties of the food are modified during oral processing to transform the food, especially solids, into a food bolus that can be swallowed safely. They described a different breakdown pathway for different food products where, for all foods, a safe swallow requires a low degree of structure and a minimum degree of lubrication. Together with oral processing time, degree of structure and degree of lubrication were described as the main parameters of bolus formation by Hutchings and Lillford. Those modifications of food by mastication, incorporation of saliva and release of fluids from the matrix influence the physical properties of the mass of food and thus its perception over oral processing time. Thus, texture perception of food is complex and depends on multiple parameters. Classification of textural characteristics started with the separation of mechanical, geometrical and other parameters (Szczesniak, 1963). Texture perception was also divided over time, from visual assessment, first bite, early and late mastication to swallowing and residual properties (Brandt et al. 1963). Hence, sensory perception of texture is a dynamic process and can be assessed by rating different attributes on a scale at a specific time of oral processing (Szczesniak, 1998). In Quantitative Descriptive Analysis (QDA), which consist of training a panel to express their perception of a product in a reliable manner, texture attributes can be incorporated next to aroma and taste attributes to obtain a complete descriptive sensory profile of a food. Even though dynamic aspects of texture were acknowledged, the previously mentioned methods require an integration of the perception of each attribute over time to a single intensity value. Time intensity (TI) has been used since 1954 to quantify the temporal response of taste (Sjöström, 1954) and was first used in 1978 to measure texture related attributes (Larson-Powers and Pangborn, 1978). A continuous tracking of attribute intensities over time is used in TI measures (Cliff and Heymann, 1993). Generally, TI is limited to the evaluation of one attribute over time whereas dual attribute TI (Duizer et al. 1995) seems to be applied less frequent. Different attributes can be measured in repeated TI tests to obtain composite TI profiles. Following the concept of TI profiling, but using discrete instead of continuous time intervals, progressive profiling is another dynamic sensory method consisting of rating an attribute on an intensity scale at different time points during oral processing (Jack et al. 1994). More recently, Temporal Dominance of Sensations (TDS) was developed as a dynamic sensory method focusing on the determination of the most “dominant” sensation over time (Pineau et al. 2009). The dominant sensation is often defined as the sensation that catches the most attention at a time point during consumption (Pineau et al. 2009). TDS can rate up to 10 sensory attributes in one test and requires little training of panellist. Lenfant et al. (2009) used TDS on breakfast cereals with a focus on texture attributes. This study demonstrated the importance of dynamic sensory methods in texture perception that can be expressed as sensory trajectories. All these sensory methods are well suited to assess texture perception. Some, such as TI, progressive profiling and TDS include a time dimension but are limited to a reduced number of attributes. Texture profiling and QDA give a holistic description of the sensory profile of a food, but provide a single intensity value for each attribute at a given time point. QDA has been described as giving complementary information to TDS (Labbe et al. 2009). TDS was reported not to be a replacement for TI (Pineau et al. 2009). Progressive profiling enables the rating of several attributes at once with less training than TI. Progressive profiling can therefore be used instead of TI when information about dynamic changes in perception is investigated without the need to assess perception continuously with a high time resolution. Therefore, the complementary use of QDA, TDS and progressive profiling is of interest to obtain a complete description of dynamic texture perception of foods.

The relationships between food structure, food breakdown and texture perception still need to be investigated to thoroughly understand dynamic texture perception. Model foods can be desired to investigate since (micro)structure and texture can be manipulated independently. Commonly used model foods for this purpose are phases separated mixed gels of proteins and polysaccharides, and emulsion-filled gels (Gwartney et al. 2004; Stieger and van de Velde, 2013). Breakdown properties of gels have been proven to have an impact on texture perception (Foegeding, 2007; van den Berg et al. 2007a; Pascua et al. 2013). Fracture properties of gels, including fracture stress and strain, can be determined instrumentally and linked to texture perception (Chen et al. 2012). For gels, fracture stress was linked to perceived hardness at first bite (Foegeding et al. 2011) and fracture strain to perceived deformability at first bite (Barrangou et al. 2007a and 2007b). Using emulsion-filled gel enables to investigate the perception of complex fat related sensations, such as creaminess (Sala et al. 2007a). In emulsion-filled gels, charge interactions between the oil droplets emulsifier and the gel matrix constituents can be controlled to obtain gels with oil droplets being bound or unbound to the gel matrix (Dickinson, 2012). Oil droplet binding was hypothesized to be related to creaminess and fattiness perception. However, this was not demonstrated when comparing creaminess perception of bound and unbound emulsion-filled gels by Sala et al. 2007b. The presence of bound or unbound oil droplets to the gel matrix in the used recipes was found to modify fracture properties of the gels and the effect of binding on perception could not be distinguished from the effect of changes in mechanical behaviour of gels in this study (Sala et al. 2007b). The effect of fracture properties of gels on first bite texture attribute has been described but the impact of fracture properties on dynamic texture perception, especially on chew down attributes such as creaminess, remains unclear.

The objective of this study is to compare dynamic texture perception of semi-solid food gels determined with different sensory methods (QDA, progressive profiling, and TDS) which, in the case of TDS, has not been described on gels. The gels were designed to show differences in breakdown properties at first bite and at later stages of mastication to obtain variations in temporal texture perception. A second objective is to understand the influence of the mechanical and physical-chemical properties of semi-solid food gels on dynamic texture perception. The effect of mechanical properties (fracture stress and fracture strain) and oil release will be analysed to provide input on designing foods with desired texture profiles.

Eight emulsion-filled gels were prepared varying in three structural parameters following a 2x2x2 full factorial design. Fracture stress (high or low), fracture strain (high or low) and binding of the oil droplets to the gel matrix (bound or unbound oil droplets) were varied. Texture perception was assessed by a trained panel using QDA, TDS and progressive profiling. First, the panel performed the QDA, then the TDS and finally the progressive profiling (creaminess and firmness). The three sensory methods were compared. The effects of the three structural parameters of the gels were related to the sensory perception determined by QDA, TDS and progressive profiling.

2.2. Material and methods

2.2.1. Gel preparation

2.2.1.1. Materials

Edible pig skin gelatine (bloom 240-260, Rousselot, Gent, Belgium) and Ferwo Agar 700 (Caldic Ingredients, Oudewater, The Netherlands) were used as gelling agents. Tween 20 (Sigma- Aldrich) and whey protein isolate (WPI) (Davisco Foods) were used as emulsifiers. Sunflower oil and sugar were purchased from a local retailer and used without further purification. Vanilla flavour (Bourbon vanilla VLB concentrate; Pamona Aroma, The Netherlands) and demineralized water were used.

2.2.1.2. Gel composition and preparation

The composition of all gels is shown in Table 2.1. The nomenclature of the gel names is the following: H stands for high and L for low, followed by the symbol of stress σ and strain ε. T stands for emulsifier Tween 20 and W for WPI.

Table 2.1 Gel properties and composition. All gels contained 15 Wt% sugar, 20 Wt% sunflower oil, 0.033 Wt% vanilla aroma and 0.6 Wt% emulsifier.

Gel properties				**Composition**			
Name	Fracture stress (σ)	Fracture strain (ε)	Emulsifier	Agar (Wt%)	Gelatine (Wt%)	Agar-gelatine ratio	Water (Wt%)
Hσ/Lε/T	High	Low	Tween 20	1.80	0	-	62.57
Hσ/Hε/T	High	High	Tween 20	0.70	5.85	1:8.4	57.82
Lσ/Lε/T	Low	Low	Tween 20	1.00	0.75	1:0.8	62.62
Lσ/Hε/T	Low	High	Tween 20	0.30	3.50	1:11.7	60.57
Hσ/Lε/W	High	Low	WPI	1.70	0	-	62.67
Hσ/Hε/W	High	High	WPI	0.30	2.75	1:9.2	61.32
Lσ/Lε/W	Low	Low	WPI	0.50	0.75	1:1.5	63.12
Lσ/Hε/W	Low	High	WPI	0.10	2.20	1:22.0	62.07

Two 1200 g solutions of 2 Wt% WPI or 2 Wt% Tween 20 were stirred for at least 1 hour before being mixed with 800 g of sunflower oil using an Ultra Turrax high shear mixer (Ultra Turrax, IKA, T50 basic, Staufen, Germany) for 1 minute. The obtained pre-emulsions were passed twice in a two stage homogenizer (Ariete, Model NS1001L 2K - Panda 2K, Niro Soavi S.p.A, Parma, Italy) at a homogenization pressure of 500/50 Bar and 400/50 Bar for WPI and Tween 20 emulsion, respectively. The resulting Sauter diameter ($d_{3,2}$) of the obtained oil droplets was 0.96±0.09 µm for WPI and 0.92±0.05 µm for Tween 20 emulsions. The emulsion droplet size distribution was measured by light scattering using a

Malvern Mastersizer 2000 (Malvern Instruments Ltd., Malvern, UK). 1.32 g of vanilla flavour was added to each emulsion after homogenization.

Agar and sugar solutions were made for each gel, heated and stirred on a heating plate until the solution reached nearly 100°C and agar was completely dissolved. These solutions were subsequently cooled to 60°C in a water bath and gelatine added while stirring for 20 minutes. After dissolution of gelatine, the 500 g solution of gelling agents was mixed with 500 g of the corresponding emulsion, previously heated to 60°C. Gels were poured into plastic tubes (Omnifix 50 mL syringes, B.Braun) of 26.4 mm internal diameter, and kept at 19˚C ± 1°C to set for 18-22 hours.

Samples containing only the matrix (same agar, gelatine, sugar, water and vanilla composition as other samples in the gels matrix) were made following a similar protocol but obtained by mixing 700 g of gelling agents' solutions with 300 g of water instead of mixing 500 g of gelling agent solution with 500 g of stock emulsion.

2.2.2. Mechanical properties of gels

Uni-axial compression tests were performed with a Texture Analyser (TA.XT plus, Stable Micro Systems-SMS) on cylindrical gel pieces (26.4 mm diameter and 20 mm height) lubricated with paraffin oil. A 75 mm diameter probe was used at room temperature, at a constant deformation speed of 1 mm/s and up to 80 % strain compression. Uni-axial compression tests were performed with 3 gel samples per variant prepared on different days and each measurement was done in triplicate. Thus, per gel variant 9 compression test were performed. The averaged values for fracture stress, fracture strain and Young modulus were calculated. Analyses of Variance (ANOVA) with stress, strain and emulsifier types as fixed factors with two levels each followed by a LSD post hoc analysis were executed to check whether products were significantly different from each other in fracture properties using SPSS (SPSS software, V19, SPSS Inc., Chicago, USA). A level of significance of $p<0.05$ was used.

2.2.3. Determination of oil release from gels under mechanical compression

The method described by Sala et al. (2007b) was used to measure release of oil from the gel matrix. Each gel was squeezed out of a syringe through an orifice of 0.9 mm diameter by applying a deformation with constant velocity (10 mm/s) on the syringe plunger with a Texture Analyser (TA.XT plus, Stable Micro Systems-SMS). The amount of sheared gel (typically 12.5 g) was diluted with distilled water (typically 25 g) to reach approximately a 1:2 dilution. The mix was vortexed (Vortex genie, Wilten&Co, Etten-leur) for 15 seconds and filtered with an Acrodisc syringe filter (5 µm pore size, PALL Corporation). The oil content of the filtrate was determined using the Rose-Gottlieb method (ISO 1211) (Qlip, Leusden, The Netherlands). The measurement was performed in triplicate per gel variant. Analyses of Variance (ANOVA) with stress, strain, emulsifier types and test temperature as fixed factors with two levels each to check whether factor influenced significantly oil release using SPSS (SPSS software, V19, SPSS Inc., Chicago, USA). A level of significance of $p<0.05$ was used.

2.2.4. Sensory assessment

2.2.4.1. Quantitative Descriptive Analysis (QDA)

A panel was selected and trained according to the principles of QDA (Stone and Sidel, 1985). The panel consisted of Dutch women (n=12) with an average age of 51.9±14.1 years. All panel members participated previously in several QDA studies on similar food gels, so they were experienced in QDA profiling and texture evaluation of food gels. The panellists were recruited and selected for their sensory abilities, basic taste and odour detection, and ability to communicate sensory descriptions of products. Training on the specific gels used in this study was executed in six sessions of two hours each with the set of 8 gels described in Table 2.1. A preliminary attribute list containing attributes of interest (first and chew down attributes) was used as input during the attribute generation by the panel. The list of attribute was generated by the panel in Dutch and translated into English. First bite attributes were instructed to be rated at the first bite with incisors. The second bite attribute brittleness was instructed to be rated by a first bite with the molars on a fragment of gel, previously detached from the gel with incisors. Chew down attributes were instructed to be rated after several chews. The attribute generation and definition was completed after two sessions followed by two more training sessions to reach consensus between panellists on rating the attributes. In two subsequent training sessions, panellists were asked to rate the samples. The last session was used to discuss the results from this test session. The samples were evaluated in individual sensory booths at 20˚C (± 1˚C), under normal light conditions in triplicate in a balanced design during two sessions of two hours. Data were registered using a web based system to collect sensory data (EyeQuestion, V3.8.13, Logic 8, The Netherlands). As individuals have a high variation in size of a natural bite (Hutching, 2009), a standardized sample size was served. All samples were prepared 24 hours prior to sensory testing and cut into cylindrical pieces of 26.4 mm diameter and 10 ± 1 mm height weighing 6.4 ± 0.1 g. During QDA profiling, all samples were served in triplicate, with 3-digit codes, in a balanced design between session and randomized order between panellists. The panellists evaluated the samples using an unstructured 100 mm line scale anchored with ‘very little’ at 10% and ‘very much’ at 90% of the line scale. All panellists followed the same tasting procedure. First, they were instructed to assess the odour of the sample, then to chew the samples once to evaluate the first bite attributes. Brittleness was then evaluated at the second bite by pushing the broken down pieces of the first bite to the molars for a second bite. Taste attributes were assessed after succeeding chews. A new piece of sample was taken to evaluate the chew down attributes. Finally, aftertaste and after-feel attributes were evaluated after spitting out the sample. Panellists rinsed their mouth with water before tasting the next sample.

To determine which attributes differed between samples, ANOVA with products as fixed and subjects as random factor was executed with LSD post hoc tests in SPSS (SPSS software, V19, SPSS Inc., Chicago, USA). A level of significance of $p<0.05$ was used. The relationships between sensory attributes and samples were analysed using Principal Component Analysis (PCA)(The Unscrambler® X software V10.2, CAMO software, Norway).

2.2.4.2. Progressive profiling

Ten of the twelve trained panellists (n=10) that completed the QDA study, participated in the progressive profiling evaluation (average age 54.7 ± 13.7 years). The panellists chewed freely on gels until they felt the desire to swallow and recorded the chewing time with a digital timer. The recorded chewing times were used to determine suitable time points for progressive profiling: 5, 10, 15 and 20 seconds. During progressive profiling, panellists were asked to chew the gels for a given time using a digital timer. At the given time point (5, 10, 15 and 20 s) panellists spitted out the gels and rated firmness and creaminess using an unstructured 100 mm line scale anchored with “very low” at 10% and with “very high” at 90% of the line scale in triplicate (EyeQuestion, V3.8.13, Logic 8, The Netherlands).

A multiple factorial ANOVA (strain, stress, oil-matrix interaction and time as fixed factors and panellists as random factors) was executed to check which study factors accounted for differences in attribute evaluation between the samples in SPSS. A Bonferroni Post-Hoc with a level of significance of $P<0.05$ was run to check differences between oral processing times and between the different gels. An additional multifactorial ANOVA was conducted on the eating time of the samples while eating freely and while performing TDS with fracture stress, fracture strain, emulsifier type and eating condition as factor with two levels each at the significance level $P<0.05$.

2.2.4.3. Temporal Dominance of Sensation (TDS)

The ten trained panellists (n=10) who completed the QDA and progressive profiling participated in the Temporal Dominance of Sensation (TDS) study. Training on the TDS methodology took place during two sessions of two hours. First, an introduction was given about the goal of TDS and the samples used in the tests. Then, the notion of the temporality of sensations was explained to the participants and the term ‘dominance’ of an attribute was defined as “the attribute that attracts the most attention at a given time point”. A concept attribute list for TDS was set up based on the QDA evaluation results. Only chew down and after-feel attributes were used in the list. When two attributes were highly correlated, one only was selected. For example: only “melting” and not

"spreadable" was selected because of the high correlation between both attributes observed in QDA. The attribute list was finalised during the training session on the TDS method, based on discussions within the trained panel. For the first TDS rating session eight mouth-feel attributes were selected and, for a second TDS screen right after swallowing, three after-feel attributes were selected. Panellists were instructed to put the gel into their mouth and click the 'start' button using the EyeQuestion Software. As soon as the panellist perceived a sensation, the dominant attribute was chosen from the attribute list and its perceived intensity was scored on a 100 mm line scale (anchored with "low" at the left end and with "high" at the right end) as described by Dinnella et al. 2013. During each run, subjects were instructed to chew the sample as they would normally do. The panellist indicated the moment of swallowing by pushing the button 'end'. The panellists were instructed to immediately press the "Next" button to reach the next TDS screen containing the list of attributes relating to after-feel sensations and rate dominance until the end of the after-feel perception. The participants evaluated the eight gels in triplicate, in a balanced design split in two session of one hour each.
At each time point dominance and intensity of each attribute per panellist per run was recorded. Data from each subject were standardised according to individual mastication durations on a scale from 0 (start of mastication) to 100 (end of mastication). Dominance rates, known as the proportion of panellists who scored an attribute as dominant, were calculated and visualized in dominance curves following Pineau et al. 2009. The line of chance level i.e. the theoretical proportion of subjects selecting an attribute at random (1/8 attributes=0.125) and the significance level at $P<0.05$ (calculated to be 0.224) were plotted in the dominance curve graphs.

A PCA on the standardised TDS data was performed (The Unscrambler® X software V10.2, CAMO software, Norway) to describe the succession of perceptual events that happen in mouth during mastication and to obtain the sensory trajectories (Lenfant et al. 2009). The loadings of the PCA plot were the sensory attributes. The plot contained ten time points per sample, representing 10%, 20%, ..., 90%, 99% of the mastication period. The observations were the dominance rates at the according time point of the mastication period following the procedure described by Lenfant et al. 2009. In addition, TDS scores for each attribute were calculated by averaging the rated intensity of the attribute over the all-time of each run. When an attribute was not rated, the value 0 was taken. The correlation of the data matrices of TDS and QDA methods was analysed by the Regression Vector (RV) coefficient (Labbe et al. 2009; Ng et al. 2012). The RV coefficient was calculated using FactoMiner in R language. In addition, Pearson correlation coefficients between QDA values and TDS scores were calculated in SPSS for each TDS attribute.

2.3. Results and Discussion

2.3.1. Mechanical properties of gels

Figure 2.1.A shows the instrumentally determined fracture stress and strain of all gels. A clear distinction in fracture stress and fracture strain between the gels is observed which corresponds to the study design (Table 2.1). High and low stress gels varied by a factor of around 2.2, high and low strain gels varied by a factor of around 1.9. The Tween 20 sample and WPI sample had adjusted gelling agent concentrations in order to compensate the effect of the emulsifiers on mechanical properties. Even though gels were significantly different in values for fracture stress and strain between the two emulsifiers for some of the four fracture stress and strain combinations, these differences were minor compared to the difference between the high and low fracture stress and the high and low fracture strain values. We conclude that the study design (Table 2.1) was realized and two distinct conditions for fracture stress and fracture strain were obtained for the Tween and WPI containing samples.

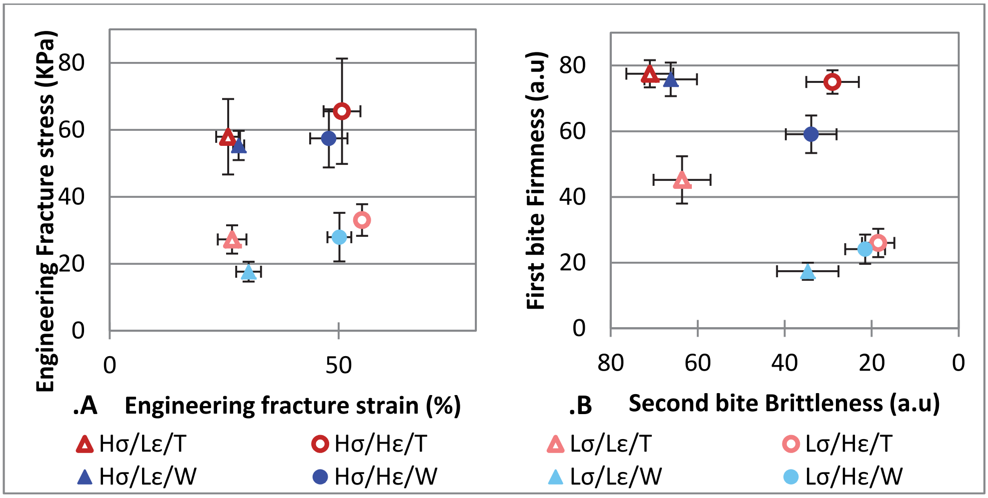


Figure 2.1.A Fracture stress and strain of all gels. Legend is explained in Table 2.1. Data points represent the average of 9 measurements. Error bars indicate the standard deviation. B. Perceived first bite Firmness and second bite brittleness (scale in reverse order) of all gels obtained by QDA. Mean intensities of the QDA profiling (n=12, triplicate) are shown with standard deviation.

The Young's modulus of gels prepared without and with (20 Wt%) sunflower oil are reported in Table 2.2. It can be seen that gels containing 20 Wt% oil emulsified with Tween 20 had a lower Young's modulus than gels without oil. The droplets stabilized by Tween 20, which is an uncharged emulsifier, were unbound to the gel matrix and consequently reduced the Young's modulus of the emulsion-filled gel (Dickinson, 2012). Tween 20 stabilized emulsion droplets can be considered as inactive fillers due to the absence of interactions with the gel matrix (unbound oil droplets). Gels containing 20 Wt% oil emulsified with WPI had a higher Young's modulus than gels containing 0 Wt% oil with the exception of gel Hσ/Lε/W which had a lower Young's modulus for the 20 Wt% oil concentration emulsified with WPI gel compared to the 0 Wt% oil concentration. As WPI is negatively charged at the average pH of the gels (pH=6.0±0.8), WPI interacts with the positively charged gelatine matrix and consequently acts as an active filler that increases the Young's modulus of the gel (Sala, 2007a). The gel Hσ/Lε/W did not contain gelatine (see Table 2.1) but agar as the uncharged gelling agent which resulted in oil droplets being unbound to the gel matrix. We conclude that the experimental, full factorial design (2x2x2 variation of fracture stress, fracture strain and binding properties of oil droplets to the matrix) was realized with the exception of gel Hσ/Lε/W that appeared to contain unbound oil droplets while it was aimed to contain bound droplets.

Table 2.2 Young's modulus of gels with 0 and 20 Wt% emulsion. Mean values ± standard deviation are shown.

Gel	Young's modulus [kPa] Gel matrix with 0 Wt% oil	Young's modulus [kPa] Gel matrix with 20 Wt% oil	Binding properties of oil droplets to gel matrix
Hσ/Lε/T	298±5	163±20	unbound
Hσ/Hε/T	43±2	41±2	unbound
Lσ/Lε/T	135±14	90±6	unbound
Lσ/Hε/T	27±6	13±1	unbound
Hσ/Lε/W	297±15	162±16	unbound
Hσ/Hε/W	30±2	48±4	bound
Lσ/Lε/W	28±1	46±1	bound
Lσ/Hε/W	3±1	21±2	bound

2.3.2. Oil release from gels under mechanical compression

Figure 2.2 shows the relative oil release from all gels upon mechanical compression. At 20°C, only gels that contained unbound oil droplets (Table 2.2) released more than 2 Wt% of oil from the matrix upon compression. The fracture properties of gels influenced slightly the oil release. Gels with a low fracture strain tended to release more oil than gels with a high fracture strain but this effect was not statistically significant (p=0.08). In the case of the gels Hσ/Lε/W and Hσ/Lε/T, which have the same breakdown properties and binding properties but different emulsifiers, the gels containing WPI released half the oil than the gels with Tween 20 suggesting that the emulsifier has an impact on oil release. At 37°C, which is close to the in mouth temperature, all gels released more oil than at 20°C (p=0.000). Gels with bound droplets also released between 5-55% oil. This could be explained by partial melting of the gelatine at elevated temperatures. These results suggest that by melting the gels at 37°C, oil droplets bound to the matrix are released from the gel matrix.

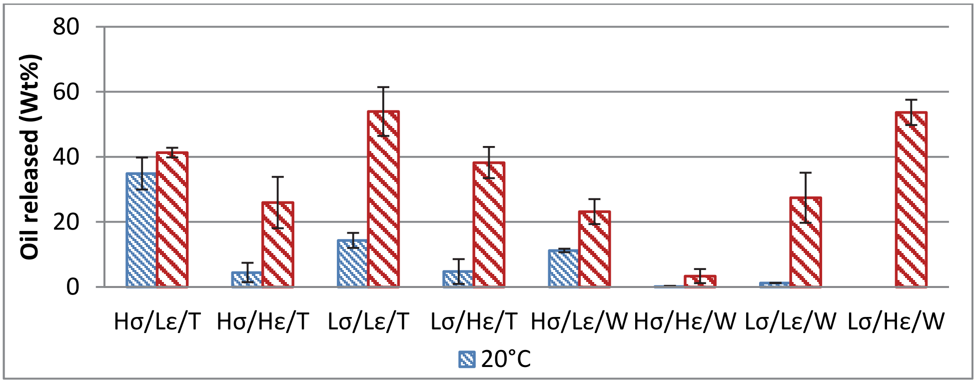


Figure 2.2 Percentage of oil released from gels in gram of oil released over total mass of oil present in the gel. Oil was released by pushing the gel though a syringe orifice. Averages of 3 measurements are shown with error bars indicating the standard deviation.

2.3.3. Sensory assessment

2.3.3.1. QDA

Table 2.3 summarizes the sensory attributes generated by the trained QDA panel together with their definitions. Texture attributes were divided into first bite and chew down attributes, texture attributes perceived during the chew down of the product as mouth-feel attributes and after-feel texture attributes perceived after swallow.

Appendix 2.1 provides an overview of the mean QDA intensity scores with standard deviations and results from the post-hoc tests of all products and attributes. Gels were perceived significantly different in taste and texture attributes but not in odour attributes. Gels with a low fracture stress were generally perceived sweeter than gels with a high fracture stress. Gels containing Tween 20 were perceived less sweet than gels containing WPI. Tween 20 is known to be a bitter compound. Bitterness was perceived with significantly higher scores for gels containing Tween 20 compared with gels containing WPI. For texture perception, gels differed significantly in first bite, second bite and chew down attributes. At first bite, perceived firmness is known to be often related to fracture stress (Gwartney et al. 2004; Foegeding et al. 2011), whereas brittleness can be related to fracture strain, but this relationship is more complex and less straightforward. The definition of brittleness used in this study was “how quick the product breaks when crushed”, which is opposite to “deformability” as described by Barrangou et al. and which could be related to strain at fracture (Barrangou et al. 2007a and 2007b). Stress and strain at fracture were the two controlled fracture properties of the gels that were designed in order to control respectively firmness and brittleness at first/second bite (see Figure

Table 2.3 List of attributes generated during the training of QDA and definitions used in the QDA assessment

Attribute group	Attribute	Definition
Odour	Intensity	Total quantity of odour
	Vanilla	Chemically, as artificial flavouring
	Sour	Like cottage cheese
Taste	Intensity	Total quantity of taste
	Sweet	Basic taste and of artificial sweetener
	Caramel	Like roasted sugar
	Vanilla	Chemically, as artificial flavouring
	Bitter	Basic taste
First bite	Sticky	Sticky, clinging to the teeth
	Firm	Effort needed to bite off
	Elasticity	Resilient when bitten off, like a rubber band
Second bite	Brittle	How quick the product breaks when crushed
Chew down	Sticky	Clinging in the mouth
	Elasticity	Resilient, like a rubber band
	Smooth	Slippery
	Moist	Watery
	Rough	Hairy teeth, like eating rhubarb
	Prickle	Pepper-like sensation
	Astringent	Tart, like from unripe apple and quince
	Spreadable	Unctuous, like chocolate spread
	Creamy	Product feels full, soft, velvety
	Fatty	Oil-like
	Melting	Dissolves, structure disappears like in ice cream
	Grainy	Grains such as semolina
	Powdery	Mealy, like uncooked corn starch in water
	Lumpy	Product has small soft lumps
	Refreshing	Cold feeling in the mouth, like eating peppermint
	Clean	Effort to clean the mouth
After-feel	Creamy	Product feels full, soft, velvety
	Fatty	Oil-like
	Rough	Hairy teeth, like eating rhubarb
	Prickle	Pepper-like sensation
	Tingling	Like soda water
	Residue	A substance remains
Aftertaste	Fatty	Oil-like
	Rough	Hairy teeth, like eating rhubarb

2.1.A). Results show that fracture stress was positively correlated with perceived firmness (R^2=0.83, regression not shown) and fracture strain was negatively correlated with perceived brittleness (R^2= 0.81, regression not shown). In the case of Lσ/Lε/W and Lσ/Lε/T, the sensory results were not completely in line with the texture analyser data (see Figure 2.1.B). Lσ/Lε/W was perceived firmer than other gels with a low fracture stress, whereas Lσ/Lε/T was perceived less brittle than other gels with a low fracture strain. Small differences between gel might be noticeable when the intensity of the stimuli is low, which might have been the case for those samples that showed small differences at a low fracture strain and a low fracture stress (Figure 2.1). In general, it can be concluded that first bite attributes were controlled by fracture properties of the gels. Chew down attributes were scored significantly differently for different gels demonstrating that the design of the gels influenced perception of texture attributes perceived at later bites. The attribute creaminess showed significant variations between samples and was correlated to spreadable, fatty, melting, fatty after-feel and creamy after-feel attributes. After-feel attributes also varied and were correlated to the mouth-feel corresponding attribute, e.g. fatty after-feel was correlated to fatty mouth-feel.

Figure 2.3 demonstrates that the two principal components explain 96% of all the variation between the samples. It is shown that perception of texture attributes at later bites varied depending on the gels fracture properties. After first bite, the gels are broken down by oral processing and parts of the dynamic aspects of this breakdown can be measured by QDA (Szczesniak, 2002). Moreover in the PCA gels varying in emulsifier are not separated from each other. These results would suggest that the emulsifier type did not influence perception of chew down attributes. As most WPI gels were bound and all Tween 20 gels were unbound, it can be extrapolated that binding of the oil to the gel matrix had a very small effect on perception of chew down attributes, including the perception of fatty related attributes.

The attributes tough and elastic were perceived in gels with a combination of high stress and high strain. In the opposite, smooth, moist and refreshing were perceived in low stress and low strain gels. The perception of moist and refreshing might be related to the gel composition, as the Lσ/Lε gels contained more water than the Hσ/Hε gels (see Table 1.1). Gels with lower water concentrations (Hσ/Hε) were negatively correlated with moist and refreshing. Lumpy and grainy perception were found in gels combining high stress with low strain (Hσ/Lε i.e. gels containing only agar. Reversely, spreadable and creamy were perceived in Lσ/Hε gels. Furthermore, it was observed that low stress and high strain samples broke down with a relatively small force enabling product breakdown by squeezing the sample against the palate by the tongue. In this study the fracture stress of

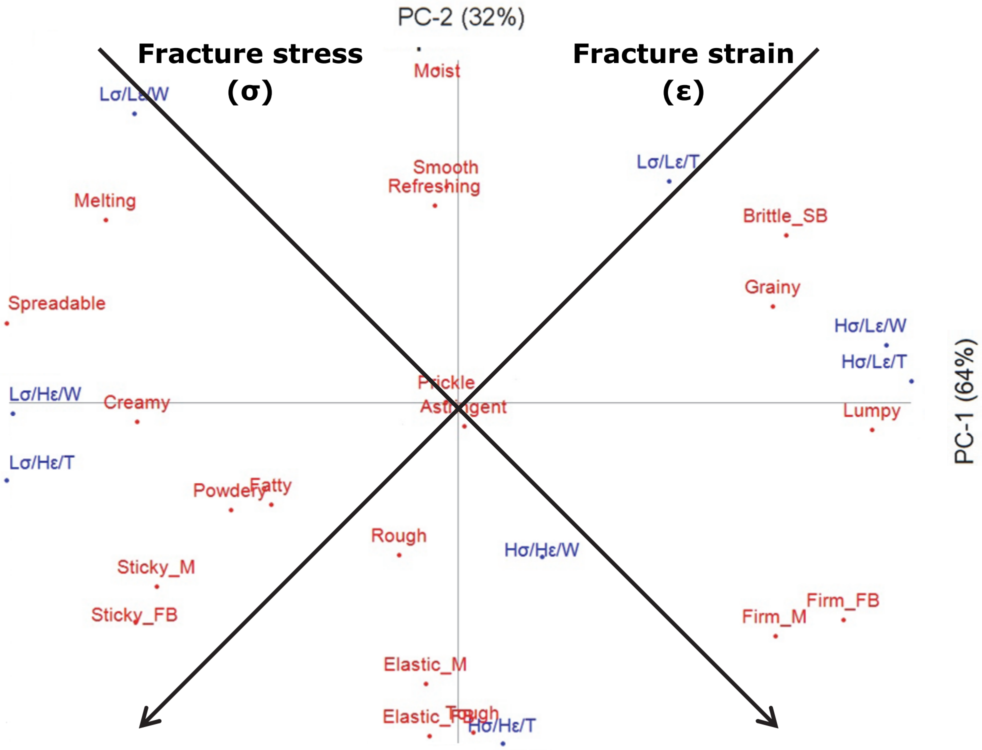


Figure 2.3 Principal Component Analysis of all texture attributes obtained from QDA. FB indicates first bite attributes, SB second bite and M indicated chew down attributes. All sensory attributes are shown in red, all gels shown in blue.

gels Lσ/Hε were 13 and 21 kPa which was relatively close to 16 kPa which is known as the value below which gels are broken down by palatal reduction for non-melting gels (Foegeding et al. 2011). The combination of a low fracture stress and a high fracture strain probably accounted for the formation of a pasty gel between the tongue and the palate that were perceived as creamy and spreadable. The perceived graininess of Lε gels was expected due to the formation of lumps and little particles as the gels broke down into many small pieces (Sala et al. 2013). Whereas in agar gels fracture properties correlated with sensory attributes perceived in mouth (Barrangou et al. 2007a and 2007b), in the emulsion-filled gels used in this study, few attributes correlated with fracture properties. Firmness was correlated with fracture stress and stickiness was correlated with fracture strain. Complex attributes such as creaminess, smoothness, spreadability and elasticity did not depend on only one fracture property. These results are in agreement with literature where chew down sensory attributes are usually not correlated to fracture properties (Foegeding et al. 2011; Stieger and van de Velde, 2013). Moreover, the combinations of stress and strain were obtained by mixing two distinctive gelling agents (agar and gelatine). Other physical-chemical properties of the gels used in this study might have varied depending on the gelling agents' concentrations and type. Agar reveals brittle fracture behaviour and does not melt at mouth temperature, whereas gelatine displays ductile fracture behaviour and melts at mouth temperature (at least the surface of gelatine gel fragments melt in the mouth). These properties might have influenced dynamic texture perception in addition to the fracture properties. In our experimental design, the effect of the gelling agents and the effect of fracture stress and fracture strain on dynamic texture perception cannot fully be separated from each other. Further studies with different model systems and controlled fracture properties might confirm the obtained results and rule out specific ingredient properties.

The bound and unbound samples of gels Hσ/Hε, Hσ/Lε and of Lσ/Hε showed similar sensory profiles, indicating a minor effect of the used emulsifiers. In gels with Lσ/Lε however, there was a considerable difference between the bound and unbound samples: bound samples were correlated with melting, whereas the unbound gels were correlated with brittleness. A variation in perception at first bite attributes was observed in these gels, which might explain the variation in perception of attributes perceived at later stages of mastication. The small observed perceptual differences between gels varying in oil binding properties suggest that fracture properties and breakdown or melting of the gelatine matrix have a larger impact on perception of fat related sensory attributes than oil droplet release in the semi-solid gels studied here.

2.3.3.2. Progressive profiling

2.3.3.2.1. Mastication time

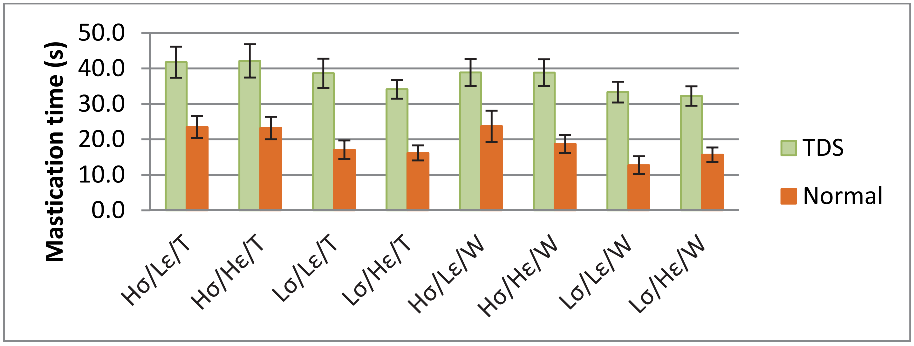


Figure 2.4 Average mastication time of gels (n=12) before swallowing of the samples during TDS and during "natural" chewing conditions ± standard error of the mean.

The oral processing time of panellists, when asked to chew freely on the gels until swallowing naturally, is reported in Figure 2.4. The average chewing time for soft gels (15.4±7.3 s) was significantly shorter ($p=.000$), compared to hard gels (22.3±10.5 s), which suggests that harder gels needed longer oral processing to ensure a comfortable and safe swallow. Fracture strain did not significantly influence chewing time ($p=.381$). Our results are in good agreement with previous research where an increase of fracture stress increased mastication time and fracture strain had no impact on eating time of gels (Çakır et al. 2012). Based on the mastication time determined under free mastication conditions, it was decided to evaluate gels for progressive profiling at 5, 10, 15 and 20 s of oral processing to cover oral processing duration of all gels.

2.3.3.2.2. Sensory results

In Figure 2.5, perceived firmness decreased continuously with oral processing time for all gels. The observed differences were significant between 5, 10, 15 and 20 seconds for all gels (p=.000). The absolute decrease in firmness was greater for the gels with a high fracture stress than for gels with a low fracture stress. Gels with high fracture stress were perceived firmer compared to gels with low fracture stress gels (p=.000). The gels with a high fracture strain and gels containing Tween 20 were perceived firmer (p=.000) compared to gels with a low fracture strain and gels containing WPI. Despite the small effect of strain and emulsifier, fracture stress seemed to be the most determinant factor for firmness perception over time.

Creaminess increased significantly over time (p=.000) for most gels implying that changes in the bolus structure during oral processing increased the perception of creaminess. As creaminess is a complex attribute, not one gel property alone could explain differences between samples. Increase in fracture stress and fracture strain had both a lowering effect on creaminess perception (p=.000) confirming the results from the QDA test. The emulsifier type had a small but statistically significant effect on creaminess (p=.000) with creaminess being higher for the gel Lσ/Lε/W compared to Lσ/Lε/T.

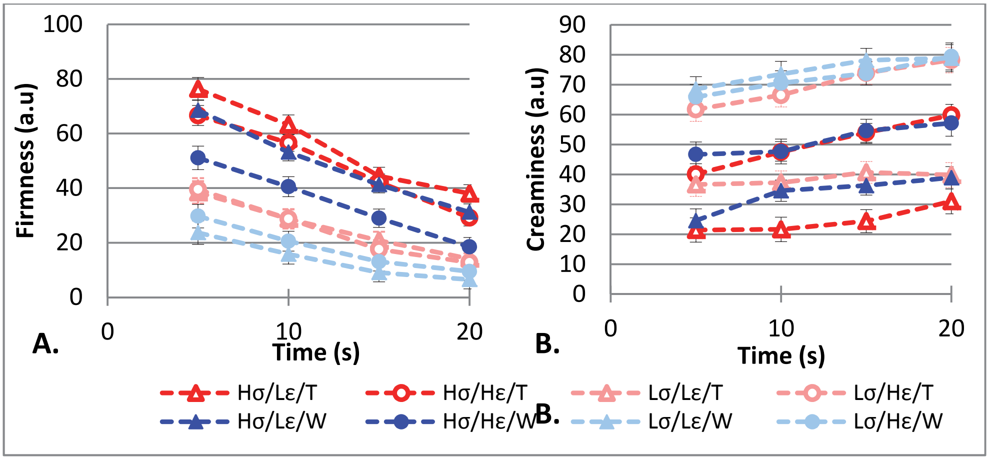


Figure 2.5 Firmness (A.) and Creaminess (B.) determined by progressive profiling (n=10, triplicate). Error bars indicate the standard error of the mean.

2.3.3.3. TDS

2.3.3.3.1. Mastication time

Figure 2.5 shows the averaged mastication time required for the panellists to chew the gels under natural, free chewing conditions in comparison to the chewing time while performing the TDS. The averaged mastication time increased by around 16 seconds for all gels when the panellist performed the TDS evaluation of the gels compared to normal eating condition. This demonstrates that the task instruction of indicating dominant sensory sensations prolonged the eating behaviour since the trained panellists focus on the analytical task of sensory evaluation.

2.3.3.3.2. TDS Dominance curves

Figure 2.6 (A-H) show a similar succession of appearance of dominant sensations in time for all samples with specific attributes appearing at the beginning, the middle and the end of mastication. In general, firmness was perceived at the beginning of mastication as it was found for breakfast cereals and biscuits in previous research (Lenfant et al. 2009; Laguna et al. 2013). Then, elasticity and stickiness were perceived as dominant sensations. These attributes could be rated as first bite or chew down attributes during the QDA. However, it seemed that even as chew down attributes, they were perceived dominant at the beginning of mastication. Close to the end of the mastication process, melting and grainy were experienced as the dominant sensations. Creaminess was only dominant at the end of mastication. The attributes refreshing and moist were dominant at different time points for the various samples. High stress samples could be mainly distinguished from low stress samples by the very large proportion of perceived firmness at the beginning of mastication followed by the dominance of stickiness. At the second half of mastication, low strain samples, which contained high concentrations of agar were perceived grainy, whereas high strain samples, which contained more gelatine were perceived creamy. In general samples containing bound or unbound oil droplets had a similar profile when compared at same fracture stress and strain combinations which was in agreement with the QDA results. The After-feel results can be found in Appendix 2.1. In general, the dominant attribute in the beginning of the After-feel was the last dominant attribute during the TDS at mastication of the gels.

2.3.3.3.3. Sensory trajectories

In Figure 2.7 the sensory trajectories of the dominance curves are summarized in a PCA biplot. 64% of all variance is explained by the first two principal components. It can be seen that dominance rates are a dynamic phenomenon with a common starting point close to the attribute firmness for all gels, followed by a sensory trajectory through the attributes elastic and sticky in case of the Hε gels and moist and refreshing in case of the Lε gels, then grainy and finishing either close to melting in case of the Hε gels or close to

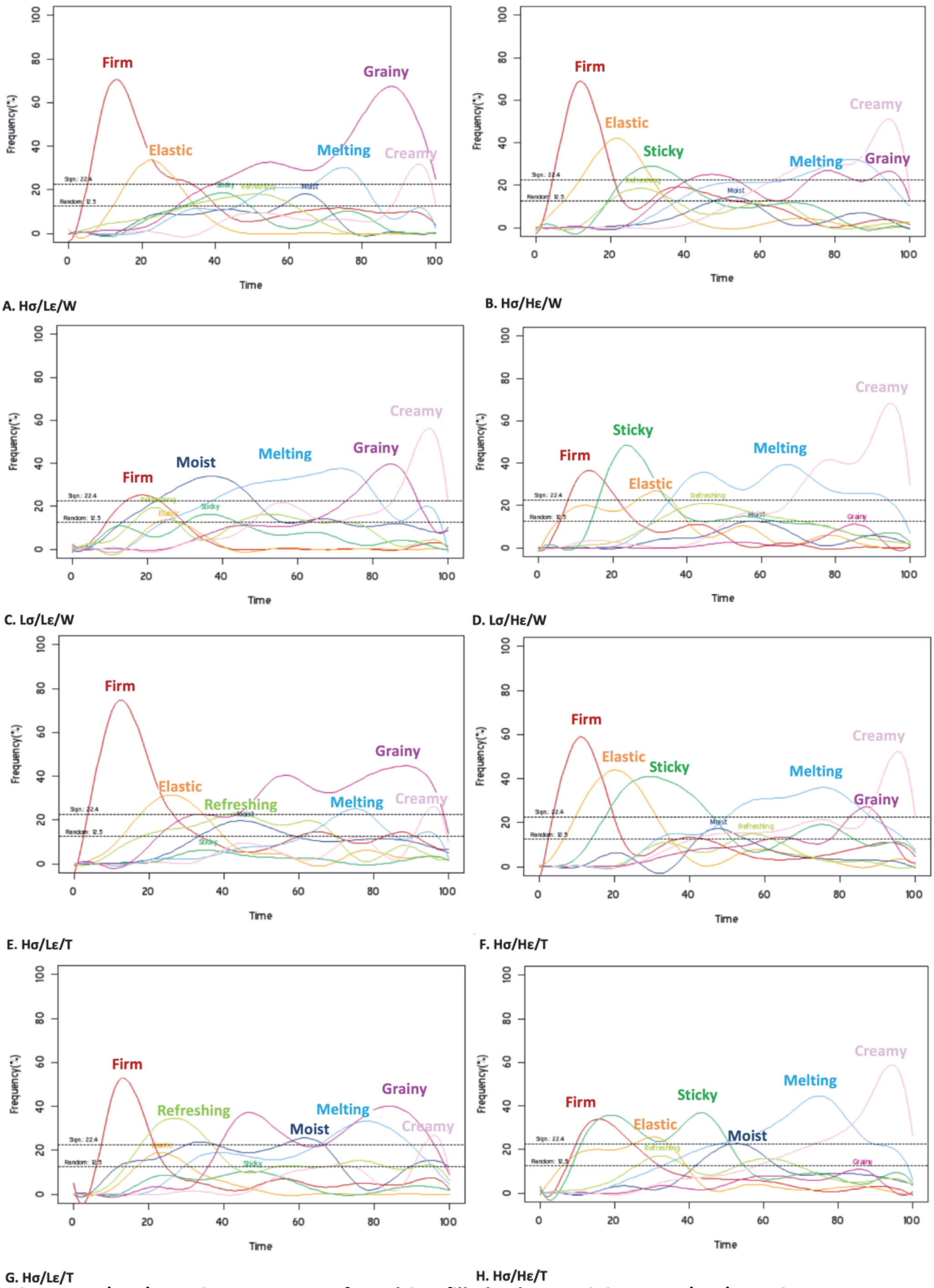


Figure 2.6 (A-D) Dominance curves of emulsion-filled gels containing WPI. (E-H) Dominance curves of emulsion-filled gels containing Tween 20. Time was normalized (% of total oral processing time).

creamy in case of the Lε gels. For gel samples with similar composition, dominance rates are similar at the starting point and the differences become clearer as oral processing time increases, with two distinct end points clearly separating gels with high and low fracture strain.

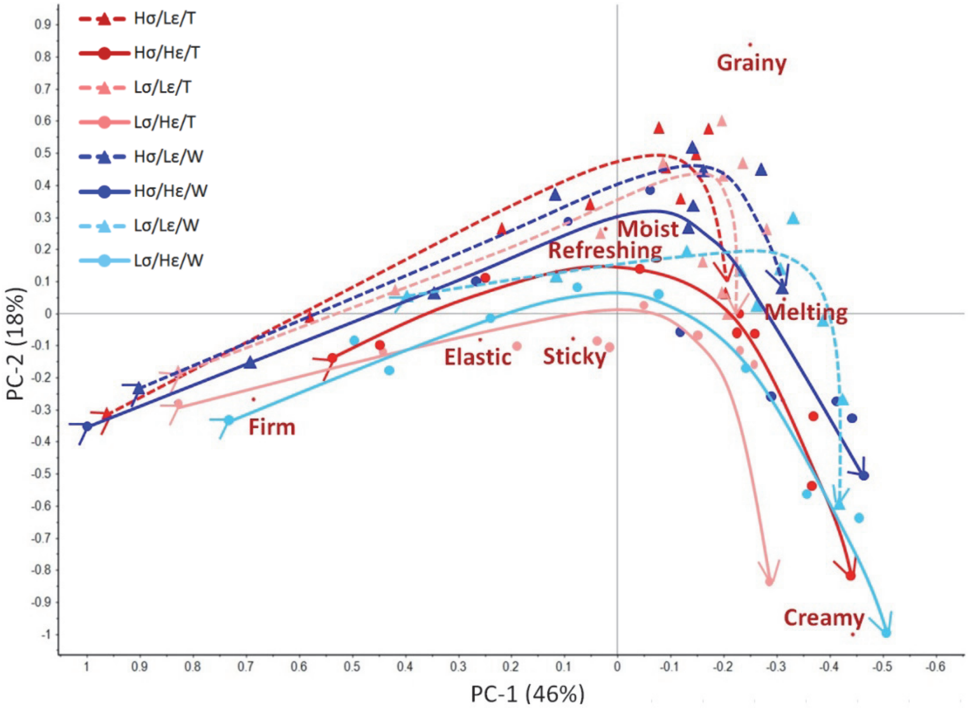


Figure 2.7 TDS sensory trajectories: dominance rates at time intervals of 10% from the beginning of mastication until the end for all gels and attributes. Gels were plotted over TDS sensory attributes in the PCA and lines were drawn to guide the reader.

2.3.4. Comparison between QDA, progressive profiling and TDS

All three sensory methods could similarly discriminate between samples but gave different types of information on the dynamics of texture perception during oral processing. QDA covered the whole sensory space of the samples, from taste to after-feel, including the scoring of 37 attributes. While QDA integrates oral processing by rating different attributes at different times of consumption, this method provides attributes intensities. Progressive profiling and TDS include a time dimension. Progressive profiling gave the intensity of an attribute at a specific time point, which enabled the evolution of this attribute to be followed over time. Due to its time consuming execution, progressive profiling could be used on only a limited number of sensory attributes. However, an advantage of progressive profiling compared to Time Intensity was that little training is required. TDS allowed to rate dominance of 8 attributes during the consumption of only one piece of sample, but this method is limited to up to 10 attributes (Pineau et al. 2012). The order in which attributes were scored was non-instructed and reflected the intuitive perception of the panelists, which is an advantage compared to QDA. Dominance was an insightful measurement to understand dynamic texture, but even though intensity was scored its evolution over the all oral processing time per attribute was not obtained. However, it could be seen that the dominance of attributes appeared at the maximum intensity measured in progressive profiling and that discrimination between samples was similar.

TDS scores could also be calculated (Appendix 2.2) from the TDS data, which were highly correlated to the QDA scores (RV=93.8%, P=0.001) as it had also been shown in previous studies in other foods (Labbe et al. 2009). Pearson correlations showed that all attributes were highly correlated between the two methods except for the after-feel attributes (Appendix 2.3). These similarities showed that TDS can substitute the QDA for the 8 attributes perceived during chew down of the gels. However, QDA gave insight into many attributes that could be measured neither by TDS nor by progressive profiling. For example, brittleness could only be calculated by TDS at first bite and was a key attribute to validate the impact of gel fracture properties on first bite perception. These results lead to the conclusion that these methods are complementary and can be used together or separately, depending on the research question. The use of TDS and QDA as complementary methods was already recommended in previous studies (Meillon et al. 2009; Ng et al. 2012).

In this study, QDA was used before TDS, as it was described previously (Ng et al. 2012). The sensory attributes used in TDS could be selected from the many attributes generated during the training sessions of the QDA panel. However, considering these results, a different approach might be considered to develop a QDA test. The TDS showed a recurrent succession of attributes for all gel samples. This succession implied that when freely assessing the texture of the gels, panelists considered some attributes as dominant in the beginning of mastication, some in the middle and the others at the end. This order corresponded to the order generated during the QDA training sessions by the panelists in order to rate attributes during the QDA test. For example, firmness and elasticity were first bite attributes. Even though the assessment protocol of attributes is discussed during the training of the QDA, it is mostly subjectively developed. TDS could be used on key attributes to optimize the QDA protocol by indicating when these attributes are more likely to be assessed correctly. However, QDA generates an attribute list in the first training, which was used to select attributes for the TDS. The use of both methods in parallel would then be advised.

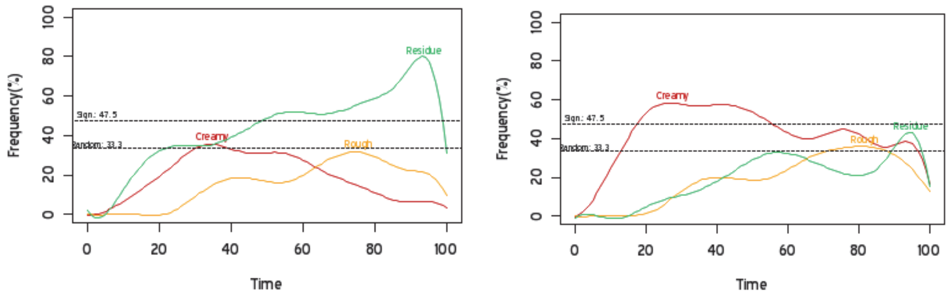
2.4. Conclusion

In this study, the perception of sensory texture was confirmed to be a dynamic phenomenon during oral processing for emulsion-filled gels. First bite attributes could be correlated to fracture properties of gels. Attributes perceived during the chew down of the gels could be explained by gel fracture properties, but could not be correlated to one fracture property only, as the gels ware broken down in the mouth by mastication. Some attributes were dominant at the beginning of mastication, such as firmness, and other attributes at the end of mastication, such as creaminess or graininess. Intensity of creaminess and firmness varied over mastication time, which might explain differences in the times when attributes became dominant. Perception of creaminess could be increased by a combination of low fracture stress and high fracture strain and was not impacted by binding of oil droplets to the gel matrix. Mainly fracture strain influenced dynamic texture perception of gels during chew down with melting and creamy perception in high fracture strain samples and grainy perceptions in low fracture strain samples. However, our experimental design does not allow to fully separate the effects of the ratio and concentration of the two gelling agents used (agar vs gelatine; brittle vs ductile fracture; non-melting vs melting) from the effects of fracture stress and fracture strain on dynamic texture perception. All three sensory methods were relevant in assessing the dynamics of texture perception and complemented each other's. QDA covered the entire sensory space and incorporated oral processing by instructing panelists when to rate which attribute. TDS and progressive profiling provided evolution of perception over time, respectively rating dominance of attributes and intensity of the attribute. However, it is unclear which are the mechanisms inducing the differences in texture perception during chew down. It is recommended to investigate this subject in a following study.

Appendix 2.1 Average intensity score of QDA attributes (n=12, triplicate) ± standard deviation; different superscript letters indicate that products are significant different at P<0.05.

Group	Attribute	Hσ/Lε/T	Hσ/Hε/T	Lσ/Lε/T	Lσ/Hε/T	Hσ/Lε/W	Hσ/Hε/W	Lσ/Lε/W	Lσ/Hε/W
Odour	Intensity	52.0 ±19.2	55.8 ±21.2	50.9 ±20.5	54.1 ±21.5	59.3 ±17.8	52.1 ±20.4	51.8 ±22.1	52.4 ±20.0
	Vanilla	41.9 ±22.3	33.6 ±21.9	42.4 ±20.5	36.6 ±25.6	48.4 ±26.9	44.2 ±24.^{A}	46.0 ±25.7	37.8 ±21.4
	Sour	23.6 ±16.7^{BC}	42.4 ±26.5^{A}	28 ±22.5^{BC}	39.4 ±24.4^{A}	26.9 ±16.8^{BC}	27.5 ±18.2^{BC}	21.3 ±13.5^{C}	28.7 ±21.1^{B}
Taste	Intensity	45.9 ±19.4^{DE}	53.6 ±21.2^{BC}	51.0 ±17.7^{CD}	58.5 ±21.7^{AB}	44.8 ±18.8^{DE}	40.3 ±16.5^{E}	62.3 ±17.5^{A}	59.5 ±16.5^{AB}
	Sweet	39.6 ±18.9^{D}	41.4 ±20.1^{D}	50.0 ±19.2^{BC}	53.8 ±23.8^{B}	44.5 ±19.8^{CD}	39.6 ±17.2^{D}	63.9 ±18.1^{A}	62.1 ±14.2^{A}
	Caramel	24.9 ±13.8^{F}	28.2 ±22.1^{CDEF}	26.0 ±16.2^{EF}	32.0 ±24.7^{CDE}	33.0 ±17.5^{BCD}	34.7 ±17.3^{BC}	38.9 ±21.2^{B}	46.3 ±22.2^{A}
	Vanilla	26.0 ±12.6^{D}	32.0 ±19.0^{CD}	34.3 ±19.1^{BC}	39.5 ±26.4^{B}	36.5 ±20.1^{BC}	40.5 ±18.8^{B}	52.9 ±21.4^{A}	52.6 ±19.4^{A}
	Bitter	39.8 ±25.5^{A}	45.6 ±20.7^{A}	41.3 ±23.0^{A}	45.4 ±25.3^{A}	17.0 ±8.3^{B}	17.2 ±12.6^{B}	20.6 ±16.8^{B}	13.9 ±5.5^{B}
First bite	Sticky	19.9 ±12.2^{E}	60.3 ±25.9^{C}	20.4 ±9.4^{E}	74.2 ±18.8^{A}	20.2 ±11.6^{E}	46.4 ±21.6^{D}	41.6 ±23.6^{D}	66.5 ±21.4^{B}
	Firm	77.5 ±14.3^{A}	75.0 ±12.4^{A}	45.2 ±24.9^{C}	26.0 ±14.9^{D}	75.8 ±17.7^{A}	59.1 ±19.8^{B}	17.4 ±9.0^{E}	24.1 ±15.4^{D}
	Elasticity	34.0 ±24.1^{E}	73.6 ±17.1^{A}	29.0 ±17.9^{E}	50.4 ±27.0^{C}	31.6 ±23.6^{E}	58.1 ±21.8^{B}	16.8 ±11.2^{F}	43.1 ±26.3^{D}
Second bite	Brittle	71.0 ±18.7^{A}	29.0 ±20.9^{C}	63.6 ±22.7^{B}	18.5 ±12.9^{D}	66.2 ±20.9^{AB}	33.9 ±20.2^{C}	34.7 ±24.5^{C}	21.5 ±15.9^{D}
Mouth-feel	Firm	71.2 ±19.7^{A}	73.2 ±13.0^{A}	42.4 ±22.5^{C}	31.2 ±21.6^{D}	68.5 ±20.1^{A}	57.0 ±21.8^{B}	15.5 ±6.2^{E}	27.2 ±18.2^{D}
	Tough	31.6 ±22.7^{DE}	69.8 ±17.7^{A}	17.9 ±10.3^{F}	37.9 ±26.3^{C}	24.9 ±17.8^{E}	46.2 ±23.9^{B}	12.8 ±3.7^{F}	27.4 ±20.6^{DE}
	Sticky	17.9 ±8.0^{D}	57.0 ±24.5^{B}	21.9 ±12.3^{D}	68.2 ±22.4^{A}	19.5 ±9.1^{D}	43.2 ±23.8^{C}	42.5 ±26.8^{C}	61.8 ±23.6^{B}
	Elasticity	32.5 ±21.1^{CD}	64.5 ±21.2^{A}	25.4 ±15.5^{D}	45.8 ±26.2^{B}	25.9 ±17.6^{D}	50.0 ±22.9^{B}	17.6 ±13.4^{E}	37.4 ±20.9^{C}
	Smooth	39.2 ±25.2^{B}	25.5 ±17.7^{D}	56.2 ±25.8^{A}	37.4 ±26.4^{B}	38.9 ±28.8^{B}	28.8 ±17.1^{CD}	59.4 ±23.4^{A}	34.7 ±24.4^{BC}
	Moist	28.7 ±17.9^{CD}	15.8 ±7.8^{E}	61.2 ±20.8^{B}	25.1 ±16.2^{D}	34.0 ±22.5^{C}	18.6 ±10.6^{E}	67.2 ±17.8^{A}	28.7 ±13.7^{CD}
	Refreshing	33.1 ±20.7^{BC}	23.2 ±16.7^{D}	54.6 ±23.6^{A}	35.8 ±20.2^{B}	34.9 ±21.1^{BC}	27.0 ±17.9^{CD}	52.9 ±27.1^{A}	33.4 ±21.6^{BC}
	Rough	26.9 ±13.1^{CD}	46.1 ±21.4^{A}	21.4 ±13.5^{D}	38.6 ±21.8^{B}	21.3 ±13.8^{D}	36.2 ±23.8^{B}	24.0 ±14.1^{D}	32.7 ±23.9^{BC}
	Prickle	27.2 ±20.7^{B}	27.7 ±20.1^{B}	33.9 ±22.1^{A}	34.7 ±22.1^{A}	19.1 ±13.2^{C}	19.4 ±17.0^{C}	22.0 ±19.9^{BC}	21.1 ±18.2^{C}
	Astringent	29.9 ±22.1^{A}	31.2 ±19.3^{A}	33.5 ±24.2^{A}	33.7 ±21.2^{A}	19.5 ±12.8^{B}	21.2 ±19.2^{B}	20.7 ±17.6^{B}	20.9 ±15.9^{B}
	Spreadable	18.9 ±10.3^{D}	35.6 ±22.1^{C}	37.0 ±21.2^{C}	80.1 ±11.4^{A}	19.0 ±7.3^{D}	36.7 ±18.4^{C}	74.5 ±17.0^{B}	81.6 ±9.0^{A}
	Creamy	20.5 ±9.3^{D}	39.5 ±17.9^{C}	26.5 ±15.5^{D}	61.1 ±21.4^{B}	20.6 ±11.2^{D}	40.1 ±20.4^{C}	56.9 ±18.2^{B}	68.8 ±16.7^{A}
	Fatty	19.4 ±9.4^{E}	41.7 ±20.7^{BC}	22.2 ±11.3^{E}	51.2 ±18.7^{A}	21.5 ±11.3^{E}	36.7 ±16.2^{CD}	35.9 ±17.9^{D}	46.3 ±20.2^{AB}
	Melting	18.0 ±8.6^{E}	20.1 ±10.3^{E}	36.1 ±20.1^{C}	61.7 ±22.8^{B}	17.5 ±8.8^{E}	28.5 ±15.9^{D}	73.1 ±15.8^{A}	61.8 ±25.1^{B}
	Grainy	58.9 ±28.2^{A}	23.7 ±18.2^{C}	48.1 ±26.9^{B}	13.5 ±6.4^{D}	63.5 ±25.2^{A}	47.0 ±24.3^{B}	28.7 ±23.1^{C}	15.3 ±8.6^{D}
	Powdery	21.8 ±16.4^{E}	51.1 ±25.8^{BC}	26.9 ±22.7^{E}	55.3 ±27.6^{AB}	26.9 ±21.1^{E}	43.7 ±23.2^{D}	46.4 ±25.5^{CD}	60.2 ±25.2^{A}
	Lumpy	75.5 ±13.2^{A}	53.1 ±27.9^{C}	67.4 ±18.0^{B}	19.0 ±13.4^{D}	70.3 ±13.6^{AB}	58.4 ±20.7^{C}	22.2 ±16.7^{D}	18.9 ±13.3^{D}
	Clean	66.1 ±19.5^{A}	61.8 ±24.4^{A}	45.3 ±24.6^{C}	42.0 ±28.0^{CD}	62.7 ±21.6^{A}	54.0 ±22.9^{B}	32.3 ±24.8^{E}	37.3 ±26.6^{DE}
Aftertaste	Sweet	33.6 ±16.6^{D}	39.6 ± 18.3^{BCD}	39.7 ±19.6^{BCD}	46.6 ±23.2^{B}	41.1 ±18.3^{BC}	45.2 ±20.4^{BC}	66.3 ±17.4^{A}	62.5 ±16.1^{A}
	Bitter	43.9 ±24.0^{A}	40.3 ±21.4^{A}	39.1 ±19.9^{A}	42.5 ±22.9^{A}	18.5 ±10.3^{B}	20.2 ±13.7^{B}	17.5 ±8.7^{B}	16.1 ±9.8^{B}
After-feel	Creamy	22.8 ±13.6^{D}	37.1 ±18.0^{C}	25.9 ±15.5^{D}	49.8 ±24.6^{B}	23.8 ±14.9^{D}	38.6 ±19.7^{C}	50.6 ±22.7^{B}	60.4 ±22.3^{A}
	Fatty	19.3 ±11.0^{C}	42.6 ±21.7^{A}	24.3 ±11.9^{C}	42.3 ±21.9^{A}	20.6 ±11.0^{C}	31.2 ±18.3^{B}	31.8 ±17.3^{B}	39.4 ±19.5^{A}
	Rough	33.8 ±21.2^{B}	42.4 ±21.3^{A}	32.7 ±17.6^{B}	37.6 ±22.9^{AB}	30.7 ±21.9^{B}	44.6 ±25.0^{A}	30.9 ±23.6^{B}	34.9 ±1207^{B}
	Prickle	33.0 ±22.7^{A}	29.6 ±19.2^{A}	33.6 ±20.1^{A}	31.2 ±20.0^{A}	18.2 ±12.9^{B}	20.6 ±13.4^{B}	18.0 ±12.3^{B}	21.7 ±21.2^{B}
	Tingling	31.8 ±19.5^{AB}	27.0 ±17.4^{BC}	36.2 ±20.4^{A}	32.4 ±19.4^{AB}	19.0 ±11.0^{D}	19.8 ±14.0^{D}	18.7 ±13.6^{D}	22.1 ±16.1^{CD}
	Residue	45.3 ±25.4^{A}	41.1 ±25.3^{ABC}	29.5 ±19.0^{DE}	34.4 ±26.1^{CD}	44.0 ±26.3^{AB}	38.9 ±24.3^{ABC}	25.4 ±21.0^{E}	37.2 ±26.5^{BCD}

Appendix 2.2 TDS dominance curves on after-feel perception of Hσ/Lε/Bo (left) and Lσ/Hε/Bo (right). Time was normalized (% of total oral processing time).



Appendix 2.3 TDS scores

Gel Attribute	Hσ/Lε/T	Hσ/Hε/T	Lσ/Lε/T	Lσ/Hε/T	Hσ/Lε/W	Hσ/Hε/W	Lσ/Lε/W	Lσ/Hε/W
elastic	30.37 ± 34.53^{CD}	62.02 ± 30.04^{A}	9.46 ± 16.44^{B}	48.49 ± 36.92^{AC}	15.69 ± 25.15^{BD}	52.95 ± 37.3^{A}	10.00 ± 23.52^{B}	33.93 ± 33.74^{C}
grainy	71.16 ± 26.24^{A}	30.05 ± 31.00^{C}	46.9 ± 26.27^{B}	8.28 ± 15.43^{D}	72.33 ± 19.04^{A}	47.51 ± 30.73^{C}	30.93 ± 28.59^{B}	9.5 ± 17.58^{D}
sticky	12.79 ± 24.31^{D}	47.13 ± 36.36^{BC}	14.24 ± 25.59^{D}	63.99 ± 35.00^{A}	21.1 ± 31.46^{DE}	30.81 ± 33.35^{CD}	36.22 ± 38.62^{CD}	54.17 ± 31.96^{AB}
creamy	15.16 ± 21.53^{C}	54.41 ± 33.17^{B}	19.45 ± 26.99^{C}	61.03 ± 34.39^{AB}	21.37 ± 28.99^{C}	55.66 ± 31.36^{B}	55.79 ± 31.53^{B}	72.67 ± 30.81^{A}
melting	19.38 ± 24.96^{D}	51.33 ± 31.98^{B}	53.94 ± 34.97^{B}	69.59 ± 30.46^{A}	30.86 ± 33.68^{CD}	39.26 ± 32.7^{BC}	78.69 ± 28.65^{A}	74.98 ± 25.32^{A}
firm	67.6 ± 36.616^{AB}	77.35 ± 23.34^{A}	28.34 ± 30.59^{C}	15.26 ± 22.35^{CD}	54.2 ± 34.33^{B}	59.59 ± 27.32^{B}	13.47 ± 25.89^{D}	14.56 ± 21.97^{CD}
moist	41.16 ± 32.12^{AB}	16.75 ± 26.07^{D}	52.26 ± 33.05^{A}	34.46 ± 38.09^{BC}	22.63 ± 29.41^{BCD}	27.48 ± 31.88^{BD}	33.84 ± 34.61^{BC}	31.19 ± 33.3^{BD}
refreshing	31.36 ± 29.49^{B}	16.77 ± 23.77^{CD}	64.49 ± 22.64^{A}	28.06 ± 35.77B^{C}	25.37 ± 28.03B^{D}	12.43 ± 18.93^{D}	65.84 ± 25.29^{A}	14.76 ± 23.94^{CD}

After-feel

creamy	10.72 ± 19.11^{C}	74.05 ± 21.24^{A}	24.92 ± 27.42^{B}	71.39 ± 23.36^{A}	28.13 ± 30.58^{B}	68.45 ± 21.27^{A}	68.76 ± 25.09^{A}	75.98 ± 19.17^{A}
residue	66.53 ± 21.09^{A}	29.98 ± 32.88^{BC}	34.06 ± 30.7^{BC}	17.25 ± 27.02^{C}	60.38 ± 23.88^{A}	25.13 ± 28.42^{BC}	21.55 ± 27.4^{BC}	18.61 ± 28.16^{C}
rough	25.81 ± 28.71^{A}	31.78 ± 29.8^{A}	27.96 ± 28.73^{A}	22.72 ± 26.24^{A}	22.25 ± 31.54^{A}	21.24 ± 27.51^{A}	18.04 ± 29.49^{A}	23.27 ± 31.54^{A}

Appendix 2.4 Pearson correlations for sensory attributes between QDA and TDS

Elasticity	Grainy	Sticky	Creamy	Melting	Firm	Refreshing	Moist	After-feel		
								residue	creamy	rough
.903**	.993**	.912**	.996**	.966**	.973**	0.661	.750*	0.654	0.412	0.359

**. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed)*

CHAPTER 3

Dynamic texture perception and oral processing of semi-solid food gels:

Part 2: Impact of breakdown behaviour on bolus properties and dynamic texture perception.

3

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Abstract

Food texture perception depends on food structure and oral processing behaviour. The aim of this study was to explain dynamic texture perception of emulsion-filled, semi-solid gels by properties of the boli formed during three stages of oral processing. Texture perception of emulsion-filled gels varying in fracture stress and strain was found to be a dynamic process. Specific texture attributes were perceived as dominant sensations in the beginning (firm), middle (moist, refreshing, elastic, and sticky) and end of oral processing (grainy, melting, and creamy). In the beginning of oral processing mechanical properties of the boli, such as first penetration peak force and flowability, were correlated to sensory firmness. In the middle of oral processing, correlations between boli properties and texture perception were more complex. Perception of moist and refreshing was related to mechanical properties of the boli, such as flowability, rather than to the amount of saliva incorporated into the boli. Perception of elastic and sticky was related to the mechanical bolus properties resilience and adhesiveness. In the end of oral processing, emulsion-filled gels were perceived either as creamy or grainy. Gels perceived as creamy revealed a high bolus flowability while gels perceived as grainy consisted of boli with a high number of broken down particles. We conclude that bolus formation and changes in the properties of the bolus underlay the changes in texture perception during oral processing.

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3.1. Introduction

Food oral processing is an essential process contributing to sensory perception of food, especially to perception of texture (Chen, 2009). As food is broken down during mastication, its properties constantly change leading to variations of texture perception in time. The main phenomena contributing to dynamic texture perception are the reduction in degree of structure and increase in degree of lubrication of foods. Those two processes contribute to the formation of a safely ready to swallow food bolus (Hutching and Lillford, 1988). Bolus properties depend on the physical and chemical properties of food and the physiological characteristics of the mastication process (Foster et al. 2011). Understanding bolus formation through *in vivo* studies has been suggested to increase understanding of dynamic texture perception (Wilkinson et al. 2000).

A wide range of methodologies is nowadays available to characterise the physical and chemical properties of food boli. The structural breakdown of boli has been studied by particle size analyses with methods, such as sieving (Peyron et al. 2011; Guo et al. 2013) and image analysis (Hutchings et al. 2011; Mosca et al. 2012; Chen, 2013). Depending on the consistency and rheological properties of boli which vary largely between different foods, various instrumental texture characterization methods have been applied including modified Texture Profile Analysis (TPA) of cereal boli (Peyron et al. 2011), oscillatory small deformation rheology of bread boli (Le Bleis et al. 2013), force-displacement mechanical testing of model cheese boli (Drago et al. 2011) and shear rheology of meat boli (Yven et al. 2005). The methodology chosen depends on the physical properties of the boli, mainly its homogeneity and cohesiveness which can vary strongly between foods depending on the level of mastication. Information that could be related to lubrication properties of food boli was obtained by quantifying saliva and dry matter content of boli (Loret et al. 2011). Release of oil from the boli during mastication was quantified (Guo et al. 2013). The lubrication properties of boli were determined using tribological measurements on soft, semi-solid foods, such as custard desserts (de Wijk et al. 2006a and 2006b). Tribological measurements are unlikely to be applicable to boli containing inhomogeneous, solid particles. The diversity of tests used to characterize the breakdown and lubrication properties demonstrates the need to adapt the characterization method to the specific properties of the bolus, which can differ considerably between foods depending on degree of breakdown. Bolus properties have been extensively studied, especially at the end point of oral processing to understand the mechanisms that trigger swallowing (Peyron et al. 2011; Chen and Lolivret, 2011; James et al. 2011; Loret et al. 2011). In addition, taste and aroma perception in relation to bolus properties (Loubens et al. 2010; Mosca et al. 2010) have been investigated. Correlations between bolus properties and taste and aroma release were difficult to obtain (Tarrega et al. 2011). Oral processing behaviour including muscle activity and jaw movements during mastication have been related to texture perception of gels (Çakır et al. 2012). Çakır et al. observed that sensory firmness was correlated to muscle activity at first bite. Sensory attributes perceived during chew down were related to jaw opening velocity and cycle duration of the first five chewing cycles. Jaw movement amplitudes of the later chewing cycles were related to after-feel sensory attributes. Despite the importance of understanding dynamic sensory perception through bolus properties throughout an entire mastication cycle, only few studies have related bolus properties to dynamic texture perception. Seo et al. (2007) identified two sensory cues, slipperiness and compliance, which were linked to bolus rheological properties at swallowing point. Cereal boli properties at intermediate mastication times were measured together with sensory hardness, stickiness and dryness in order to identify the sensory triggers of swallowing (Peyron et al. 2011). It was found that sensory hardness decreased together with mechanical hardness of the boli. Using a more dynamic approach, dynamic sensory perception determined by temporal dominance of sensation (TDS) was compared recently to mechanical and rheological bolus properties (Young et al. 2013). Changes in bolus properties were found to be a possible cause contributing to changes in dominance of sensation of texture attributes during mastication.

Previously, it was found that texture perception at the beginning of oral processing of emulsion-filled, semi-solid gels depended on fracture properties of the gels (Devezeaux de Lavergne et al. 2015a). The fracture properties influenced perception of texture attributes at later stages of oral processing. Analysing bolus formation and properties is likely to help understanding the link between initial mechanical and structural properties of food, properties of the bolus and dynamic texture perception.

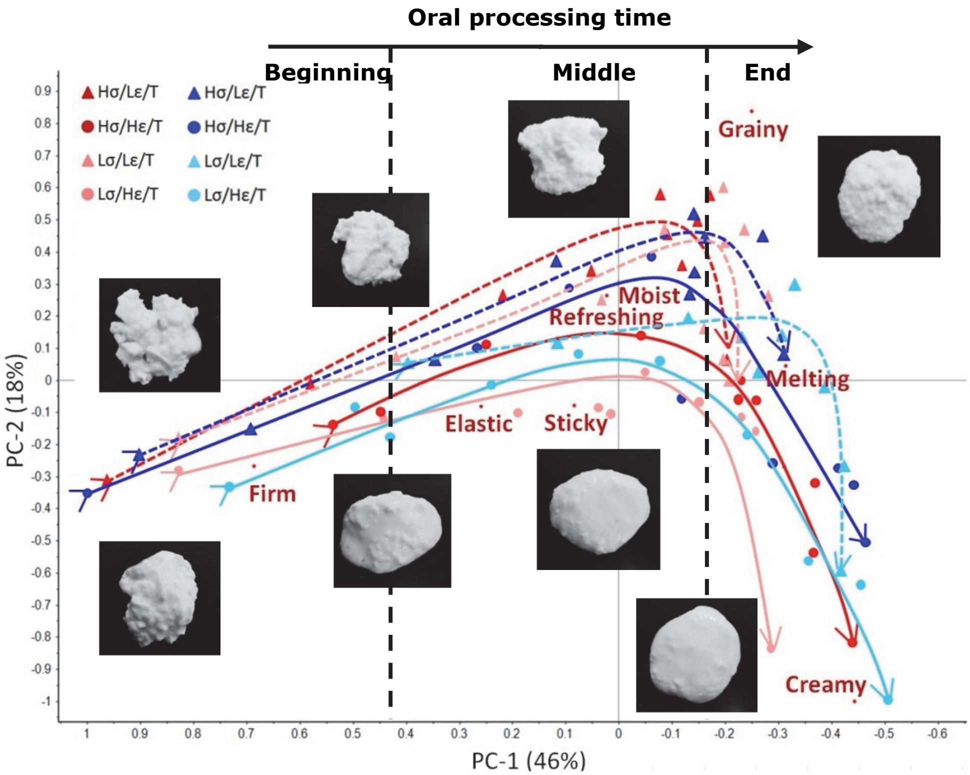


Figure 3.1 TDS sensory trajectories: Dominance rates at different time intervals from the beginning of oral processing until the end (0, 10, 20,….., 90, and 100% of mastication time) for emulsion-filled, semi-solid gels. Three phases of mastication time are defined (beginning, middle and end of oral processing). Gels were plotted over sensory attributes in the PCA. Lines are drawn to guide the reader. Pictures from boli of Hσ/Lε/W (up) and Lσ/Hε/W (down) gels were placed close to the corresponding TDS data points in time for illustration. Sample codes are explained in table 1. Figure 1 is adapted from Devezeaux de Lavergne et al. (2014).

The physical-chemical and sensory properties determined using Qualitative Descriptive Analysis (QDA), TDS and progressive profiling of emulsion-filled gels varying in fracture stress (high/low), fracture strain (high/low) and interactions between oil droplets and gel matrix (bound/unbound) were described previously by Devezeaux de Lavergne et al. (2015a). Changes in texture perception during mastication could be quantified using sensory trajectories which were obtained from TDS measurements (Lenfant et al. 2009). Figure 3.1 shows the sensory trajectories of the emulsion-filled, semi-solid emulsion-filled gels together with selected images of expectorated boli. Three phases of oral processing were identified based on the appearance of dominant sensations: beginning (dominant sensation is firm), middle (dominant sensations are moist, refreshing, elastic and sticky) and end phase of oral processing (dominant sensations are grainy, melting and creamy). We hypothesize that the dominant texture attributes perceived during each phase of oral processing are linked to physical and chemical bolus properties. In the present study, we analyse the relationships between the physical-chemical bolus properties and texture perception following the order of appearance of the texture attribute as dominant sensation in time. In the beginning of oral processing, all gels were perceived mainly as firm. In the middle of oral processing, gels were perceived elastic, sticky, moist and refreshing, and in the end of oral processing, as creamy, melting and grainy. The aim of this present study is to explain dynamic texture perception of emulsion-filled, semi-solid gels by properties of the boli formed during three stages of oral processing. Saliva content, mechanical properties, fat release and fragment size and shape were analysed in food boli obtained at different oral processing times. The physical-chemical data was correlated with dynamic texture perception.

3.2. Materials and methods

3.2.1. Samples

Table 3.1 Full factorial experimental design (2x2x2) of gels varying in fracture stress (high/low), fracture strain (high/low) and oil binding to the matrix (bound/unbound) together with sample names.

Name	Fracture stress (σ)	Fracture strain (ε)	Emulsifier	Binding of oil to gel matrix
Hσ/Lε/T	High	Low	Tween 20	Unbound
Hσ/Hε/T	High	High	Tween 20	Unbound
Lσ/Lε/T	Low	Low	Tween 20	Unbound
Lσ/Hε/T	Low	High	Tween 20	Unbound
Hσ/Lε/W	High	Low	WPI	Unbound*
Hσ/Hε/W	High	High	WPI	Bound
Lσ/Lε/W	Low	Low	WPI	Bound
Lσ/Hε/W	Low	High	WPI	Bound

** The gel Hσ/Lε/W contained emulsion droplets unbound to the gels matrix, despite the use of WPI as an emulsifier (which creates charge interactions with gelatine), since the gel matrix contained only agar (Devezeaux de Lavergne et al. 2014a).*

Emulsion-filled agar/gelatine gels were prepared following the protocol described by Devezeaux de Lavergne et al. 2015a. The details of the preparation procedure and characterization of gels including sensory characterization (QDA, progressive profiling, TDS), uniaxial compression test and oil release have been described previously (Devezeaux de Lavergne et al. 2015a) and are not summarized here. All sensory data can be found in detail in Devezeaux de Lavergne et al. 2015a. In the present study, the previously published sensory data is compared to and correlated with additional data of bolus properties. The full factorial experimental design of gels varying in fracture stress (high/low), fracture strain (high/low) and oil binding to the matrix (bound/unbound) is summarized in Table 3.1 together with the corresponding sample names.

3.2.2. Bolus collection

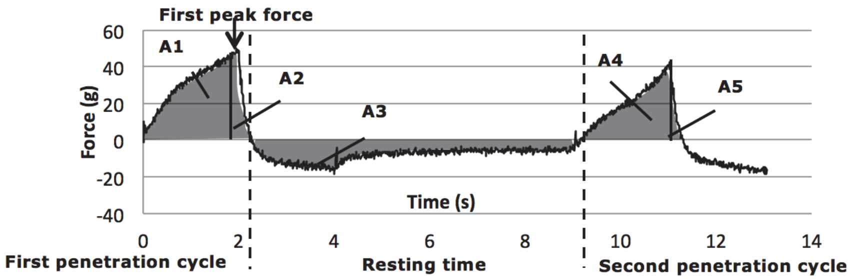
A panel consisting of 10 Dutch women all of whom have previously participated in the QDA and TDS sensory study of the gels (Devezeaux de Lavergne et al. 2015a) was selected. All subject had a healthy dentition. The average age of the panel was 54.9 ± 13.8 years. Five sessions of 1.5 hours were organised to collect boli from gels, boli from each session were used for a specific analysis. Two boli collections sessions were needed to obtain sufficient volumes of boli to perform the Two Cycle Penetration Tests (TCTP). Between 18 and 22 hours after gel preparation, gels were cut into cylindrical pieces of 26.4 mm diameter and 10 mm height. Boli from gels were collected after mastication for 5, 10, 15 and 20 s from n=10 panellists. In each spit out sessions, 32 gel samples corresponding to a single piece of gel for each gel type and spitting time, were served per panellists except for the TCPT test (128 pieces were served over 2 sessions). Samples were presented in a randomized order between gel samples but spitting times were always kept from longer to shorter time per gel type. Time points correspond to 25, 50, 75 and 100 % of the maximum oral processing time of the gels reported by Devezeaux de Lavergne et al. 2015a. At the desired time points, panellists expectorated the bolus in a plastic cup (screw cap urinary cup 120 ml, VWR). For each tests, one cup per panellist, per gel sample and per spitting time was collected corresponding to a total of 320 cups.

Pictures from the gel boli of one subject were taken with a digital camera (Casio, EX-ZR1200) right after oral processing of the gels for illustration purposes. Pictures were not used for further image analysis.

3.2.3. Two Cycle Penetration Test (TCPT) of expectorated gel boli

A two cycle penetration test (TCPT) on the boli, adapted from the modified Texture Profile Analysis described by Peyron et al. (2011), was applied immediately after expectorating the boli. Each bolus sample was collected in quadruplicate in one cup per subject (n=10). The bolus surface was gently evened with the back of a spoon to obtain a cylindrical mass of approximately 20 mm height and 45 mm diameter. A two cycle penetration test (TCPT) was performed consisting of two successive uniaxial compression tests with a 20 mm diameter cylindrical steel probe using a Texture Analyser (TA.XT plus, Stable Micro Systems-SMS). The boli were penetrated to 75% of their height (approximately 15 mm) at a constant speed of 5.0 mm/s. Retrieval of the probe was at a speed of 5.0 mm/s. The resting time between two penetrations was 5 s. Data acquisition was carried out using a 5 kg load cell at a sample frequency of 40 Hz. From this test several parameters were obtained as shown in Table 3.2. TCPT data was transformed into square root of first peak force, logarithm of resilience and inverse of adhesiveness to obtain normally distributed data for further statistical data analysis. All (transformed) data was analysed by repeated measures ANOVA to take into account the physiological variability between subjects. The effect of fracture stress, fracture strain, emulsifier type and oral processing time were analysed as factors using SPSS (SPSS software, V19, SPSS Inc., Chicago, USA). A Bonferroni Post-Hoc test was conducted between the 4 oral processing times and the 8 gels. A significance level of $p<0.05$ was chosen.

Table 3.2 Definition and description of mechanical properties of boli obtained by TCPT



Parameter	Definition	Description
First peak force	Maximum peak force during first penetration cycle	Represents bolus firmness
Resilience	Area under force-time curve during withdrawal of the first penetration cycle (A2) divided by area under force-time curve during penetration of first penetration cycle (A1): A2/A1	Represents degree of bolus springing back to its initial state and shape after one penetration
Adhesiveness	Area under force-time curve between time point that probe returned to its initial position after first penetration cycle and time point that second penetration cycle starts: A3	Represents adhesion of bolus after one penetration cycle
Flowability	Area under force-time curve during second penetration cycle divided by area under force-time curve during first penetration cycle: (A4+A5)/(A1+A2)	Represents degree of bolus returning back to its initial state and shape after one compression cycle (penetration and withdrawal) by a combination of flowing and springing

3.2.4. Gravimetrical determination of saliva content of expectorated boli

Cups containing one bolus for dry matter content determination were sealed and stored at 4°C for maximum three days. Boli were weighed (wet mass bolus [g]) and dried in an air dry oven for at least 24 h at 105°C (Prime Oven 100-310K, Gallenkamp). After cooling the boli in a desiccator for 20 min, dry mass of boli [g] was determined. Water content of boli [wt%] was calculated based on the composition of gels (Devezeaux de Lavergne et al. 2015a, Table 3.1). Saliva content of boli [wt%] was calculated as:

$$Saliva\ content\ (bolus) = \left(\frac{Wet\ mass\ bolus - Dry\ mass\ bolus}{Wet\ mass\ bolus}\right) - Water\ content\ (gel)$$

Saliva incorporation rate into the bolus (calculated in g/s and converted in mL/min) was calculated for each gel at each 5 s time intervals as, for (t) representing an expectoration time of 5, 10, 15 or 20 s and saliva content taking a value of zero at t=0s:

$$Saliva\ incorporation\ rate\ (t) = \left(\frac{Saliva\ content\ (t) - Saliva\ content\ (t-5\ s)}{5\ s}\right) \times Mass\ of\ gel$$

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Saliva content of the expectorated boli and salivary incorporation rate into the bolus were statistically analysed using SPSS for repeated measures ANOVA with the effect of fracture stress, fracture strain, emulsifier type and time as factors. A Bonferroni Post-Hoc test was conducted between the 4 mastication times and between the 8 samples. A significance level of $p<0.05$ was chosen.

3.2.5. Particle size analysis of expectorated boli

20 mL of water was added to each bolus before sealing the cups and storing them at 4°C for a maximum of three days. Single Boli collected from the gels were rinsed on a 335 µm mesh sieve under running water for 1 minute to remove fragments smaller than 335 µm and released oil. The boli fragments remaining in the sieve (particle diameter > 335 µm) were then dispersed by gently stirring them with a spatula on two petri dishes (plastic 94/16 mm, Greiner) containing distilled water. A grayscale picture at resolution of 800 dpi was taken by placing the petri dishes on a 9950F scanner (Canon Inc., JP). A second picture was taken after re-dispersion of the fragments. Pictures were imported into ImageJ (National Institutes of Health, Version 1.45 K) and analysed for particle size after applying a black and white threshold and a watershed. Results from ImageJ for each picture consisting of a list of area and roundness of each detected fragment were exported to Excel (Microsoft, 2010). The diameter of each fragment was calculated assuming that the obtained fragment is a disc projection of a sphere. Fragments of calculated diameter below 335 µm were discarded as part of these fragments was lost during sieving. The average roundness of the fragments, mean Sauter diameter, the median diameter, the number of all detected fragments and the sum of all individual areas of the fragments were obtained. The median diameter (data not shown) showed similar results as the mean Sauter diameter. The mean Sauter diameter was selected to be further used as the descriptor of fragment size in the bolus. The data of roundness was transformed logarithmically and the inversed number of fragments and total bolus surface area were used to obtain a normally distributed data for statistical data analysis. All data were

analysed by repeated measures ANOVA in order to take into account the physiological variability between subjects. The effect of fracture stress, fracture strain, emulsifier type and oral processing time were analysed as factors. A Bonferroni Post-Hoc test was conducted between the 4 oral processing times and between the 8 samples. A significance level of $p<0.05$ was chosen.

3.2.6. Determination of amount of fat released from expectorated boli

Fat release determination from the boli was applied immediately after expectorating the boli. Single boli (typically 5 to 8 g) were diluted with distilled water (typically 25 g) to reach approximately a 1:4 dilution. The mix was vortexed (Vortex genie, Wilten&Co, Etten-leur) for 15 s and filtered with an Acrodisc syringe filter (5µm pore size, PALL Corporation). The oil content of the filtrate was determined using the Rose-Gottlieb method (ISO 1211) by Qlip (Leusden, The Netherlands). The square root value of the amount of fat released from the expectorated boli was analysed in SPSS by repeated measures ANOVA. The effect of fracture stress, fracture strain, emulsifier type and oral processing time were analysed as factors. A Bonferroni Post-Hoc test was conducted between the 4 oral processing times and between the 8 samples. A significance level of $p<0.05$ was chosen.

3.2.7. Correlations between gel properties, bolus properties and dynamic texture perception

To correlate gel fracture properties and bolus properties determined at 4 time points of oral processing with sensory perception determined using QDA, Pearson correlations were calculated using SPSS (SPSS software, V19, SPSS Inc., Chicago, USA). To correlate bolus properties to sensory perception determined using progressive profiling, regressions were calculated using SPSS (SPSS software, V19, SPSS Inc., Chicago, USA).

3.2. Results and Discussion

3.2.1. Correlations between gel properties, bolus properties and dynamic texture perception

The correlations between bolus properties at 5, 10, 15 and 20 s of oral processing with intensity scores from Qualitative Descriptive Analysis (QDA) are given in Table 3.3. The choice of QDA attributes for the Pearson correlation analysis is limited to the texture attributes which were used also in the TDS characterisation of the gels leading to the sensory trajectories shown in Figure 3.1. QDA scores were chosen for correlation analysis with bolus properties. Devezeaux de Lavergne et al. 2015a demonstrated that for the emulsion-filled, semi-solid gels QDA sensory data provided similar and complementary results in the assessment of dynamic texture perception as the TDS sensory data shown on Figure 3.1. All texture attributes, except the attributes creamy and melting which were dominant at the end of oral processing, correlated to either fracture stress or strain. Binding of oil droplets to the gel matrix as well as the amount of oil released from the bolus during mastication did not correlate to any texture attributes. Fracture properties expectedly correlated with texture attributes mainly at the beginning and the middle of oral processing while bolus properties correlated with attributes at all stages of oral processing. TCPT test results correlated with texture attributes perceived at all stages of oral processing, particle analysis results correlated with attributes perceived in the middle and the end of oral processing while saliva content and oil released upon mastication hardly correlated with texture attributes. Correlations between perception and bolus properties are discussed further in the text following the order of appearance of dominance in TDS (see Figure 3.1).

3.2.2. Bolus properties linked to texture attributes perceived in the beginning of oral processing: Firmness

Firmness perception assessed in QDA correlated with fracture stress of gels (Table 3.3). Firmness was perceived as dominant at the beginning of oral processing (TDS, see Figure 3.1) and its intensity decreased over oral processing time (sequential profiling, see Devezeaux de Lavergne et al. 2015a).

First peak force of boli was measured by TCPT. First peak force of the boli expectorated after 5 and 10 s correlated with perceived firmness, whereas first peak force of the boli expectorated later during oral processing (15 and 20 s) did not reveal correlation with perceived firmness. In Figure 3.2, first peak force of the boli is shown to decrease for all gels to reach a plateau at 15 s of oral processing ($p<0.001$). High fracture strain gels containing Tween 20 (Hσ/Hε/T and Lσ/Hε/T) had a significantly higher first peak force than the corresponding gels containing WPI as emulsifier ($p<0.001$). The boli from those gels were found to form clusters that may increase the force needed to compress the boli. Both fracture stress and strain had a significant impact on first peak force of boli. Gels with a high fracture stress required a higher force to compress the boli independently from gel fragments size. The effect of fracture strain on bolus first peak force was small. As explained before, in gels containing Tween 20, the boli from high fracture strain gels showed a higher first peak force due to the clustering of fragments. During progressive profiling on perceived firmness (Devezeaux de Lavergne et al. 2015a) only fracture stress of the gels and oral processing time influenced sensory firmness. In Figure 3.4.A, sensory firmness correlated with first peak force of the boli following a semi-logarithmic relationship suggesting a relationship following the Weber-Fechner law. However, the correlation coefficient was not very high ($R^2=0.606$) which might mean that first peak force mimicking a bolus compression might not be the most representative physical measure of the gel boli to determine firmness perception during oral processing.

Table 3.3 Pearson correlations between bolus properties at different time points of oral processing (5, 10, 15 and 20s) and intensity scores of QDA texture attributes. *Correlation is significant at the p<0.05 level (2-tailed). **Correlation is significant at the p<0.01 level (2-tailed).

			Oral processing stages							
			Beginning	Middle				End		
			Firm	Sticky	Elastic	Moist	Refreshing	Grainy	Creamy	Melting
Gel	Fracture	strain		**.926****	.789*			-.770*		
		stress	**.950****			-.749*	-.807*			
	Binding of oil									
Bolus properties	First peak force	5 s	**.843****				-.747*			-.735*
		10 s	.786*		.745*	-.708*	-.747*			
		15 s			.790*		-.718*			
		20 s			.811*		-.714*			
	Resilience	5 s		.769*	**.925****	-.719*				
		10 s		**.840****	.795*			-.718*		
		15 s		**.870****				-.802*		
		20 s		**.877****	.750*			-.815*		
	Adhesive-ness	5 s		**.928****				**-.905****	-.780*	
		10 s		.800*	.758*			-.730*		
		15 s			.823*					
		20 s			**.894****					
	Flowability	5 s	**-.918****					-.795*	**.885****	**.948****
		10 s	**-.866****					-.815*	**.850****	**.893****
		15 s	**-.921****							**.893****
		20 s	**-.856****			.768*	.802*			.819*
	Number of Fragments	5 s			-.782*					
		10 s			-.754*					
		15 s			-.733*					
		20 s		-.749*				.734*		
	Area of Fragments	5 s		**-.929****				**.906****	**-.843****	
		10 s		**-.926****	-.740*				-.713*	
		15 s		**-.913****				**.884****	-.824*	
		20 s		**-.939****				**.920****	**-.907****	
	Average Diameter	5 s								
		10 s								
		15 s								
		20 s								
	Oil released	5 s								
		10 s								
		15 s								
		20 s								
	Saliva content	5 s								
		10 s			.736*					
		15 s			.722*					
		20 s			.820*					

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Furthermore, firmness perception during oral processing might differ from firmness perception at first bite and require other types of measurement than a compression test.

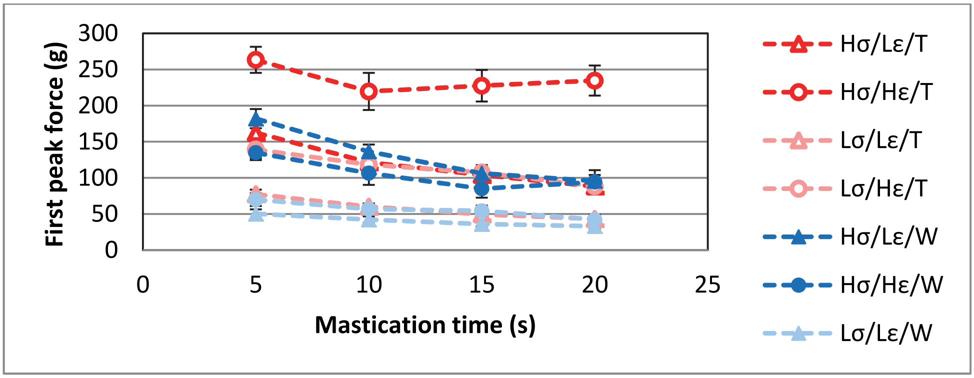

Figure 3.2 First peak force of the gel boli measured by TCP over oral processing time. Error bars indicate the standard error of the mean (n=10).

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Flowability of the gel boli, shown in Figure 3.3, correlated at all time points of oral processing with sensory firmness (Table 3.3). Flowability corresponds to the degree of the bolus returning back to its initial state and shape after one compression cycle (penetration and withdrawal) by a combination of flowing and springing behaviour during the TCPT. During oral processing, the flowability of gels increased significantly for most gels between 5 and 15 s and between 10 and 20 s of oral processing ($p<0.001$). Flowability was high for low fracture stress gels already after 5 s of oral processing and did not seem to increase anymore. For gels with a low value of flowability at 5 s, flowability seemed to increase towards a target value. After 5 s of oral processing, gels were significantly different from each other's depending on their fracture properties ($p<0.05$). After 20 s, all gels had a flowability value between 0.5 and 0.7. Only Lσ/Lε/W was significantly different from the other boli ($p<0.05$). This demonstrates that flowability of the gel boli converged to a value at the end of oral processing to ensure a comfortable and safe swallow. The type of emulsifier did not significantly effect flowability except between Lσ/Lε/T and Lσ/Lε/W ($p<0.05$) which showed also a different sensory trajectories (Figure 3.1). Both stress and strain had a significant impact on boli flowability. Gels with a low fracture strain broke down in boli with low flowability values ($p<0.05$) and gels with a high fracture stress resulted in boli with a low flowability value ($p<0.001$). This is coherent with the fact that boli from high fracture stress gels are harder to deform and do not flow back in place after the first compression. In literature, cohesiveness of the food bolus measured by modified TPA has been hypothesized to be a deciding factor for the swallowing process (James et al. 2011). Cohesiveness of bolus from cereal flakes was found to increase until the point of swallowing (Loret et al. 2011). However, this was not found in biscuits (Young et al. 2013). Moreover, Chen and Lolivret (2011) hypothesised that, rather than a target value of cohesiveness, a target value of flowability was needed to trigger swallowing. In our study, the convergence of bolus flowability through the mastication process for all gels supports this hypothesis. Moreover, gels with a higher flowability were the ones that were swallowed only after 15 s of oral processing while gels with a low flowability needed to be masticated for at least 20 s (Devezeaux de Lavergne et al. 2015a). Figure 3.4.B shows that perceived firmness determined by progressive profiling was linearly correlated with bolus flowability. Flowability may explain firmness perception better, as the broken down bolus is probably moved around in the mouth, rather than mechanical properties measured by a compression. These results are confirmed in Table 3.3 were QDA scores for sensory firmness during chew-down are shown to be correlated to first peak force of bolus at 5 and 10 s of oral processing and no more at 15 and 20 s when the bolus might be too fluid; whereas flowability of the bolus is negatively correlated to QDA firmness at all bolus collection times.

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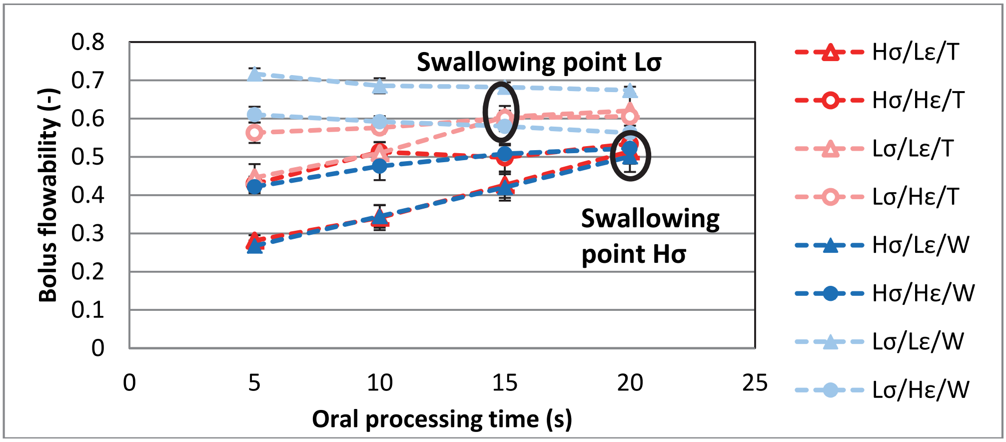

Figure 3.3 Flowability of gel boli determined by two cycle penetration test (TCPT) over oral processing time. Error bars indicate the standard error of the mean (n=10).

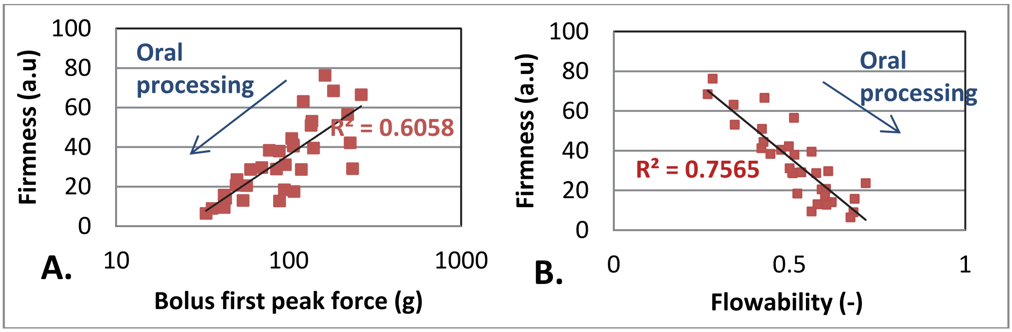

Figure 3.4 A. Sensory firmness determined by progressive profiling in relation to first peak force of gel boli. B. Sensory firmness determined by progressive profiling in relation to flowability. Results of A. and B. are obtained from boli of 8 different gels at 4 oral processing times averaged over n=10 panellists.

3.2.3. Bolus properties linked to texture attributes perceived in the middle of oral processing

At the middle of oral processing, the sensory trajectories of gels separated into two groups between low and high fracture strain gels (Figure 3.1). High fracture strain gels were dominantly perceived as elastic and sticky in the middle of oral processing whereas low fracture strain gels were perceived as dominantly moist and refreshing in the middle of oral processing. Therefore, we first discuss elastic and sticky followed by moist and refreshing.

3.3.3.1. Elastic and sticky

Elasticity and stickiness were the dominant attributes perceived in the middle phase of oral processing mainly for gels with a high fracture strain. Elasticity and stickiness are hypothesised to be linked to mechanical properties of the food bolus during oral processing. In Table 3.3, elasticity and stickiness assessed in QDA were positively correlated with fracture strain of gels.

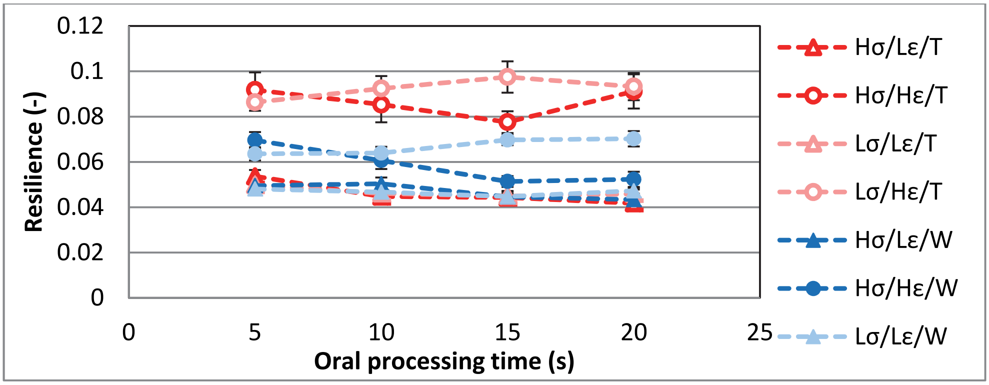

Figure 3.5 Resilience of food bolus over oral processing time measured by TCPT. Error bars represent standard error of the mean (n=10).

Elasticity supposedly depends on the way the material responds under and after compression. Sensory elasticity assessed by QDA revealed the highest correlation with resilience at 5 s of oral processing compared with other bolus properties and oral processing times (Table 3.3). As shown in Figure 3.5, resilience of the gel boli that corresponds to the degree of the bolus springing back to its initial state and shape after one penetration did not significantly evolve in time ($p>0.05$). This suggests that the resilience of the boli did not change during oral processing. The type of emulsifier had a significant impact for gels with a high fracture strain ($p<0.001$). In those high fracture strain gels, Tween 20 gels showed a higher resilience. Fracture strain of the gels also had a significant impact on resilience ($p<0.001$). Gels with a low fracture strain broke down in boli that were less resilient than those from high fracture strain gels. The low fracture strain gels broke down in many pieces that would resist little on the first compression of the TCPT test compared to a bolus containing large fragments. In Table 3.3, elasticity also correlated with bolus adhesiveness which is discussed together with sensory stickiness.

Stickiness was hypothesised to be linked to adhesiveness of gel boli. In Table 3.3, sensory stickiness assessed in QDA correlated with bolus adhesiveness mainly at 5 s of oral processing. Adhesiveness (data not shown) varied with fracture strain of the gels, gels having a high fracture strain resulting in more adhesive boli ($p<0.05$). This difference could be explained by the high content of gelatine of these gels which increased their stickiness more compared to gels with low gelatine and high agar content. In Table 3.3, stickiness measured by QDA was also found to be negatively correlated with area of the bolus fragments which was also correlated to fracture strain (results discussed in chapter 3.3.4.1.).

3.3.3.2. Moist and refreshing

Moist and refreshing were two attributes perceived as dominant sensations during the middle phase of oral processing, mainly for low fracture strain gels (Figure 3.1). In Table 3.3, moist and refreshing assessed in QDA correlated negatively with fracture stress.

Perception of moist was defined as perception linked to presence of water in samples and is hypothesised to be linked to content of water in the gel and saliva content in the bolus. The perception of refreshing was defined as a cooling sensation that is also speculated to be linked to presence of saliva in the bolus (Devezeaux de Lavergne et al. 2015a). No correlations were found between saliva content of bolus and sensory moist and refreshing assessed by QDA (Table 3.3). Despite the lack of correlation, the evolution of saliva content during oral processing is reported in Figure 3.6. Saliva content increased constantly for all gels during oral processing ($p<0.001$) to reach an end value at the point of swallowing ranging from 7.9 wt% to 10.6 wt%. Saliva incorporation rate into the bolus was shown to be higher during the first 5 s of oral processing ranging from 4.3 mL/min to 2.8 mL/min depending on the gels. It decreased until the 10th second to remain constant for the last 10 s with a value of 1.0 mL/min. Our results are in agreement with previous research where salivary flow of panellists was greater in the first chewing cycle than in later chewing cycles (Tarrega et al. 2011). However, rather than changes in saliva production, this result could also be due the presence of saliva in the mouth prior to mastication which would result in a greater addition of saliva in the bolus within the first 5 s. Saliva incorporation rate into the bolus varied between gels depending on their properties. Fracture stress did not have a significant impact on saliva incorporation, however hard gels needed a longer oral processing time to be swallowed which would result in higher saliva content in high fracture stress gels at swallow. It has been shown that in hard cheeses more saliva was incorporated as the result of an increase in chewing time rather than an increase in salivary flow (Tarrega et al. 2011) which is in agreement with our results. Low fracture strain gels required less saliva incorporation (p<0.001). This difference may have been due to the high brittleness of low fracture strain gels and their low adhesiveness which lead easily to a safe swallow requiring less lubrication by saliva. Gels containing WPI incorporated significantly less saliva than gels containing Tween 20 (p<0.001). Gels with Tween 20 had lower initial dry matter content (Devezeaux de Lavergne et al. 2015a). Supposedly, more saliva incorporation was needed for gels with high dry matter content, maybe to enhance lubrication. Moreover, it was found that the final content of saliva was negatively, linearly correlated to initial dry matter of the gel (R^2=0.755). Water content in the gels ranged between 57.8 wt% and 63.2 wt% while in the bolus, at the end of oral processing, water content ranged between 70.0 % and 71.9 wt% for all gels. This result suggests that a target water content of the bolus is needed to ensure a safe swallow. As mentioned above, saliva content did not correlate with moist or refreshing perception. The two sensory attributes were negatively correlated with TCPT first peak force of the bolus and positively correlated with bolus flowability towards the end of oral processing (Table 3.3). This suggests that the moist and refreshing perception were more linked to mechanical properties of the bolus than to incorporation of saliva.

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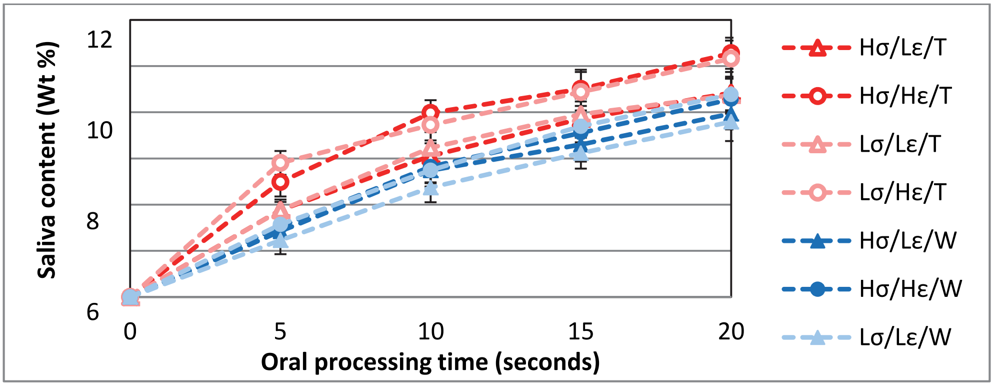


Figure 3.6 Saliva content of gel boli [g saliva/g bolus] over oral processing time. Error bars represent standard error of the mean (n=10).

3.2.4. Bolus properties linked to texture attributes perceived in the end of oral processing

At the end of oral processing, the sensory trajectories of gels separated clearly into two groups between low and high fracture strain gels (Figure 3.1). Low fracture strain gels were dominantly perceived as grainy in the end of oral processing whereas high fracture strain gels were perceived as dominantly melting and creamy in the end of oral processing. Therefore, we first discuss grainy and then creamy and melting

3.3.4.1. Graininess

Graininess was perceived as dominant towards the end of the oral processing, before swallowing, and was higher in gels with a low fracture strain. In Table 3.3, graininess assessed in QDA was expectedly negatively correlated to fracture strain.

Graininess is hypothesized to be linked to the presence of gels fragments in the bolus that can generate friction against the oral cavity. Graininess was positively correlated to area of the boli fragments at 5, 15 and 20 s of oral processing and with number of particle in the boli at 20 s of oral processing. In Appendix 3.1, pictures of the dispersed fragments of the boli can be seen. Pictures from boli before dispersion in water can be seen in Appendix 3.2. Roundness of the fragments (data not shown) did not vary between gels or oral processing time and was around 0.67 for all boli which suggests that the gel fragments were generally not roundly shaped. For the calculations of the Sauter diameter, it was assumed that particles were the disc projection of a sphere despite a value of roundness lower than 1 suggesting that gel fragments were not “perfect” spheres. In Figure 3.7.A and 7.B the number of gel fragment and the average radius of those fragments are given, respectively. The number of fragments increased continuously with oral processing time ($p<0.001$) but the fragment mean Sauter diameter decreased significantly only in the first 15 s ($p<0.001$) from 4-8 mm after 5 s of oral processing to a mean Sauter diameter of 1.5-6 mm at 15 s of oral processing. Gels containing WPI gave boli containing more fragments and smaller fragments than gels containing Tween 20 ($p<0.001$). Lσ/Hε/T was the gel breaking down in the smallest number of biggest fragments, Hσ/Hε/T and Lσ/Hε/T were observed to generate clusters of fragments which explains that these samples contained bigger and less numerous fragments than Hσ/Hε/W and Lσ/Hε/W. Lσ/Lε/T and Hσ/Lε/T did not differ from the WPI gels. Fracture stress of the gels did not have a significant impact on number of fragments nor fragment size which suggests that panellists might have adapted their chewing strategy supposedly by increasing chewing force or chewing frequency (Foster et al. 2006). In previous studies comparing a wide range of foods, food hardness was shown to have an impact on fragment size of the food bolus (Chen et al. 2013), however, in that study the food had much larger variations in hardness and also in structure than the gels in this study. Fracture strain of the gels had a significant impact on both fragment size and number ($p<0.001$). Low fracture strain gels were broken down quickly in many small pieces as they required small deformation to fracture. In Figure 3.8, the total generated area of all boli fragments is shown as a function of oral processing time. The area did not evolve over the oral processing time as many small fragments were generated since the first 5 s and the increase in number of these small fragments was compensated by a decrease in area of fragments. The total surface area of the gel boli did not depend on the type of emulsifier used but on fracture stress ($p<0.05$) and fracture strain ($p<0.001$) of the gels. High fracture stress gels generated slightly bigger areas. Low fracture strain gels had a bigger total surface area than high fracture strain gels as they broke down easily in many fragments. In Table 3.3, perceived graininess rated in QDA showed positive correlation with total generated area in the boli and with the number of gel fragments (at 20 s of oral processing). However, fragment size did not show an influence on graininess perception. As total generated area depend both on number of fragment and fragment size, it describes best the perception of graininess which is higher in gels containing many small fragments.

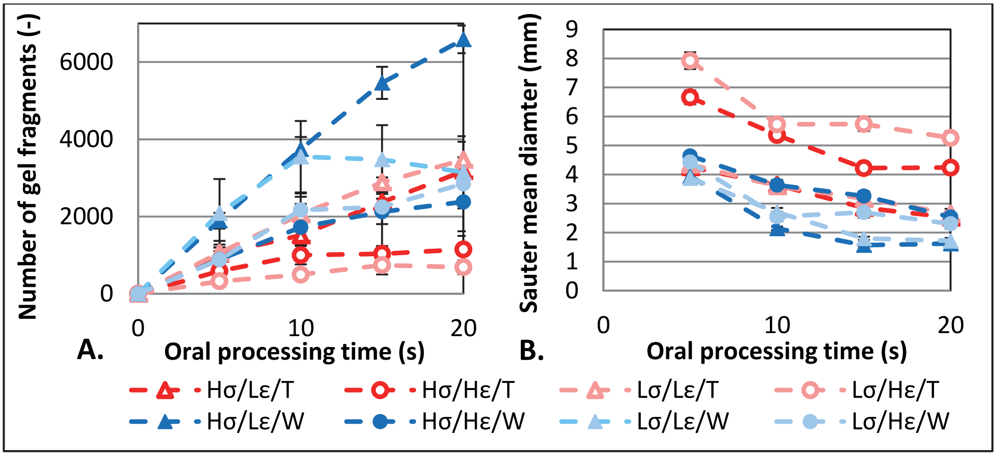


Figure 3.7 A. Number of gel fragments of boli over oral processing time. Error bars indicate the standard error of the mean (n=10). B. Sauter mean diameter of gel fragments of boli over oral processing time. Error bars indicate the standard error of the mean (n=10).

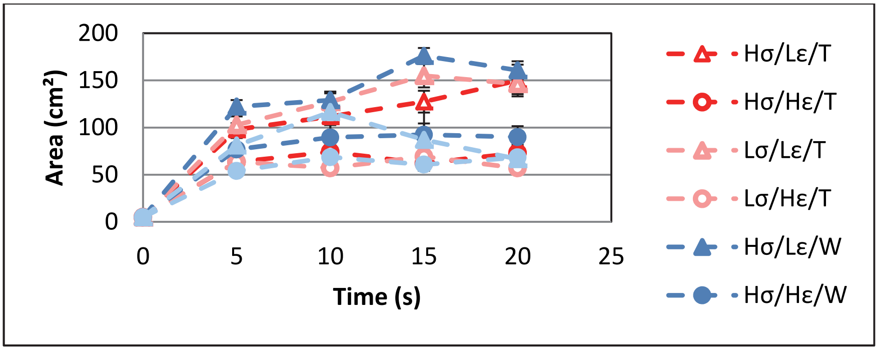


Figure 3.8 Sum of all fragments area of gel boli over oral processing time. Error bars indicate the standard error of the mean (n=10).

3.3.4.2. Creaminess and melting

Creaminess is a complex sensory attribute that was perceived dominant at the end of oral processing mainly for gels with a high fracture strain. However, sensory creaminess assessed in QDA did not correlate with fracture strain of the gel (Table 3.3) suggesting that complex mechanisms of breakdown are involved.

As creaminess is a fat related attribute, it is firstly hypothesised to be linked to the presence of oil in contact with the oral cavity or the amount of oil being released from the matrix into the bolus. However, in Table 3.3, sensory creaminess assessed by QDA was not correlated with oil released from the gel matrix. Despite the lack of correlation, oil release data are reported as a function of oral processing time in Figure 3.9. Oil is shown to be released during oral processing of the gels from the matrix into the bolus; more oil was released with increasing oral processing time ($p<0.001$). After 10 s of oral processing, oil release from the gel into the bolus did not significantly increase with further oral processing time. Gels that contained oil droplets bound to the gels matrix (Devezeaux de Lavergne et al. 2015a) released less than 1% of oil at each time point of oral processing. Gels containing bound oil droplets to the matrix have previously been found to release very little oil which is in accordance with these results (Sala et al. 2007b; Guo et al. 2013). Gels containing unbound oil droplets to the matrix released 1.5 % oil from the gel matrix at the beginning of oral processing and 7 % oil at the end of oral processing. Release of oil depended not only on the interaction between the oil droplet and the gel matrix (bound/unbound), but also on the fracture properties of the gels: high fracture strain gels released less oil than low fracture strain gels ($p<0.001$) and high fracture stress gels released less oil than low fracture stress gels ($p<0.001$). This was due to the fact that low fracture strain gels generated more surface area upon breakdown from which the oil droplets could be released. Fat released from the boli of gels containing Tween 20 was linearly correlated with total surface area of boli ($R^2=0.647$, regression not shown). However, low and high fracture stress gels differed in surface area of broken down fragments. The low fracture stress gels released slightly more oil which could be explained by the formation of a softer bolus that might have been mixed easier in the mouth causing the oil to detach from the matrix. The type of emulsifier also impacted oil release for two unbound gels with similar fracture behaviour: less fat was released into the bolus of Hσ/Lε/W compared with Hσ/Lε/T. In previous work, the release of oil by shearing gels at 20 and 37 °C was measured (Devezeaux de Lavergne et al. 2015a) but oil release from masticating the gels did not correlate with results from oil released by mechanical shearing. Gels were found to partly melt at 37 °C because of their gelatine content which caused bound gels, which did not release fat at 20 °C, to release fat under shearing. However, in the expectorated bolus of bound gels no more than 1 % of the oil was released even at long mastication times. This could be due to only partly melting of the gelatine containing bolus fragments due to the structuring effect of agar and an insufficiently long oral processing time for total melting of the gelatine. It was found by Devezeaux de Lavergne et al (2015a) that binding of oil to the matrix did not significantly influence creaminess perception. In Figure 3.9, the released oil content of the bolus was given and was shown to depend as well on the fracture properties as on the binding of oil to the gel matrix. This could explain the observed lack of correlation between mechanical oil release at 20 °C and 37 °C and oil release in the boli. However, by correlating free oil content in the bolus with sensory creaminess measured by progressive profiling (regression not shown) and correlating free oil content with QDA scores (see Table 3.3), no significant relations were found. Creaminess is a complex sensory attribute that depends on properties of the bulk of the bolus such as viscosity as well as properties of the surface of the bolus, such as lubrication (de Wijk et al. 2006a and 2006b). The melting at the surface of the gel fragments and lubrication by a thin layer of free oil may happen as it was shown that gels melted and released more oil under shear at 37 °C. In this study, the total free oil released from the matrix and the surface properties of the gel fragment might be independent variables.

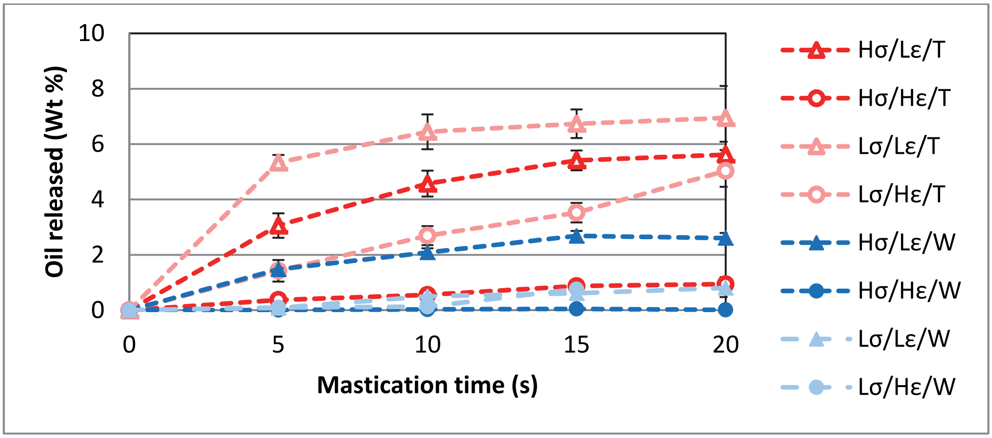


Figure 3.9 Amount of oil released from gel matrix into bolus divided by oil content of gel over oral processing time. Error bars indicate the standard error of the mean (n=10).

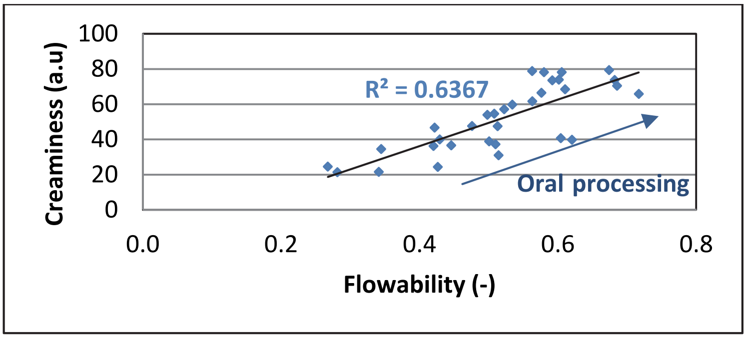


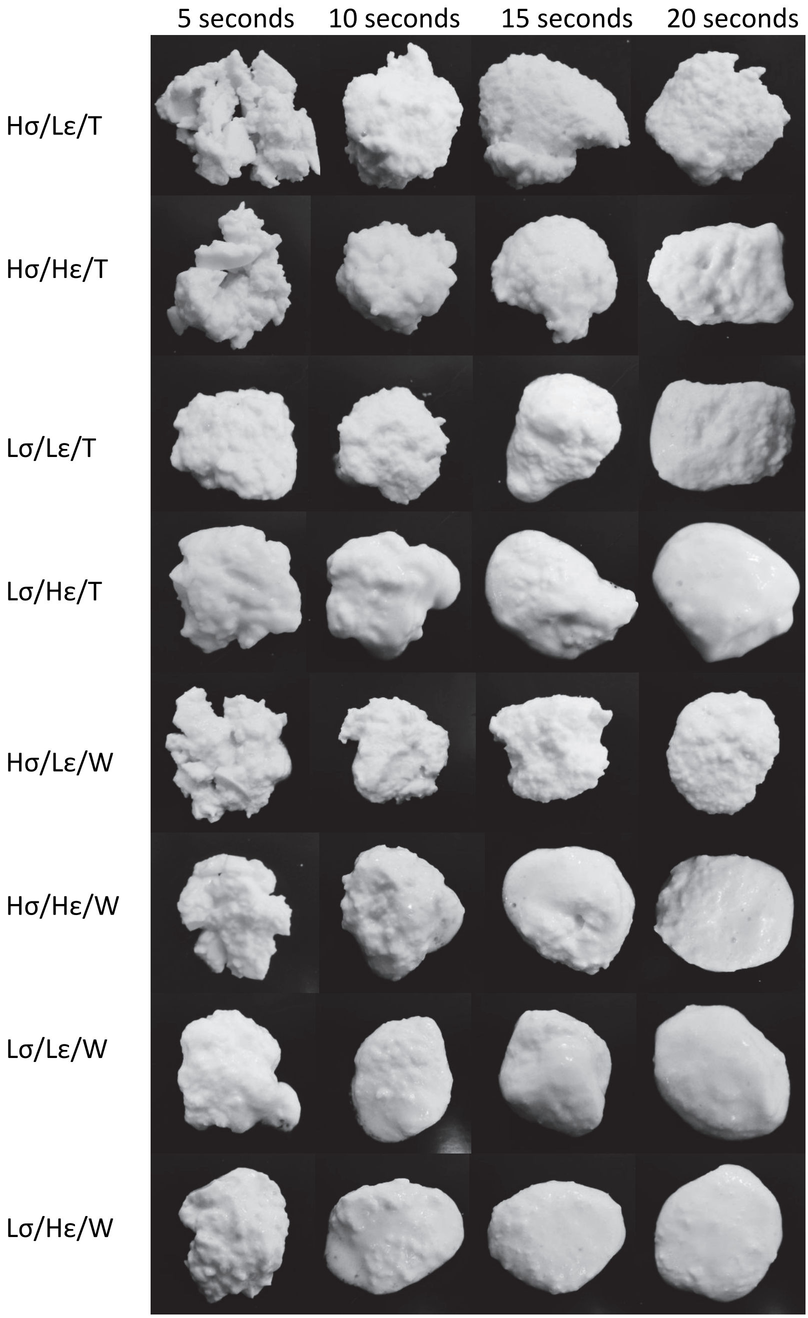
Figure 3.10 Creaminess determined by progressive profilling as a function of boli flowability. Results for boli of 8 gels each at 4 different oral processing times averaged over n=10 panellists are shown.

Sensory melting assessed by QDA correlated with bolus flowability at all oral processing time and sensory creaminess correlated positively with bolus flowability at 5 and 10 s of oral processing time (Table 3.3). Moreover, creaminess perception measured by progressive profiling was positively correlated to flowability of the bolus, which is a mechanical property of the bolus (Figure 3.10). As the gels were broken down during oral processing and saliva content increased, the formation of a flowing mass may have increased creaminess perception. The generated area of fragments, which correlated to graininess, was negatively correlated to creaminess at all oral processing stages suggesting that the presence of grainy particle greatly reduced creaminess perception. Partial least square regression analysis (data not shown) between bolus properties and creaminess perception confirmed that creaminess is positively correlated to flowability and negatively to generated area of particles but did not provide further information.

3.3. Conclusions

Dynamic texture perception of emulsion-filled gels was found to be linked to fracture properties and dynamic evolution of bolus properties during oral processing. In the beginning of oral processing, firmness was perceived as the dominant sensation and was correlated to fracture stress, bolus first peak force and bolus flowability. In the middle of oral processing, elasticity and stickiness were perceived as dominant texture sensations for gels with high fracture strain. Sensory elasticity and stickiness were correlated with resilience and adhesiveness of the boli during the first 10 s of oral processing. In the middle of oral processing, the attributes moist and refreshing were perceived as dominant sensations for gels with low fracture stress. These attributes were not correlated to saliva content of boli but negatively correlated to TCPT first peak force. In the end of oral processing, gels with low fracture strain yielded boli with a high number of fragments and generated a high surface area which was correlated with graininess perception. Creaminess was the dominant sensation at the end phase of oral processing for gel with high fracture strain and was positively correlated to bolus flowability and negatively to generated fragments area. Creaminess did not correlate to binding of oil to the gel matrix nor oil content released from the bolus during oral processing. Other bolus properties, such as lubrication or melting at the surface of the gel fragments, might be of interest to consider for a better understanding of texture perception at the end of oral processing. We conclude that bolus formation and changes in the properties of the bolus underlay the changes in dynamic texture perception during oral processing. Our study confirmed that oral processing is key to dynamic texture perception.

Appendix 3.1 Pictures of expectorated Boli from one panellist



Appendix 3.2 Pictures of separated fragments of gel boli of one panellist

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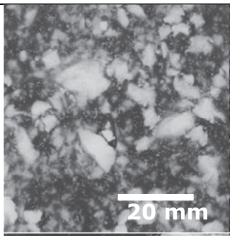
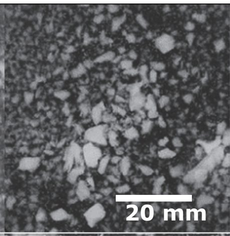
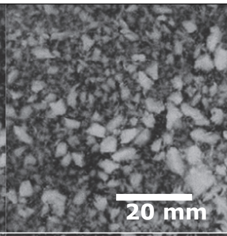
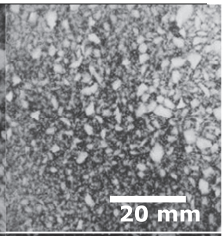
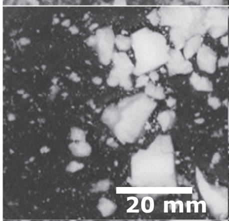
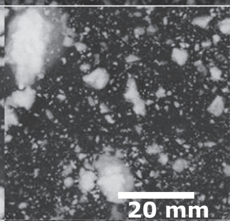
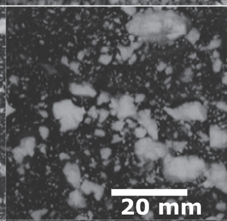
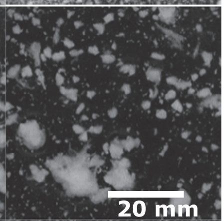
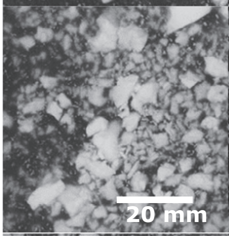
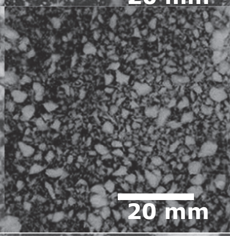
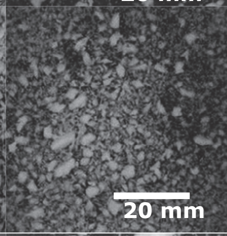
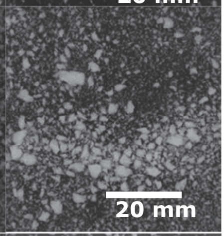
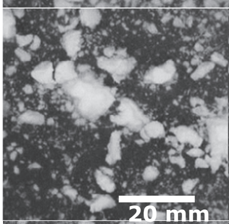
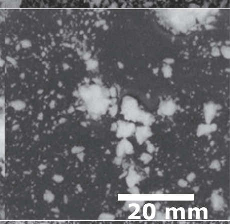
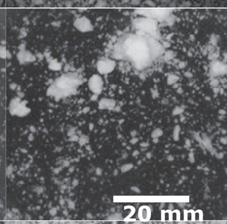
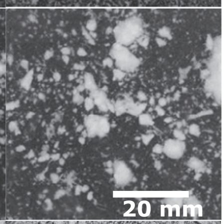
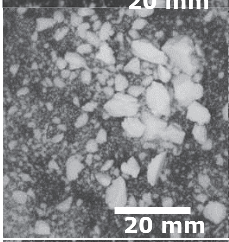
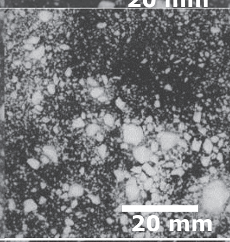
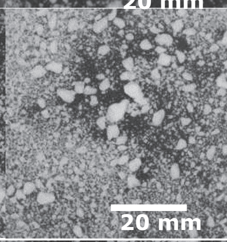
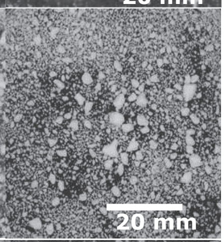
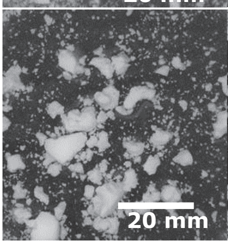
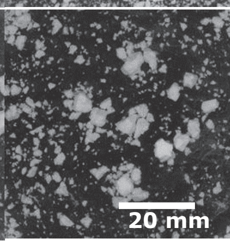
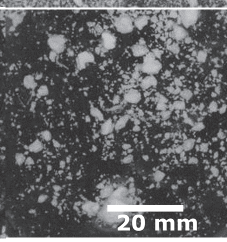
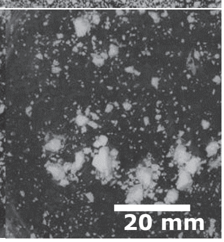
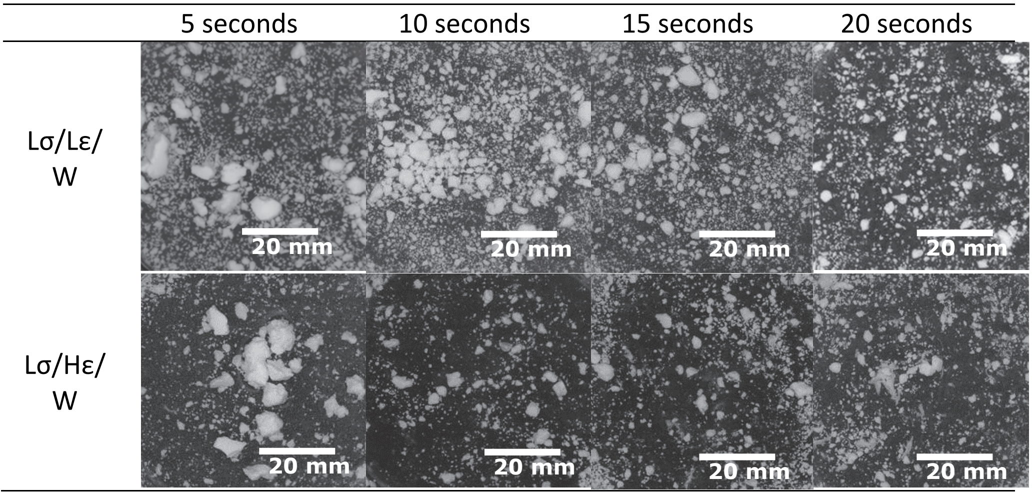
Hσ/Lε/T				
Hσ/Hε/T				
Lσ/Lε/T				
Lσ/Hε/T				
Hσ/Lε/W				
Hσ/Hε/W				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CHAPTER 4

Uncoupling the impact of fracture properties and composition on sensory perception of emulsion-filled gels.

4

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Submitted for publication

Abstract

The aim of the current study is to investigate the effect of fracture properties and composition of emulsion-filled gels on dynamic texture perception. Twelve emulsion-filled gels varying in fracture stress and fracture strain were prepared using three different mixed gelling agents. Mechanical properties, syneresis, friction properties, microstructure, melting behaviour, oral breakdown and texture perception of the gels were measured. Gels varying in composition but exhibiting similar fracture properties were obtained. Serum release, melting in mouth and friction were varied by changing the composition of the gels. Fracture properties and melting of gels impacted oral breakdown. Fracture properties impacted perception of texture attributes at first bite and during chew down. Melting and syneresis impacted chew down perception of gels. We conclude that fracture properties of gels impact perception of chew down texture attributes. However, composition of the gels impacted properties which accounted for high variation in perception between the samples.

Practical applications

Fracture properties of food are known to impact the perception of first bite texture attributes. Moreover, they are known to control breakdown of food during oral processing. However, little is known about the impact of fracture properties on perception of chew down texture attributes. The current study highlights the impact of fracture properties on chew down texture perception. Moreover, it identifies other gel properties, depending on gels composition, that account for variation in perception between gels. The use of emulsion-filled gels enabled the investigation of fat perception related attributes. Such an input can be used for food reformulation, for instance low fat formulation for soft solids. This study indicates which mechanical properties should be monitored and controlled for obtaining a desired texture profile of soft solid food.

4.1. Introduction

Texture of food is a major factor of perceived quality for consumers. Szczesniak (2002) defined food texture as a sensory property that derives from the structural, mechanical and surface properties of foods. Therefore, controlling these properties in order to obtain a desired texture profile of food is of high relevance for industry. Food properties can be controlled by the use of structuring ingredients or processing (Dickinson, 2006; Ubbink et al. 2008; Funami, 2011; Dickinson, 2013). However, linking instrumental properties of foods to sensory perception is often complex. Sensory-instrumental correlations have been obtained in fluid and semi-solid food matrices, such as correlations between viscosity and thickness (de Wijk et al. 2003; Akhtar et al. 2005). In semi-solid and solid foods, many complex sensory attributes are perceived, such as adhesiveness and creaminess (Guinard and Mazzucchelli, 1996; Koç et al. 2013a), and are difficult to correlate to solely one instrumental measure of a property of foods. Food texture is considered a multi-parameter attribute with texture attributes determined at initial contact, first bite, chew down and after swallowing (Foegeding and Drake, 2007). Therefore, designing food texture requires a better understanding of the effect of structural, mechanical and surface properties of food on dynamic sensory texture perception.

The main factor determining food texture perception is food structure. Microstructure is known to be related to perception. For instance, in mixed whey protein/polymer gel systems, microstructure influences breakdown of gels and, therefore, sensory perception (Çakır et al. 2012; Van den Berg et al. 2007a). Often microstructure and mechanical measurements are combined to explain texture perception, for instance in baked products (Lassoued et al. 2008) and extruded snacks (Anton and Luciano, 2007). Mechanical properties of foods are partly determined by structure (Pascua et al. 2013). The Young's modulus has been correlated to perceived hardness in gels (Çakır et al. 2012). Fracture properties are mechanical properties measured during fracture of the food (Pascua et al. 2013). Two important fracture properties are fracture stress, which is related to the strength of the food material, and fracture strain, which is related to the deformability of the food (Koç et al. 2013a). Fracture properties often correlate with attributes perceived at first bite, when early breakdown of the food takes place. For instance, fracture stress correlates with hardness perception of cellular foods, biscuits and sponge foods (Attenburrow et al. 1989; Kim et al. 2012), as well as hardness perception of cheeses (Everard et al. 2006; Foegeding and Drake, 2007). However, it remains difficult to relate instrumental measures on food structure or mechanical properties to texture attributes perceived after first bite i.e. in the chew down phase of oral processing.

The main difficulty in predicting texture perception by food properties is the constant modification of food structure during oral processing, especially in solid and semi-solid foods, which require mastication. Starting at first bite, several oral manipulations lead to breakdown of structure and increase in lubrication of food, in order to form a food bolus that can be swallowed safely (Chen, 2009; Hutchings and Lillford, 1988; Foegeding et al. 2010). Moreover, similarly that food structure impacts food mechanical properties, food mechanical properties impact food oral breakdown (Pascua et al. 2013). Therefore, perception of texture in the mouth is a dynamic process which is related to mechanical properties of food and the breakdown of food in the mouth by oral processing (Hutchings and Lillford, 1988; Wilkinson et al. 2000). Recently, food breakdown in mouth has been investigated (Peyron et al. 2011; Chen and Lolivret, 2011) as well as its impact on texture perception (Aken et al. 2007; Seo et al. 2007; Saint-eve et al. 2015). Techniques are developed to mimic oral processes and understand better the structural transition of the food in mouth during oral processing. For instance, an emerging field is food tribology. As a result of a decrease in the length-scale of food structure and an increase in lubrication, texture perception during chew down is supposed to transit from the food rheology regime to the oral tribology regime (Stokes, 2012; Chen and Stokes 2012). Tribological measurements can be used to mimic mouth condition and the measured fiction relate to perception of fat related attributes (Prakash et al. 2013). However, many sensory texture attributes are multimodal, such as creaminess, and are not fully predicted by tribology (Stokes, 2013). Therefore, the use of a multidisciplinary approach combining measures of food structure, oral processing and sensory perception is advised for investigation of texture perception.

Since food products are usually complex in terms of structure, model foods are often used to investigate the relation between food structure and texture perception (Foegeding, 2007; Pascua et al. 2013; Stieger and van de Velde. 2013). The use of model foods enables to control structural properties of the food. One type of model foods is emulsion-filled gels, which give the opportunity to investigate fat related texture attributes, such as creaminess (Sala et al. 2007a). Another type of model foods is mixed gels, since mixing gelling agents enables to modify fracture properties of gels (Barrangou et al. 2006a and 2006b; Koç et al. 2014). Texture attributes perceived at first bite are correlated to fracture properties of gels generally obtained by uniaxial compression. Similarly to other foods, the sensory texture attribute firmness is positively correlated to fracture stress of gels (Barrangou et al. 2006a; Devezeaux de Lavergne, et al. 2014; Foegeding, et al. 2011; Gwartney, et al. 2004; Kim, et al. 2012). Brittleness is negatively correlated to fracture strain (Barrangou et al. 2006a; Devezeaux de Lavergne, et al. 2014). The relation between fracture properties of gels and attributes perceived at later stages remains unclear. Few studies relate the impact of fracture properties to texture attributes perceived at later stages of oral processing. These studies showed that fracture properties influence perception of attributes perceived at later stage of oral processing, such as adhesiveness (Çakır et al. 2012). In emulsion-filled gels, the attributes tough and elastic were related to high fracture stress and high fracture strain, while lumpy and grainy were related to high fracture stress and low fracture strain. It was also found that lowering fracture stress and increasing fracture strain could increase the perception of creaminess in gelatine and agar mixed gels (Devezeaux de Lavergne et al. 2015).

However, those studies were limited to investigations of one type or one combination of two types of gelling agents. Modification of fracture properties of gels implies modification of the gel composition. Consequently, other structural and mechanical properties of the gel matrix that influence texture perception are simultaneously altered, such as recoverable energy, water holding properties and melting properties (van den Berg et al. 2008; Çakır et al. 2012; Sala et al. 2008). According to Çakır et al. (2012) recoverable energy and water holding were highly correlated to texture attributes, such as particle size distribution, cohesiveness, adhesiveness and moisture release. It was found that recoverable energy and water-holding capacity have a big impact on the breakdown properties of gels (Çakır et al. 2012). Water-holding properties of gel networks are known to influence the perception of release of moisture with first chew (Gwartney et al. 2004; van den Berg et al. 2008a; Çakır et al. 2012). Moreover, recoverable energy of gels could be related to sensory crumbliness of gels (van den Berg et al. 2008b). Sala et al. (2008) found that matrix properties, such as melting of the gel at human body temperature lead to a more creamy perception of emulsion-filled gels. They concluded that the melting behaviour of gels is more important for the sensory perception compared to the fracture properties. Such results suggest that while investigating the effect of fracture properties on perception, changes in recoverable energy, water holding capacity and melting should be monitored. In the study by Sala, et al. (2008) it was found that texture attributes such as crumbly, slippery and melting differ between different gelling agent systems. Therefore, the use of different gelling agents to manipulate fracture properties of gels might have an effect on chew down texture attributes. For instance, manipulation in fracture strain of mixed k-carrageenan/locust bean gum gels by lowering the k-carrageenan ratio was found to decrease water retention of the gels (Dunstan et al. 2001). The understanding of the interplay between general fracture properties of semi-solid food gels and specific matrix properties, which depend on the gelling agents used, is limited.

The aim of this study was to better understand the influence of fracture properties and composition on dynamic texture perception of emulsion-filled gels with similar fracture properties but varying matrix properties. Twelve emulsion-filled mixed gels were prepared following a 2x2x3 factorial design: gels varying in fracture stress (high/low) and fracture strain (high/low) were prepared using three different mixed gelling agents (agar/gelatine; k-carrageenan/locust bean gum; high/low acyl gellan). Thus, for each fracture stress and strain condition, three mixed gels were obtained differing in specific matrix properties due to the different types of gelling agents used.

The following hypotheses are formulated for the texture perception of gels varying in fracture and matrix properties:

(1) Fracture properties control perception of gel texture at first bite independently from gel composition.

(2) Composition of gels dominates the perception of chew down texture attributes, especially moist and melting perception.

(3) Both fracture properties and composition of gels impact the perception of fat related attributes, such as creaminess.

4.1. Materials and methods

4.1.1. Materials

Gelling agents used were agar (Ferwo Agar 700; Caldic Ingredients, Oudewater, The Netherlands), pig skin gelatine (bloom 240-260; Rousselot, Gent, Belgium), locust bean gum (GENU® GUM type RL-200Z, CP Kelco, Levallois-Perret, France), κ-carrageenan (GENUGEL® carrageenan type CHP-2, CP Kelco, Levallois-Perret, France) and two types of gellan, high acyl gellan (Kelcogel LT100, CP Kelco US, Atlanta, USA) and low acyl gellan (Kelcogel F, CP Kelco US, Atlanta, GA, USA). Tween 20 (Polyoxyethylene sorbitan monolaurate, in text referred to as Tween) obtained from Sigma-Aldrich (Steinheim, Germany) was used as emulsifier. Potassium chloride, tri-Sodium citrate and calcium chloride dihydrate were provided by Merck (Darmstadt, Germany). Sunflower oil and sugar were purchased from a local retailer and used without further purification. Vanilla aroma (In2Food, Duiven, the Netherlands) and demineralized water were used.

4.1.2. Preparation of gels

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The composition of the gels is shown in Table 4.1. The gel names are coded with the symbols (σ) for fracture stress and (ε) for fracture strain preceded by the letters H or L which respectively stand for high and low. The subsequent letters AG, CL, or G, which respectively stand for agar/ gelatine, κ-carrageenan/ locust bean gum and gellan, are used to indicate the gelling agents used.

Table 4.1 Final composition of the 12 emulsion-filled gels.

Gel name	Agar (wt%)	Gelatine (wt%)	κ-carrageenan (wt%)	LBG (wt%)	High acyl gellan (wt%)	Low acyl gellan (wt%)	Water (wt%)
LσLε/AG	0.80	3.50					65.67
LσHε/AG	-	2.20					67.77
HσLε/AG	1.00	5.50					63.47
HσHε/AG	-	3.50					66.47
LσLε/CL			1.00	-			68.91
LσHε/CL			0.17	0.24			69.50
HσLε/CL			1.50	-			68.41
HσHε/CL			0.20	0.42			69.29
LσLε/G					0.25	0.40	68.98
LσHε/G					0.58	0.05	69.00
HσLε/G					0.80	0.80	68.33
HσHε/G					0.80	0.10	68.73

All gels contained 10 wt% sugar, 0.033 wt% vanilla flavour, 20 wt% sunflower oil and 0.072 wt% Tween 20. Carrageenan/LBG gels contained 0.06 wt% KCl. Gellan gels contained 0.17 wt% Na-citrate and 0.17 wt% $CaCl_2$

Typically 500 g of mixed emulsion-filled-gels were prepared by mixing a 40 wt% oil in water emulsion with a polymer solution in a 1 to 1 mass ratio. A 2 wt% Tween solution was mixed with sunflower oil (40 wt%) using an Ultra Turrax (Ultra Turrax, IKA, T25 digital, Staufen, Germany) for 2 min at 12000 rpm. Subsequently, the obtained pre-emulsion was passed through a two stage homogenizer (Ariete, Model NS1001L 2K e Panda 2K, Niro Soavi S.p.A, Parma, Italy) at homogenisation pressure of 400/50 Bar. The obtained Mean Sauter diameter, measured by light scattering using a Malvern Mastersizer 2000 (Malvern Instruments Ltd., Malvern, United Kingdom), was 0.64 ± 0.01 µm.
Preparation of the polymer solutions and addition of the emulsion to the polymer solution required a different method depending on the gelling agent system, as explained in the following sub-chapters. The gels obtained by mixing the emulsion and the polymer solution were poured into plastic tubes (Omnifix 50 mL syringes, B.Braun) of 26 mm internal diameter, and kept in the fridge at 4°C for 15-18h before analysis.

4.1.2.1. Agar/gelatine mixed gels

For the low strain agar/gelatine gels, agar and sugar were added to water and stirred for 30 min to allow hydration of agar. The agar and sugar solution were heated, in Schott bottles, in a water bath of 90°C for 30 min, and subsequently heated on a stirring plate and kept at boiling temperature for 2-3 min until agar was completely dissolved. After dissolution of agar, the solutions were cooled to 60°C in a water bath and gelatine was added while stirring. The obtained solutions were kept at 60°C for 20 min. The emulsion was heated for 20 min in a water bath at 60°C and mixed with the polymer solution. For the high strain gels, gelatine was added to demineralized together with sugar, stirred for 30 min to allow hydration of gelatine and then heated in a water bath at 60°C for 20 min. The polymer solution was mixed in a 1 : 1 ratio with the emulsion, which was previously heated for 20 min in a water bath at 60°C.

4.1.2.2. K-Carrageenan/locust bean gum mixed gels

A 0.15 wt% KCl solution was prepared by adding KCl to demineralized water and stirring the solution for a few min. LBG, κ-carrageenan and sugar were added to the KCl solution, and stirred for 30 min to allow hydration of the powders. The solutions were heated, in Schott bottles, in a water bath at 90°C for 30 min and subsequently heated on a stirring plate and kept at boiling temperature for 2-3 min until all powders were dissolved. After total dissolution, the polymer solution was mixed in a 1 to 1 ratio with the emulsion, which was previously heated for 20 min in a water bath at 90°C.

4.1.2.3. High/low acyl gellan mixed gels

A 0.42 wt% sodium citrate solution was prepared by adding tri-sodium citrate to demineralized water and stirring the solution for a few min. High acyl gellan, low acyl gellan and sugar were added to the tri-sodium citrate solution, and stirred for 30 min to allow hydration of the powders. The solutions were heated, in Schott bottles, in a water bath at 90°C for 60 min, and subsequently heated on a stirring plate and kept at boiling temperature for approximately 5 min until all powders were dissolved. After total dissolution of the powders, $CaCl_2$ was added to the boiling polymer solution to reach a final concentration of 0.35 wt% in the polymer solution. The polymer solution was stirred 1 min and mixed in a 1 to 1 ratio with the emulsion, which was previously heated for 20 min in a water bath at 90°C.

4.1.1. Gel characterisation

4.1.1.1. Fracture properties

Gels were stored at 4°C and equilibrated at 20°C during 30 min before mechanical testing. Gel cylindrical pieces were cut in size of 20 mm height and 26 mm diameter and were lubricated with paraffin oil. Uni-axial compression test were performed using a Texture Analyzer (TA.XT plus, Stable Micro Systems-SMS) with a load cell of 50 kg and a probe of 75 mm diameter. Gels were compressed at room temperature up to 80% strain at a constant deformation speed of 1mm/s. For each gel type, three pieces were measured from gels prepared on 10 different days. In total 30 gel pieces were measured per gel type, and average values for fracture stress and strain were calculated.

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4.1.1.2. Recoverable energy

Recoverable energy was measured by compressing cylindrical gel pieces of 20 mm height and 26 mm diameter at a deformation speed of 1 mm/s. Low and high fracture strain samples were compressed up to a strain of 20% and 35% respectively, corresponding to approximately 50% of their fracture strain. Subsequently the gels were decompressed at a deformation speed of 1 mm/s to their initial height. Recoverable energy was defined as the ratio between the energy released as mechanical work during decompression and the energy applied during compression. The energy is calculated as the area below the force over deformation curve. Measurements were performed on two different days of preparation of the gels in triplicate.

4.1.1.3. Serum release

4.1.1.3.1. Micro centrifugation

Serum release was measured by using an adapted version of the centrifugation procedure from Urbonaite et al. (2014). In this study the serum phase is defined as water, sugar, emulsified oil droplets and vanilla flavour. To measure the amount of serum release from the gels, microcentrifuge filtration units composed of an inner spin tube and a 2mL Eppendorf tube (Axygen Biosciences, Inc., Union City, CA, USA) were used. A piece of filter paper with a diameter of 5.5 mm was used to cover the bottom of the inner spin tube. Gel pieces of 10mm height and 4.8mm diameter were placed on the filter paper at the bottom of the spin tube and centrifugation was performed at a g-force of 200 for 10 min at 20°C.

The weight of the serum collected at the bottom of the Eppendorf tube, was determined and was seen as a measure for the amount of serum release. The serum release was calculated as the amount of serum (%) left at the bottom of the Eppendorf tube after centrifugation over the total amount of serum present in the gel. Measurements were performed on two different days of preparation of the gels in triplicate.

4.1.1.3.2. Syneresis

Syneresis was measured by storing a gel cylindrical piece of 26 mm diameter and 10 mm height in a sealed container at 20°C for 48 hours. The amount of serum left in the container was weighed after removing the gel piece. Syneresis was calculated as the amount of serum (%) left in the cup over the total amount of serum present in the gel. Measurements were performed on two different days of preparation of the gels in quadruplicate.

4.1.1.4. Melting

The melting behaviour of the gels was measured using an AP-501 rheometer (Anton Paar, Graz, Austria). The rheometer was operated in oscillatory mode with a parallel plate-to-plate geometry, with a rough surface, at a frequency of 1Hz and a strain of 1%. Gel cylindrical pieces of 26 mm diameter and 5 mm height were compressed up to a normal force of 0.5N. Subsequently, while operating in oscillatory mode, the temperature was increased from 20°C to 50°C at a rate of 1°C/min. The temperatures at which the melting process of the gels starts and ends ($T_{m,onset}$ and $T_{m,end}$) were obtained from the melting curves, according to Mosca et al. (2014). $T_{m,onset}$ was defined as the temperature at which the storage modulus (G') started to decrease sharply during heating and $T_{m,end}$ was defined as the temperature at which the G' remained approximately constant upon further heating. Measurements were performed on two different days of preparation of the gels in triplicate

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4.1.1.5. Tribology

The tribological properties of the gels were determined with a self-built Optical Tribological Configuration (OTC) according to the method described by Liu et al. 2015. Prior to the OTC tribological measurements, gels were pre-treated by being disrupted into smaller pieces to mimic chewed foods under oral conditions. The gels were squeezed through the orifice of a syringe of 0.9 mm internal diameter. This squeezing was performed by moving vertically the syringe plunger at a constant speed (1 mm/s) for 40 s with Texture Analyzer (TA.XT plus, Stable Micro Systems-SMS). The broken-down gel pieces were collected and around 200 mg of gel was sheared in the OTC between two surfaces. The upper surface is a flat-bottom rough PDMS probe (Sylgard 184 Dow Corning, USA; mixing ratio of PDMS: cross linker ¼ 10:1; diameter 6 mm) and the lower surface is made of glass. The load (F_z) between the upper surface and sample was 0.5 N. During each measurement the lower glass plate was oscillating 10 cycles over a distance of 16 mm at an increasing oscillating speed from 10 mm/s to 80 mm/s, with incremental steps of 10 mm/s. The friction force (F_x) was measured during the movement of the glass plate. Each measurement was performed using a new probe and after cleaning the surfaces of probe and glass with ethanol and water. Tribological measurements were conducted at 22°C and after keeping the syringe containing the gel at 37°C for 20 min in a water bath. All measurements were conducted in triplicate on one preparation day.

4.1.1.6. Microstructure

Confocal Laser Scanning Microscopy (CLSM) was used. For CLSM, during gel preparation a 0.005% solution of Nile blue was added to the emulsion together with the addition of vanilla flavour to reach a final concentration of 0.05 wt% in the emulsion-filled gels. The gels were poured in a glass cuvette on top of a glass lamella and were covered with a lid during setting of the gels. The images were recorded using a LEICA TCS SP5 Confocal Laser Scanning Microscope (Leica Microsystems CMS GmbH, Manheim, Germany) equipped with an inverted microscope (Leica DM IRBE) and two lasers were used: Argon and HeNe633. The objective lens used was HCX PL APO Water CORR CS zoom 2 (Leica). The images were acquired at a resolution of 1024x1024 pixels.

4.1.1.7. Data analysis of gel properties

Gel properties were exported in SPSS (SPSS software Statistics 21. SPSS Inc., Chicago. USA) and analysed by ANOVA. Gelling agent matrix, fracture strain and fracture stress were used as fixed factors (for tribological measurement temperature was used as an additional factor). A Bonferroni post-hoc was conducted when interaction effects between factors were significant. A significant p-value of 0.05 was chosen.

4.1.2. Oral breakdown of gels

4.1.2.1. Bolus collection

A homogeneous group of subjects (n=10) was selected based on the subjects natural eating time of the gels. Subjects had a healthy BMI (18< BMI <25) and complete dentition (minimum 24 teeth). The subjects were male (3) and female (7) students aged between 21 and 26 years. Cylindrical pieces of gels of 26 mm diameter and 10 mm height, corresponding to 6.1±0.2 g of gel, were cut and stored 2-3 hours in a fridge at 4 °C prior to the bolus collection sessions. Each subject joined two sessions of 45 min, when they were invited to chew on gel pieces keeping their behaviour as natural as possible. They were instructed to expectorate a first piece of gel after 5 seconds and a second and a third piece of gel at the time they felt the desire to swallow, simultaneously they recorded their eating time. Samples were presented in a randomized order and coded with 3 digits. Subject received 18 gel pieces per session.

4.1.2.2. Gravimetrical determination of saliva content

Boli expectorated at the end of eating time were collected for saliva content determination. The expectorated gel pieces were collected directly on aluminium dishes and weighed. They were subsequently dried in an oven at 105°C for 24 hours, cooled for 60 min in a desiccator and weighed for a second time. The saliva content was measured as the added amount of moisture to the gels (wt%):

$$saliva = \frac{Moisture\ boli - Moisture\ gel}{Moisture\ gel}\ x\ 100\%$$

4.1.2.3. Analysis of gel fragments in the bolus

Boli were expectorated in a sealable cup (screw cap urinary cup 120 mL, VWR). 20 mL of water was added immediately after expectoration to the cups containing boli from agar/gelatine and gellan gels in order to prevent the bolus particles sticking together. The boli collected from the gels were rinsed on a 335 µm mesh sieve with approximatively 200 mL water to remove fragments smaller than 335 µm. The boli fragments remaining in the sieve were collected and dispersed by gently stirring them with a spatula on two petri dishes (plastic 94/16 mm, Greiner) containing distilled water. A grayscale picture of each boli was taken in duplicate at resolution of 800 dpi by placing the petri dishes on a 9950F scanner (Canon Inc., JP). Pictures were imported into ImageJ (Nation Institutes of Health. Version 1.45 K) where a black and white threshold was applied and a particle size analysis was conducted. Results from ImageJ for each picture consisting of a list of area and roundness of each detected fragment were exported to Excel (Microsoft. 2010). For each boli, the average roundness of the fragments, mean Sauter diameter and number of fragments were obtained.

4.1.2.4. Data analysis of bolus properties

Outliers (z>2) were eliminated from the dataset. Number of fragments, diameter, roundness and saliva content required to be square rooted to obtain a normal distribution before statistical analysis. A factorial repeated measure ANOVA were conducted with spitting time (5 s and before swallow only for particle size analysis), gels system (agar/gelatine, carrageenan/locust bean gum, low/high acyl gellan), fracture strain (high and low) and fracture strain (high and low). A significant p-value of 0.05 was chosen.

4.1.3. Qualitative descriptive analysis (QDA)

A panel was selected and trained according to the principles of QDA (Stone and Sidel, 1985). The panel consisted of Dutch women (n=12) with an average age of 54.5 ± 9.9 years. 10 of the 12 panellists participated previously in several QDA assessments of similar model food gels, which imply they were experienced in performing texture evaluation of

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this kind of gels. Six training session of two hours were conducted with the 12 gel samples. During the first two training sessions, the panel generated a list of attributes using the list described by Devezeaux de Lavergne et al. (2015) as input. The following two training sessions aimed to reach consensus between panellists on rating of the attributes, with focus on texture attributes. In the fifth training session, the panellists had to rate the samples in test conditions in sensory booths. In the last training session, the obtained results were discussed to optimize the consensus between the panellists. After completion of the training, the samples were evaluated in individual sensory booths at 20°C (± 1°C), under normal light conditions in triplicate in a balanced design during three sessions of 2h. All samples were prepared 24 h prior to the sensory assessment and cut in cylindrical pieces of gels of 26 mm diameter and 10 mm height, corresponding to 6.1±0.2 g of gel, 2-3 hours before sensory analysis and stored in a fridge at 4 °C. During the profiling sessions three pieces of a sample were served in one cup, numbered with 3-digit codes and provided in a randomized order between panellists. The panellists evaluated the samples using an unstructured 100 mm line scale anchored with 'very little' at 10% and 'very much' at 90% of the line scale. All panellists followed the same tasting procedure. First, they were instructed to bite, with teeth and lips, a piece of the gel to evaluate the first bite attributes. Then brittleness was evaluated at the second bite by pushing the gel to the molars for a second bite. Taste attributes were assessed after subsequent chews. A new piece of sample was taken to evaluate the chew down attributes. Finally, after-taste and after-feel attributes were evaluated after spitting out the sample. Panellists took a break of at least 2 min, rinsed their mouth with water and ate a cracker before tasting the next sample. Data were registered using a web based system to collect sensory data (EyeQuestion. V3.8.13. Logic 8. The Netherlands).

The data was exported in SPSS (SPSS software Statistics 21. SPSS Inc., Chicago. USA). For all attributes an ANOVA was conducted with gel type as a fixed factor and panellist as a random factor followed by a Tukey Post-Hoc between samples. For attributes of specific interest, such as first bite attributes and fat related attributes, a factorial ANOVA was conducted with gels system (agar/gelatine, carrageenan/locust bean gum, low/high acyl gellan), fracture strain (high and low) and fracture strain (high and low) as fixed factors and panellists as random factor. A significant p-value of 0.05 was chosen. Principal Component Analysis (PCA) was conducted for all texture attributes and all samples in Unscrambler (The Unscrambler® X software V10.2, CAMO software, Norway). Pearson correlations between physical properties of gels and QDA ratings of sensory attributes in SPSS.

4.2. Results and discussion

4.2.1. Gel physical properties

4.2.1.1. Fracture properties

Values of fracture stress and strain of the gels can be seen in Figure 4.1. High fracture stress gels had a fracture stress 2.2 times larger (in average 70.7±1.8 kPa) than low fracture stress gels (in average 32.9±2.7 kPa). High fracture strain gels had a fracture strain 1.9 times larger (average 67.2±4.3 %) than low fracture strain gels (average 35.9±4.4 %). Using different gelling agents, at a given fracture stress and strain combination, did not significantly impact fracture stress of gels with the exception of the HσLε gellan gel ($p<0.001$). Fracture strain, at a given fracture stress and strain combination, was not different between the gelling agent systems ($p>0.05$). Compared to the large differences between high and low fracture stress gels, the variation in fracture stress between gelling agent within a stress/strain combination was considered negligeable. The full factorial design is considered achieved with distinct high and low values of fracture stress and fracture strain and only small variations between gels differing in composition within a fracture stress/strain combination.

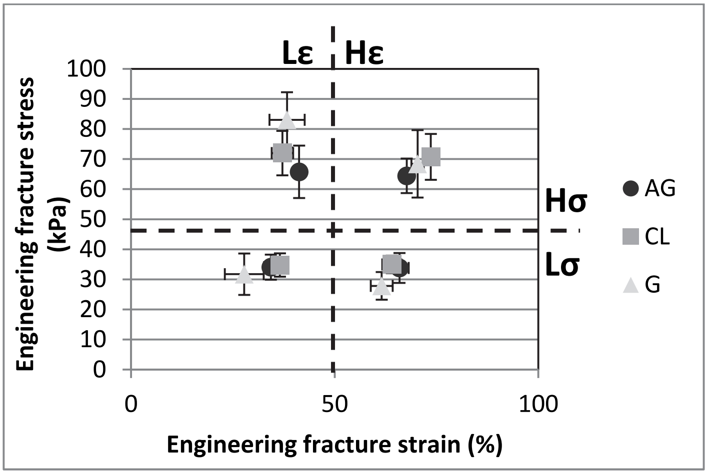

Figure 4.1 Fracture stress (σ) and strain (ε) of gels. Error bars indicate the standard deviation.

It can be seen in Appendix 4.1 that, at low fracture strain, the shape of the fracture curve of agar/gelatine gels is slightly different from the fracture curve of carrageenan/LBG and gellan gels. At low fracture strain, agar/gelatine gels do not decrease as sharply as other systems after fracture and continue to resist to compression despite the decrease in stress. At high fracture strain, the fracture curve of agar/gelatine gel is narrower and becomes similar to the curve of carrageenan/LBG and gellan gels which decreased less sharply in stress after fracture than low fracture strain gels. Such a difference in the fracture curve might impact perception as discussed by van den Berg et al. (2008b).

Young's modulus and fracture energy of gels are given in Appendix 4.2. Young's moduli of high fracture strain gels were all similar between gelling agent systems. Young's modulus was high in low fracture strain gels and higher in low fracture strain and high fracture stress gels. Fracture energy was high in high fracture stress gels and low in low fracture stress gels, and did not vary with different fracture strain, gelling agent systems had similar values of fracture energy.

4.2.1.2. Recoverable energy

Recoverable energy of the gels is shown in Appendix 4.2. Recoverable energy of gels were below 100% as the gels were filled with an emulsion stabilised by Tween 20 and the droplets acted as inactive fillers (Sala et al. 2007a). For most gels, fracture stress did not influence significantly recoverable energy. For all gelling agent systems, fracture strain influenced recoverable energy ($p<0.001$). High strain gels of agar/gelatine and gellan gels had a higher recoverable energy, while, for carrageenan/LBG gels, the high strain gels had a lower recoverable energy. Such an effect in carrageenan/LBG gels could be the presence of junction zones in the high fracture strain gels due to addition of LBG which could lead to extra energy dissipation by decoupling of the junction zones. When comparing the different gelling agent systems, it appeared that agar/gelatine gels had the highest recoverable energy, especially for pure gelatine gels, while carrageenan/LBG gels have the lowest recoverable energy. These differences might be related to serum release which is expected in carrageenan/LBG and gellan gels and could dissipate the compressive energy applied on the gels. Recoverable energy is expected to influence perception of crumbliness, therefore differences between gelling agents systems are expected for this sensory attribute.

4.2.1.3. Serum release

Two methods to quantify serum release were used. One used microcentrifugation that applied a mechanical force on the gels and is expected to reflect the amount of serum release during mastication, when a force is applied to the gel by the molars. The second method consisted measuring the amount of serum leaving the gel matrix without any mechanical constrain and reflects syneresis of the gels, which is expected to affect surface properties of the gels. In both methods, serum was turbid and is therefore expected to contain oil droplets, which were not bound to the matrix. In Figure 4.2, it can be observed that agar/gelatine gels released almost no serum with both quantification methods, while carrageenan/LBG and gellan gels show some serum release. It is known that gelatine has good water holding properties (Ares et al. 2007), therefore the large amounts of gelatine present in the gels result in small amounts of released serum. Both carrageenan/LBG and gellan gels released serum. More serum was released during microcentrifugation than during syneresis of the gels.

Results of serum release by microcentrifugation are shown in Figure 4.2.A. Carrageenan/LBG and gellan gels release between 5.6 wt% and 27.6 wt% of serum. Low fracture stress gels released more serum than high fracture stress gels ($p<0.001$). The high fracture stress gels, at both fracture strains and in both gelling agent systems, released significantly different amounts of serum but the differences were small. For carrageenan/LBG gels, the LσHε gel which contained the least amount of carrageenan released more serum. For gellan gels, the LσLε gel, which contained the least amount of high acyl gellan, released a large amount of serum. The results on gellan gels are in line with literature. In high/low acyl gellan mixed gels, Huang, et al. (2003) found that gels containing high acyl gellan have better water holding capacities compared to gels containing low acyl gellan. Results of syneresis are shown in Figure 4.2.B. Carrageenan/LBG and gellan gels released between 0.1 wt% and 6.6 wt% of serum by syneresis. It can be seen that carrageenan/LBG gels released more serum than gellan gels ($p<0.001$). Decreasing fracture stress and increasing fracture strain resulted in more serum release for both gelling agent systems ($p<0.001$). Considering the composition of carrageenan/LBG gel systems (Table 4.1), such results are overall in line with literature. Measuring syneresis of carrageenan/LBG gels, it was found that lowering carrageenan concentrations lead to higher amounts of syneresis and that addition of LBG to the gel network did not influence syneresis (Dunstan et al. 2001). However, in the current study addition of LBG seemed to reduce syneresis.

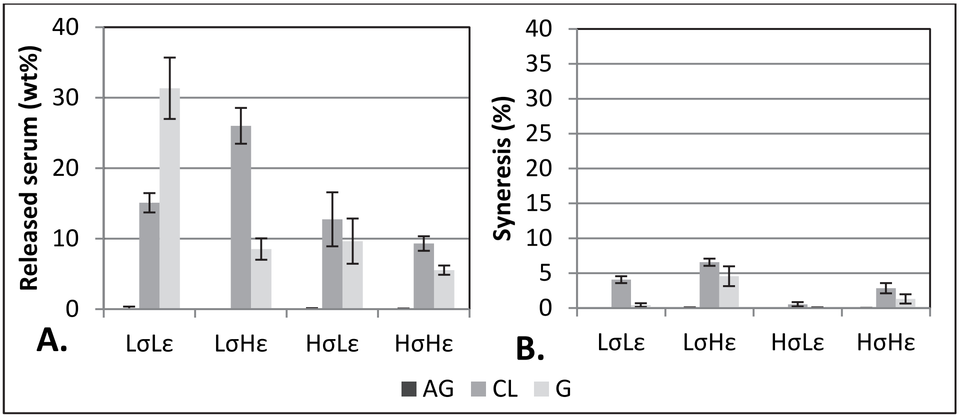

Figure 4.2 Serum release from of the gels measured by micro-centrifugation (A.) and by syneresis (B.). Error bars indicate the standard deviation.

It was confirmed that serum release is influenced by the composition of the gels and varied between fracture properties and gelling agent systems. It can be expected that serum release will lead to a more watery perception (van den Berg et al. 2007b) together with higher sweetness perception (Sala et al. 2010). Eventually fat related perception will be affected by serum release as oil droplets are present in the serum. Serum release by microcentrifugation is expected to relate to watery perceptions during chew down whereas, syneresis is expected to impact texture attributes related to surface properties of the gels.

4.2.1.4. Melting

In Figure 4.3 the melting curves for all gels are shown. From Figure 4.3.A. it is visible that only high strain agar/gelatine gels, contain only gelatine, show a true melting behaviour. For the LσHε gel the $T_{m,onset}$ is approximately 28°C and $T_{m,end}$ is approximately 33°C. For the HσHε gel $T_{m,onset}$ is approximately 30°C and $T_{m,end}$ is approximately 35°C. Moreover Tanδ became higher than 1 at temperatures around 31°C for low fracture stress gelatine gel and around 32°C for high fracture stress gelatine gel, indicating that they transitioned from a gel to a liquid. The temperature range for both gels is just below human body temperature, which indicates that these gels melt during oral processing. The low strain agar/gelatine gels do not show a clear melting curve, but a slight decrease in G' could be observed between 27 and 40°C. This decrease in G' could indicate melting of the gelatine. However, due to the presence of agar in the low strain agar/gelatine gels, these gels do not melt as much as pure gelatine gels and Tanδ remained below 1. In Figure 4.3.B. and C. the melting curves of the carrageenan/LBG and gellan gels are shown. From these curves it can be seen that none of the gels melts at human body temperature. Though a relatively small constant decrease of G' is visible, mainly in carrageenan/LBG gels, which indicates that firmness decreases slightly. Complete melting of these gels is expected to occur at temperatures between 40-60 °C for carrageenan/LBG gels (Brennera et al. 2013) and 80-90°C for gellan gels (Mao et al. 2000). It is therefore expected that agar/gelatine gels will behave differently than other gels during oral processing which will results in differences in perception of chew down related texture attributes.

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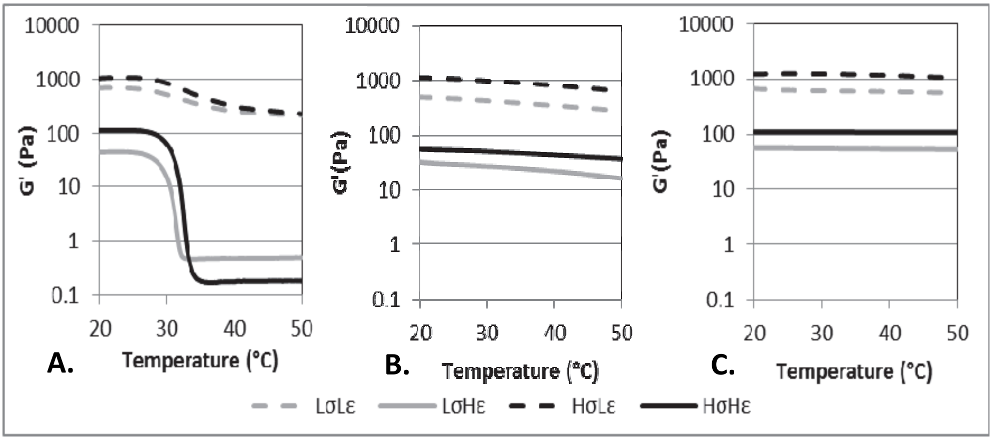


Figure 4.3 Typical melting curves obtained from agar/gelatine (A.), k-carrageenan/locust bean gum (B.) and high/low acyl gellan gels (C.).

4.2.1.5. Tribology

Friction properties of gels at 22°C and 37 °C are given in Figure 4.4. The three gelling agents differed significantly in friction forces ($p<0.001$). Agar/gelatine gels showed the highest friction force, followed by gellan gels. Carrageenan/LBG gels had the lowest friction force. Fracture properties of gels impacted friction of agar/gelatine and gellan gels. In gellan gels a higher friction was found for low fracture stress gels and for low fracture strain gels. For agar/gelatine gels, the impact of fracture properties was not clear. It can be seen that changing the temperature of the gels from 22°C (Figure 4.4.A.) to 37°C (Figure 4.4.B.) had an impact on friction properties for all gel systems. The impact of temperature on gellan and carrageenan/LBG gels was small. With increasing temperature, the friction force increased for LσLε carrageenan/LBG and gellan gels and did not impact friction of other gels. For agar/gelatine gels, an increase in temperature to 37°C, which is above the melting temperature of gelatine, had a higher impact on friction force than in carrageenan/LBG and gellan gels. In high fracture strain agar/gelatine gels that melted below 37°C, friction decreased as a result of melting of gelatine. For low fracture strain gels, that partially melted below 37°C, friction either increased (LσLε gel) or decreased (HσLε gel) with increasing temperature.

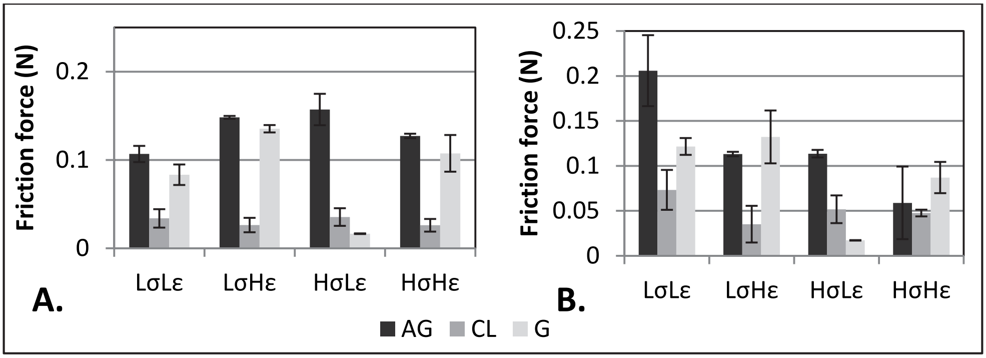


Figure 4.4 Friction force measured in triplicate at a speed of 80 mm/s of gels at 22°C (A.) and 37°C (B.) Error bars indicate the standard deviation.

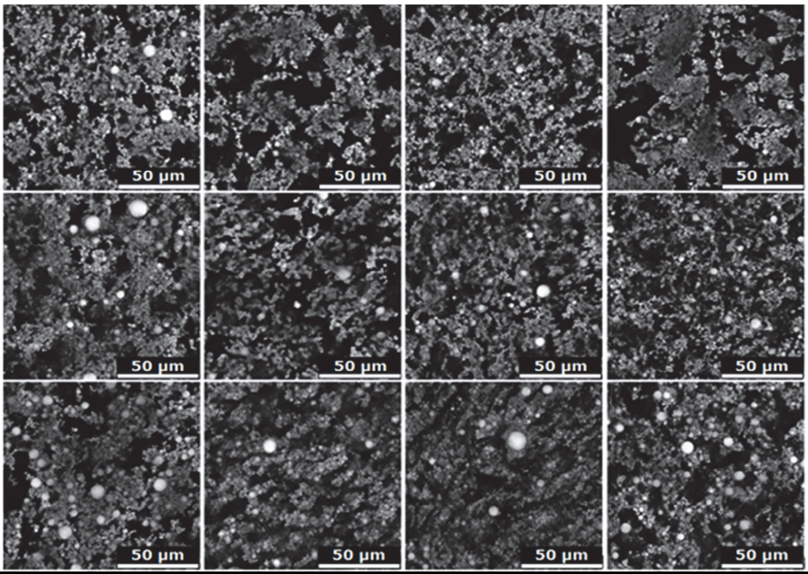
Fracture properties had an impact on friction force in gellan gels but not in other gels suggesting that after breakdown of the gels, fracture properties do not impact the lubrication properties. Carrageenan/LBG gels had the lowest friction force, probably due to a thin film of serum released to the surface of the broken down gel. Moreover, friction force at 22°C negatively correlated to serum release during microcentrifugation ($r=-0.616$, $p<0.05$). Agar/gelatine gels had the highest friction force which decreased with melting at 37°C except for the LσLε gel, in which partial melting might have caused inhomogeneity which increased friction. Overall, the melting of gelatine improves lubrication properties of gels but at a lower extend than serum release under the conditions tested.

4.2.1.6. Microstructure

Images of the microstructure of the gels obtained by CLSM are shown in Table 4.2. For all gels, oil droplets were stabilized by Tween which has no physical or chemical affinity to the gel matrices used (Dickinson, 2012). Slightly bigger oil droplets could be seen in carrageenan/LBG gels and in gellan gels, which could be due to coalescence of the oil droplets during the heat treatment of the emulsion required to make the gels. The oil droplets are inhomogeneously distributed in all gels and were most visible in gels containing only gelatine. Overall, it can be considered that the oil is distributed similarly in the gels regardless of their composition. Therefore, microstructure of the different gelling agent systems, observed above 1 µm length scale, is not expected to impact greatly fat related texture perception of the gels.

Table 4.2 CLSM images obtained from gels stained with Nile blue. Fat appears in white, the gel matrix and the serum phase appear in black.

Gelling agent system	Fracture properties			
	LσLε	LσHε	HσLε	HσHε
Agar/gelatine				
Carrageenan/ LBG				
Gellan				



4.2.2. Oral processing of the gels

4.2.2.1. Eating duration

The eating time required for the subjects to chew on the gels is given in Figure 4.5.A. It can be seen that eating time varied between samples between around 8 s to 15 s. Gels made from different gelling agents systems were masticated for significantly different durations ($p<0.001$). Carrageenan/LBG gels were masticated significantly shorter than the other gels.

Agar/gelatine and gellan gels were masticated for similar durations except for LσLε gels. Fracture properties of gels also impacted eating duration. An increase in fracture stress increased the eating duration on the gels significantly for all gels ($p<0.001$). An increase in fracture strain decreased significantly the eating duration of agar/gelatine and carrageenan/LBG gels ($p<0.001$). An increase in fracture strain increased the eating duration of gellan gels but only for low fracture stress gels ($p<0.05$).

Such results suggest that carrageenan/LBG gels were easiest to swallow compared to other gels, which could be due to a higher syneresis increasing lubrication of the bolus. Gels with a high fracture stress were probably harder to break down as they required a higher chewing force. Therefore, subjects required more time before being able to swallow high fracture stress gels safely. An increase in fracture strain decreased eating time for agar/gelatine gels which contained only gelatine at high fracture strain and had a steep melting curve below mouth temperature. Such a decrease in eating time could be due to melting of the gelatine.

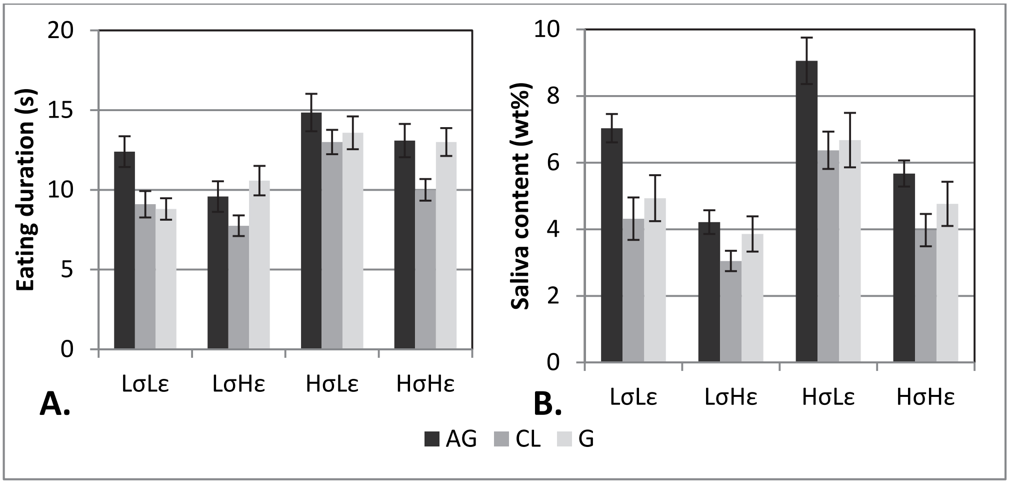


Figure 4.5 Eating duration (A.) while subjects (n=10) masticated freely on gels. Saliva content in boli (B.) from these subjects (n=10) expectorated just before swallowing of gels. Error bars indicate the standard error to the mean.

4.2.2.2. Saliva incorporation

The amount of saliva incorporated in the boli before swallow is given in Figure 4.5.B. It can be seen that saliva content varied between 3 wt% and 9 wt%. Gels containing different gelling agents produced boli containing different amounts of incorporated saliva ($p<0.001$). Boli from agar/gelatine gels contained more saliva than other gelling agent systems for low fracture strain gels. Fracture properties of gels also impacted saliva incorporation. Boli from gels with a high fracture stress contained significantly more saliva than boli form low fracture stress gels. Boli from high fracture strain gels contained significantly less saliva than boli from low fracture strain gels, in all gel systems (p<0.001). These results suggest that agar/gelatine gels required more incorporation of saliva into the gel bolus than other gels to be safely swallowed. Such results were not expected as gelatine is known to melt at mouth temperature which increases lubrication (Sala et al. 2008). These differences could be due to the high water holding capacity of gelatine and the absence of serum release and syneresis in agar/gelatine gels, requiring a higher saliva incorporation to ensure sufficient lubrication of the boli. The high saliva incorporation in high fracture stress gels coincides with a longer eating time (Tarrega et al. 2011; Devezeaux de Lavergne et al. 2015b). The lower saliva incorporation in high fracture strain gels could be due to the slightly shorter eating time. However, it is probably due to melting of the high fracture strain agar/gelatine gel and syneresis of the high fracture strain carrageenan/LBG and gellan gels.

4.2.2.3. Gel fragments in the boli

Number and size of the gel fragments in the boli after 5 s of mastication and at swallow are given in Figure 4.6. The average diameter is given after 5 s of mastication (Figure 4.6.A.) and at swallow (Figure 4.6.B.), and the number of fragments in the boli is given after 5 s of mastication (Figure 4.6.C.) and at swallow (Figure 4.6.D.). It can be seen that the average fragments size varies between 2.53 mm and 0.74 mm and that the number of gel fragments in the boli varies greatly between gels, from 101 to 1530 gels fragments. An increase in eating time significantly lowered fragment size of high strain gels (p<0.05) and increased significantly the number of gels fragments in the boli of all gels (p<0.001) except for agar/gelatine gels. For the LσHε and HσHε gels, boli from agar/gelatine gels contained significantly smaller and more numerous fragments than boli from other gels (p<0.001). Boli from carrageenan/LBG and gellan gels were not significantly different. Fracture stress of gels did not significantly impact the size or number of fragments. An increase in fracture strain significantly increased the size of fragments (p<0.001), this effect was smaller for gelatine gels. Roundness (data not shown) is a descriptor of shape of the gel fragments in the boli. Roundness did not change significantly with eating time (p=0.318) and was higher in agar/gelatine gels (p<0.001) than in other gel systems, and was higher in low fracture strain gels (p<0.001).

Such results on fragments number size and shape in the boli suggest that, as gels are broken down during chewing, more fragments of smaller size and rounder shape are formed. For agar/gelatine gels, which partially melt in mouth, melting and breakdown occurred simultaneously and produced smaller fragments than in other gel systems. The impact of fracture properties on boli fragments was small in agar/gelatine gels but high in carrageenan/LBG and gellan gels that did not melt. Fracture strain had the highest impact with low fracture strain gels producing boli containing many small and round fragments as the gels were easily broken down at small deformations. High fracture strain gels produced boli with few big particles which could be swallowed as such probably due to their high deformability.

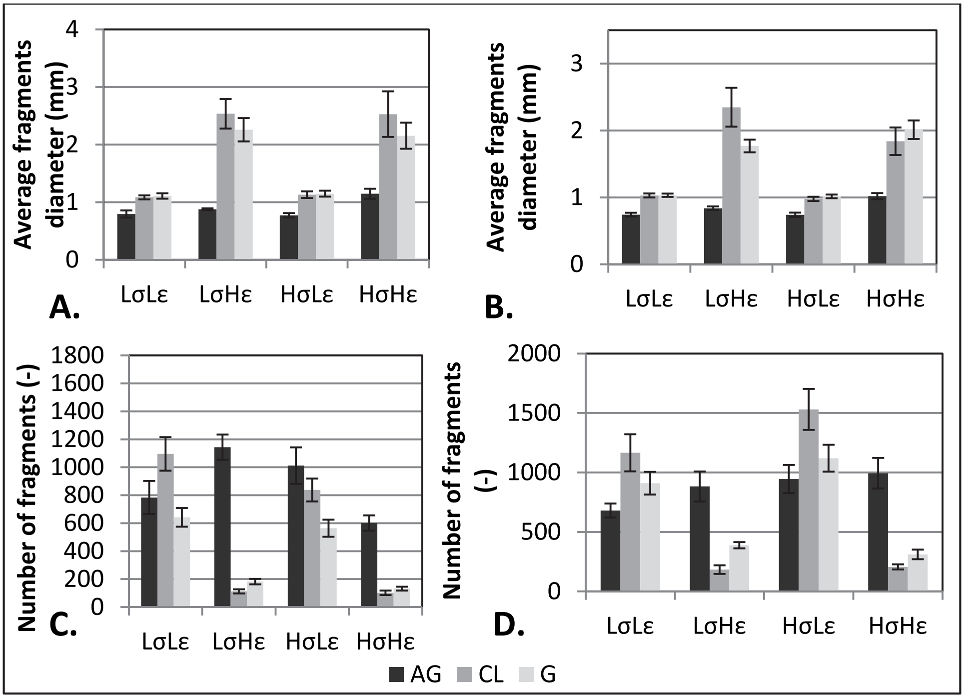


Figure 4.6 Average diameter of gel fragment in boli expectorated by subjects (n=10) after 5 s (A.) and just before swallow (B.). Average number of gel fragments in boli expectorated by subjects (n=10) after 5 s (C.) and just before swallow (D.). Swallowing time of gels corresponded to eating durations shown in Figure5.A. Error bars indicate the standard error to the mean.

4.2.3. Qualitative descriptive analysis

The 31 texture attributes generated during the QDA training sessions are shown in Table 4.3. Texture attributes were divided in first/second bite texture attributes (4 attributes), chew down texture attributes (15 attributes) and after-feel texture attributes (5 attributes). 7 attributes were used to describe taste and after-taste perception.

The mean intensity scores with standard deviations for all attributes together with the results form statistical data analysis are summarized in Appendix 4.3. Perception of taste attributes varied between gels. Agar/gelatine gels were perceived as high in total taste intensity, sweetness, vanilla flavour and bitter taste. Overall, gels with a low fracture strain were perceived with higher taste intensity. Results of after-taste perception were similar

Table 4.3 Sensory attributes and definition used for the QDA.

Group	Attribute	Description
Taste	Intensity	Total quantity of taste
	Sweet	Basic taste and of artificial sweetener
	Vanilla	Toffee, vanilla, caramel
	Bitter	Basic taste
First bite	Sticky	Sticky, clinging during biting
	Firm	Effort needed to bite off with incisive and molars
	Elastic	Resilient
Second bite	Brittle	How easily the product breaks when crushed between molars
Chew down	Firm	Effort needed to crush the product
	Tough	Effort to bite of and to process; strong coherence
	Sticky	Clinging in the mouth
	Elastic	Resilient
	Slippery	Sliding easily in the mouth
	Moist	Watery
	Rough	Hairy teeth, like eating rhubarb
	Spreadable	Unctuous
	Creamy	Products feels full, soft, velvety
	Fatty	Oil-like, like unctuous
	Melting	Dissolves, structure disappears like in ice-cream
	Powdery	Mealy, like uncooked corn starch in water
	Crumbly	Breakdown in pieces during chewing
	Refreshing	Cold feeling in the mouth
	Clean mouth	Difficulty to clean the mouth
After-taste	Sweet	Basic taste and of artificial sweetener
	Bitter	Basic taste
	Liquorice	Liquorice-like, salmiak, laurel drop
After-feel	Creamy	Products feels full, soft, velvety
	Fatty	Oil-like, like unctuous
	Dry	A dry after-feel
	Pepper	Pungent, tingling, sparkling
	Residue	A substance remains

to the results of taste perception. It can be seen in Appendix 4.3 that perception of taste, and specifically of bitter taste, correlated positively with the number of gels fragments in the bolus and negatively with the size of the fragments both after 5 seconds chewing and at swallow. As the total surface area of the particles increases, it is known that more tastants migrate through the matrix surface into the oral cavity (Mosca et al. 2012). These results can explain that agar/gelatine gels and low fracture strain gels were perceived

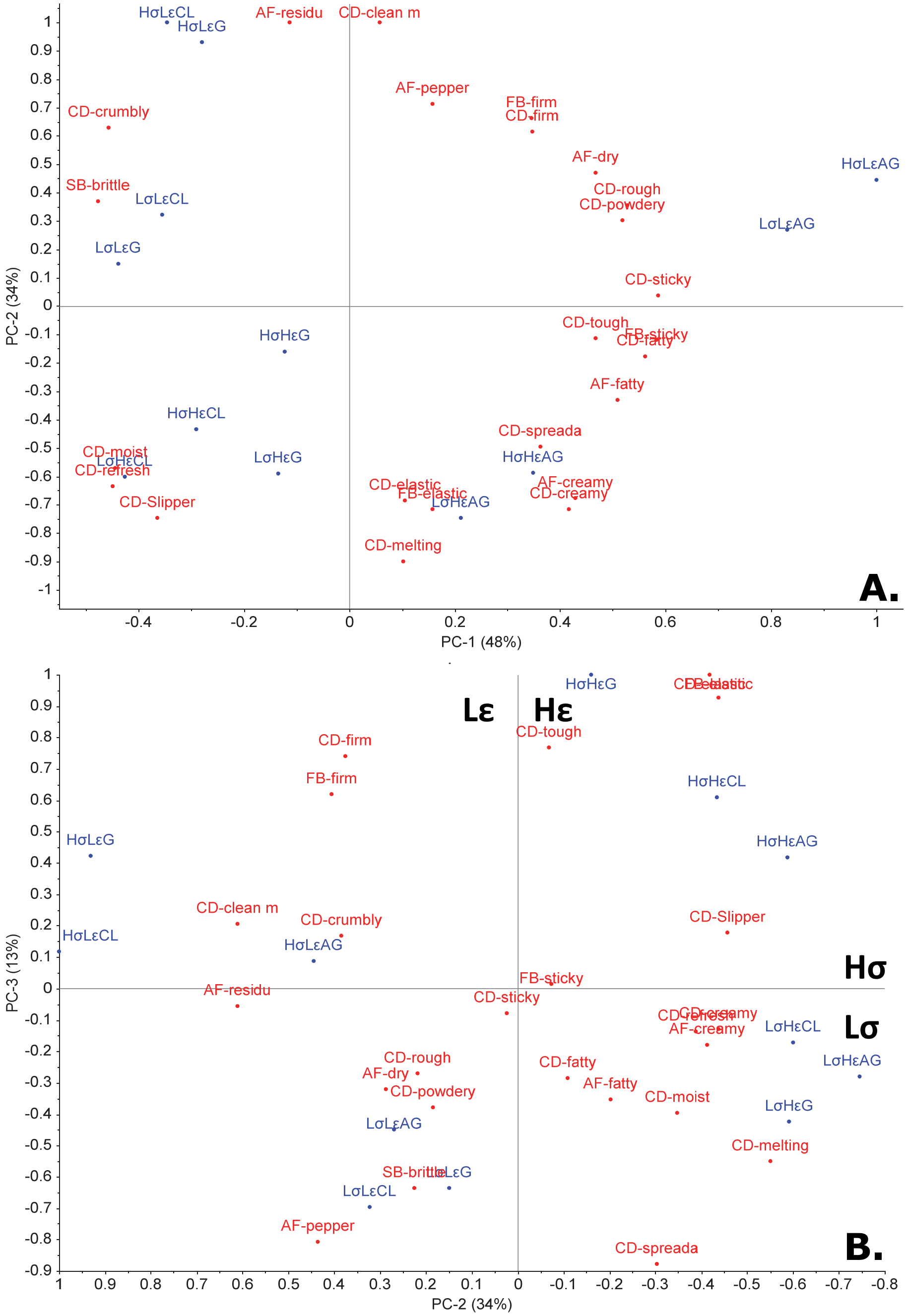


Figure 4.7 PCA plot of the gels on the texture related sensory attributes of the QDA. PC2 over PC1 is plotted in A. while PC3 over PC2 is plotted in B. FB stands for first bite attributes, SB for second bite attributes, CD for chew down attributes and AF for after-feel attributes.

more intense in taste as they generated many small particles upon chewing, respectively due to melting at mouth temperature and fast breakdown at low deformation. Moreover, serum release of carrageenan/LBG and gellan gels did not coincide with an increase in taste perception suggesting that the effect of fracture properties overruled the effect of released serum.

Sensory perception of texture attributes is summarized using principal component analysis in Figure 4.7. PC1 represents 48% of the variance between the samples and separates gels made of agar/gelatine, on the right side of PC1, compared to carrageenan/LBG and gellan gels on the left side (Figure 4.7.A.). Agar/gelatine gels are perceived sticky, rough, tough powdery, fatty and creamy, while carrageenan/LBG and high/low acyl gellan gels are perceived brittle, slippery, moist, crumbly and refreshing. PC2 and PC3 represent respectively 34 and 13 % of the variability between the samples (Figure 4.7.B.). PC2 and PC3 separate gels varying in fracture properties. It can be seen that gel with high fracture strain are elastic, slippery, creamy, melting and refreshing, while gels with a low fracture strain are perceived crumbly, with higher effort to clean the mouth and more residues in the mouth after expectoration. Gels with a high fracture stress are perceived as firm and elastic while gels with low fracture stress are perceived as spreadable.

Such results suggest that the use of different gelling agents has a high impact on texture perception with agar/gelatine gels being perceived differently than the other two gelling system and this accounting for 48 % of variation between the gels (PC1). Fracture properties also have a high impact on perception and account for 47 % of the variation between samples (PC2 and PC3). Specific texture attributes are described in more details in the following subchapters.

4.2.3.1. First bites texture attributes

Firmness perception at first bite is given in Figure 4.8.A. Agar/gelatine gels were perceived higher in firmness than other gels ($p<0.001$). Firmness perception decreased with increasing fracture strain ($p<0.001$) and increased greatly with increasing fracture stress ($p<0.001$) for all gels. These results on firmness confirm that firmness perception at first bite is mainly dependent on fracture stress, being significantly correlated ($r=.719$, $p<0.001$). However, fracture strain and gelling agent system also impacted first bite firmness perception. As the gels were more deformable, they were perceived as less firm eventhough the same force was required to break them. Agar/gelatine gels, which after fracture still resist to compression (Appendix 4.1), are perceived firmer. Firmness perception at first bite correlated with fracture energy ($r=.686$, $p<0.05$) but this effect was less than for fracture stress. Firmness perception at first bite also correlated with eating duration ($r=.909$, $p<0.001$) and saliva incorporation ($r=.919$, $p<0.001$). Such result suggest that as gels were perceived firmer, they were masticated longer, therefore, more saliva was added to the bolus.

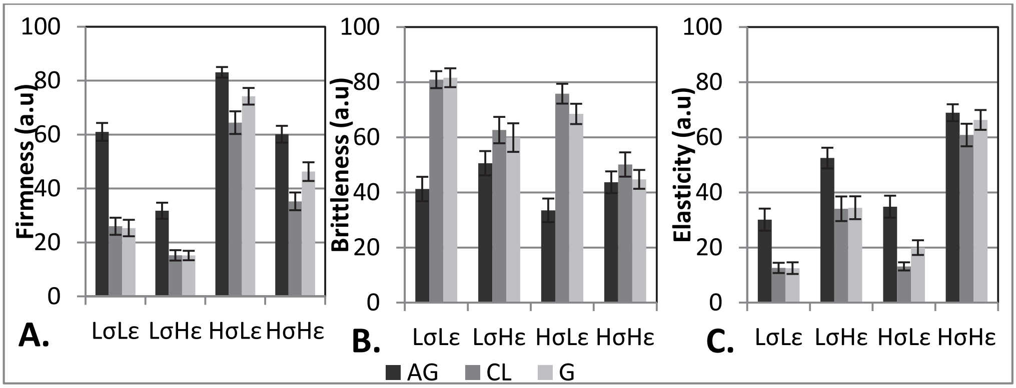


Figure 4.8 Sensory Firmness (A.), Brittleness (B.) and Elasticity (C.) perceived at first bite (n=12). Error bars indicate the standard error to the mean.

Brittleness perception at second bite, by crushing a piece of gel between the molars, is shown in Figure 4.8.B. Brittleness perception was lower in agar/gelatine gels than in other gels ($p<0.001$) and did not vary significantly between carrageenan/LBG and gellan gels. Brittleness perception decreased significantly with increasing fracture strain ($p<0.05$) except for agar/gelatine gels. Brittleness perception significantly decreased with increasing fracture stress ($p<0.05$) for high fracture strain gels. Such results suggest that fracture strain can be controlled to impact britleness perception of carrageenan/LBG and gellan gels. However, as fracture stress also influenced brittleness perception, probably because the high bitting force required in high fracture stress gels makes brittleness perception secondary, no correlation was found. Moreover, agar/gelatine gels were not perceived high in brittleness regardless of fracture strain. This suggest that other factors than fracture strain, such as the shape of the fracture curve, might be relevant in britleness perception.

Elasticity perception at first bite is given in Figure 4.8.C. Elasticity was higher in agar/gelatine gels than in other gels ($p<0.001$). It increased with increasing fracture strain for all gels ($p<0.001$) and increased with increasing fracture stress for high fracture strain gels ($p<0.001$). Eventhough fracture stress impacted elasticity and gelatine gels were perceived more elastic, it seems that elasticity perception depends mainly on fracture strain, showing a positive correlation ($r=.878$, $p<0.001$). In literature, it is known that K-carrageenan gels become more elsatic with addition of LBG (Hayakawa et al. 2014), that gelatine gels are perceived as elastic (Muñoz et al. 1986a; Muñoz et al. 1986b) and that high acyl gellan gels are perceived elastic (Hayakawa et al. 2014). As such ingredients were added in higher amount to increase fracture strain of the gels, changes in elasticity could be due to ingredients specific properties. Therefore, it is not known if high elasticity perception is due to high fracture strain or to to composition of the gels.

Stickiness (data shown in Appendix 4.3) was significantly higher in agar/gelatine gels ($p<0.001$) but did not vary between carrageenan/LBG and gellan gels nor depending on fracture properties. Such result on stickiness suggest that stickiness is an attribute that depend on the gel matrix composition. Stickiness was positively correlated to friction force of the gels at 22°C and 37°C ($r=0.756$, $p<0.001$ & $r=0.595$, $p<0.05$) suggesting that agar/gelatine gels might have adhered to the oral cavity which increased friction. Such a difference in stickiness at first bite between the gelling agent systems might interfere with perception of the other first/second bite texture attributes, contributing to the agar/gellatin system being perceived differently form the other two systems.

4.2.3.2. Texture attributes related to matrix properties varying between gelling agents

The attributes slipery and refreshing were positively correlated to the attribute moist ($r=.865$, $p<0.001$ and $r=.948$, $p<0.001$ resp.). As the attribute moist is direclty related to perception of water in the mouth, it is shown in Figure 4.9.A. and is used to describe the attributes slipery and refreshing as well. Moistness, was lower in gelatine gels than in carrageenan/LBG and gellan gels, and was slightly higher in carrageenan/LBG gels than in gellan gels ($p<0.001$). Moistness perception increased with increasing fracture strain ($p<0.001$) and decreased with increasing fracture stress ($p<0.001$) for all gels. Such results showing a high moistness perception in carrageenan/LBG and gellan gels suggest that the presence of syneresis (serum at the surface of the gel), increased the perception of moistness in the gels, which is confirmed by the positive correlation ($r=.749$, $p<0.001$; Appendix 4.4). However, moistness perception increased in agar/gelatine gels with increasing fracture strain while these gels did not show any syneresis. Such results could

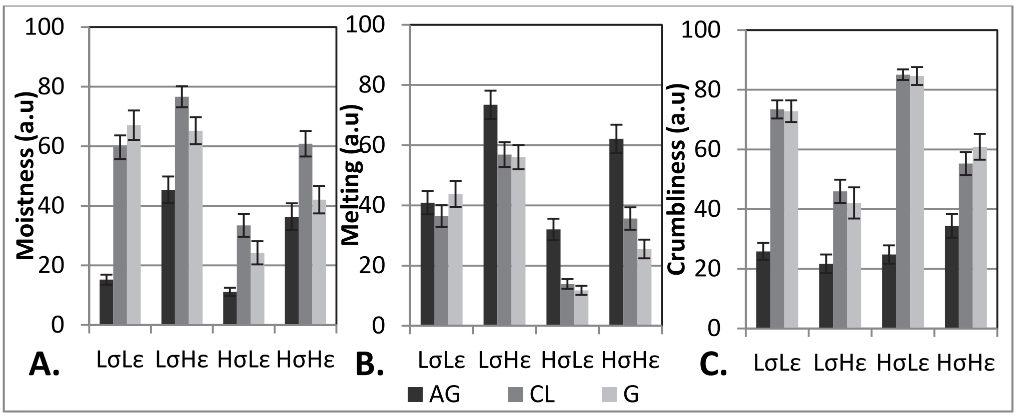


Figure 4.9 Sensory Moistness (A.), Melting (B.) and Crumbliness (C.) perceived during chew down (n=12). Error bars indicate the standard error to the mean.

be due to melting of the gelatine matrix in high fracture strain gels. Overall, these results confirm the role of syneresis in perception of moisture/water related attributes and the importance of controlling syneresis for texture perception. Serum release measured by microcentrifugation did not correlate with moiture/water related attributes, suggesting that water perception in mouth is not reflected by serum release in gels while applying a force. This could be due to the fact that the amount of serum at the surface of the gels since the beginning of mastication is more relevant for perception than serum expelled from the gel matrix during chewing, or that microcentrifugation does not reflect serum release during chewing.

Melting perception is given in Figure 4.9.B. Melting perception was significantly higher in agar/gelatine gels ($p<0.001$) than in carrageenan/LBG and gellan gels which did not significantly differ from each other's. Melting perception increased with increasing fracture strain ($p<0.001$) and decreased with increasing fracture stress ($p<0.001$) for all gels. Such results confirm that agar/gelatine gels melted in mouth and were perceived as such with a higher perception of melting. However, carrageenan/LBG abd gellan gels were also perceived as melting especially in low fracture stress and high fracture strain gels. It has been shown in litterature that gels made of k-carrageenan and low acyl gellan could be perceived as melting eventhough they did not melt in mouth. Such perception is due to the easy disruption of the gel by sheering the product in the mouth between the tongue and the palate (Hayakawa et al. 2014). It is therefore expected that higher melting is perceived for easily broken down samples with low fracture stress. However, it was shown that high fracture strain gels, which were perceived as melting, were broken down in few larges fragments. The increased melting perception could be due to the deformability of these pieces or eventualy, serum release from the gels matrix.

4

Crumbliness perception, which is related to the breakdown of gels in particles during chewing, is shown in Figure 4.9.C. Crumbliness perception was significantly lower in agar/gelatine ($p<0.001$) gels than in carrageenan/LBG and gellan gels which did not significantly vary from each others. Crumbliness decreased with increasing fracture strain ($p<0.001$) and increased with increasing fracture stress ($P<0.001$) except for agar/gelatine gels. Results on crumbliness perception suggest that gels with low fracture strain broke down in particles during chewing. This results are in agreement with low fracture strain gels being brittle and producing boli containing many gel fragments. Crumbliness would therefore be expected to be corelated to fragments number in the bolus, which was not the case (Appendix 4.3). This could be due to gelatine gels having low scores on crumbliness eventhough their boli contain many particles. Probably due to breakdown of these gels being largely influenced by melting, the breakdown is not perceived in mouth as crumbly. Crubliness is known to be positively correlated to recoverable energy of whey protein/polysaccaharide gels (van den Berg et al. 2008b), however this was not observed for the gels in the current study. This could be due to the different gelling agents used.

4.2.3.3. Fat related texture attributes

Results of creaminess perception are given in Figure 4.10.A. Creaminess perception was significantly higher in agar/gelatine gels than in other gelling egents systems (P<0.001) and did not vary depending on fracture properties. Carrageenan/LBG and gellan gels were not significantly different from each other's. Creaminess perception increased with increasing fracture strain (p<0.05) and decreased with incresing fracture stress (p<0.05) in carrageenan/LBG and gellan gels, however, the effect of fracture stress was small. This results confirm that melting of the agar/gelatine gels matrix increases greatly creaminess perception and overrulled almost completely the affect of fracture properties in this sytem. The incease of creaminess perception by melting behaviour during oral processing was observed in litterature (de Wijk, 2006b; Sala et al. 2008). In carrageenan/LBG and gellan gels, increasing fracture strain increased creaminess perception. This high creaminess perception could be due to, similarly as melting, either the deformability of the large gels fragments in the boli or their lubrication by syneresis. The properties of the gel fragment is probably the most reliable explanation as creaminess was negatively correlated to young's modulus of the gels (r=-0.604, p<0.05) (Appendix 4.4). Fracture stress had also a small inpact on creaminess perception, low fracture stress gels being perceived creamier, as they were probably easier to sheer in the mouth. A similar result was found with spreadability (Appendix 4.3), that decreased with increasing fracture stress (p<0.001). Fatiness perception is shown in Figure 4.10.B. Fatiness perception was higher in agar/gelatine gels (p<0.05) and did not significantly vary depending on fracture properties for all gels. Creamy, fatty and spreadable sensations were positively correlated

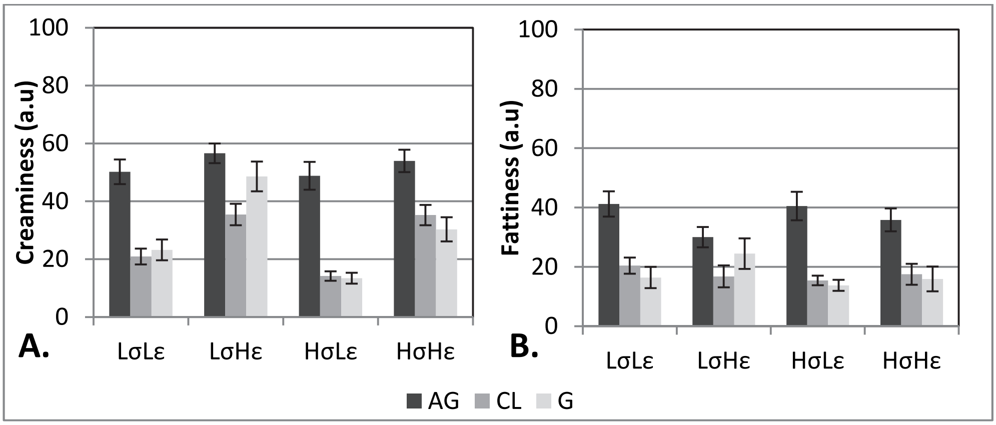


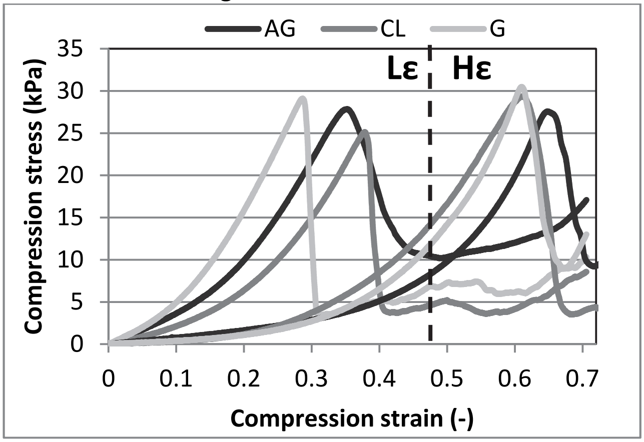
Figure 4.10 Sensory Creaminess (A.) and Fattiness (B.) perceived during chew down (n=12). Error bars indicate the standard error to the mean.

with friction force of the three gels (at 22°C: r=0.799, p<0.001; r=0.737, p<0.001 & r=0.688, p<0.05 resp.). We would have expected the inverse effect that a lower friction force would increase fat releated attributes. However, agar/gelatine gels did not show perceived as more creamy. This suggests that a high firction force is not the main mechanism explaining differences in fat related perception between the different gels used in this study. These results confirm the large differences between agar/gelatine gels and other gel systems in the perception of fat related attributes.

4.2. Conclusions

Differences in fracture properties explained 47 % of variance, whereas gel composition explained 48 % of variance between the samples. Fracture properties of gels are relevant for modifying perception of texture attributes. First bite texture attributes, such as firmness, elasticity and brittleness, were impacted by fracture properties but many chew down texture attributes, such as slipperiness, toughness, moistness and even creaminess, varied as well due to changes in fracture properties. However, some of these changes in chew down texture perception were due to other properties of the gels than fracture properties only. For instance, agar/gelatine gels were perceived differently for almost all attributes from carrageenan/LBG and gellan gels, the later were being perceived similarly. These differences started at first bite with agar/gelatine gels being perceived firmer, stickier and less brittle than the other two gelling agents systems. During chew down, agar/gelatine gels were perceived high in creaminess, while other systems were high in moistness and crumbliness. Such results seem to be mainly elicited by the melting properties of gelatine, which broke down in mouth very differently form the other gels. Another main difference between gelling agents system is syneresis which increased moistness and slipperiness perception in in carrageenan/LBG and gellan gels. Therefore, fracture properties can be measured in semi-solid gels to predict chew down texture perception. However, differences in matrix properties between gels can occur due to modifying the gels composition in order to control fracture properties or to the use of different gelling agents. These matrix properties, such as melting, can overrule the effect of fracture properties in texture perception of the gels. Mechanical tests on large deformation properties that take into account changes in temperature during eating may predict better texture attributes perceived during chew down.

Appendix 4.1 Example of a fracture curves from low fracture stress gels. Similar shapes were observed at high fracture stress.



Appendix 4.2 Young's modulus, fracture energy and recoverable energy measured at a compression of 50% of the fracture strain of the gels ± standard deviation. Different superscript letter indicate a significant difference at $p<0.05$.

Gel	Modulus (kPa)	Fracture energy (kPa)	Recoverable energy (%)
LσLε/AG	52.8 ± 2.8^{B}	4.2 ± 0.5^{A}	68.6 ± 0.9^{G}
LσHε/AG	6.0 ± 1.6^{A}	4.7 ± 1.4^{AB}	80.0 ± 1.3^{H}
HσLε/AG	66.4 ± 2.8^{C}	8.7 ± 1.7^{C}	70.6 ± 0.5^{G}
HσHε/AG	9.0 ± 4.5^{A}	8.1 ± 3.5^{B}	77.6 ± 1.0^{H}
LσLε/CL	38.3 ± 2.1^{B}	4.4 ± 0.5^{A}	62.7 ± 0.4^{F}
LσHε/CL	13.3 ± 1.4^{A}	3.9 ± 0.4^{A}	24.0 ± 0.5^{A}
HσLε/CL	82.6 ± 9.9^{D}	10.3 ± 0.9^{CD}	59.3 ± 0.5^{E}
HσHε/CL	9.5 ± 1.1^{A}	10.0 ± 0.9^{CD}	28.4 ± 0.5^{B}
LσLε/G	81.0 ± 5.1^{D}	3.9 ± 0.8^{A}	45.3 ± 2.7^{C}
LσHε/G	6.0 ± 0.5^{A}	3.4 ± 0.6^{A}	58.0 ± 0.6^{DE}
HσLε/G	93.8 ± 5.5^{D}	14.9 ± 1.9^{D}	55.9 ± 1.7^{D}
HσHε/G	7.9 ± 2.5^{A}	10.4 ± 1.0^{CD}	63.8 ± 1.7^{F}

Appendix 4.3 Sensory scores obtained by QDA ± standard error of the mean. Different superscript letter indicate a significant difference at $p<0.05$.

Type	Attribute	LσLε/AG	LσHε/AG	HσLε/AG	HσHε/AG	LσLε/CL	LσHε/CL	HσLε/CL	HσHε/CL	LσLε/G	LσHε/G	HσLε/G	HσHε/G
Taste	Intensity	63.0±2.5D	62.9±3.0D	60.2±3.0D	60.2±2.5D	56.8±2.8D	39.9±3.3ABC	48.2±3.6BCD	31.6±2.3A	54.6±3.9CD	39.2±3.8AB	39.1±4.2AB	31.1±3.8A
	Sweet	46.3±4.0ABC	61.9±3.7C	41.1±4.1AB	54.3±3.6BC	44.4±4.4ABC	37.1±3.7AB	31.6±3.5A	34.0±3.2A	40.7±5.0AB	43.4±5.2ABC	31.6±4.3A	28.2±3.4A
	Vanilla	35.6±4.5ABC	48.2±4.2C	32.4±4.5ABC	42.1±4.2BC	29.2±4.1AB	25.5±2.8AB	23.0±3.4A	29.1±2.8AB	31.3±5.0ABC	33.3±4.3ABC	24.6±4.5AB	23.2±2.7AB
	Bitter	46.0±4.0A	40.0±3.6ABCD	43.9±4.4CD	41.3±4.0BCD	42.2±3.8CD	30.0±3.2ABCD	34±3.8ABCD	22.3±2.3A	38.2±4.6ABCD	26.1±3.5ABC	29.6±5.0ABCD	23.1±3.7AB
First bite	Sticky	63.7±4.3DE	46.1±3.9C	70.7±4.3E	50.1±4.3CD	20.7±2.3AB	17.0±2.5A	13.8±1.6A	20.7±2.6AB	16.1±1.6A	23.1±3.5AB	17.1±2.0A	34.8±4.0BC
	Firm	61.0±3.3DE	31.8±3.0B	83.1±2.0F	60.1±3.1DE	26.0±3.2AB	15.2±1.9A	64.4±4.2E	35.2±3.3DE	27.8±3.9AB	15.6±2.4A	72.7±4.3EF	48.2±4.1CD
	Elastic	30.1±4.0BC	52.5±3.7DE	34.8±4.0C	68.9±3.1EF	12.6±1.9A	34.1±4.5C	13.2±1.5AB	60.9±4.1EF	14.0±3.1AB	36.0±5.1CD	19.4±2.9ABC	69.9±3.7F
Second bite	Brittle	41.2±4.5AB	50.6±4.4ABCD	33.5±4.3A	43.7±4.0ABC	80.9±3.1F	62.6±4.8CDEF	75.8±3.6EF	50.1±4.4ABCD	81.7±4.1F	57.2±6.1BCDE	69.9±4.5DEF	41.5±4.4AB
Chew down	Firm	55.4±3.2D	30.3±3.0AB	79.7±2.0E	53.0±3.5D	20.9±2.0AB	17.7±2.3A	58.6±4.5D	36.6±3.4BC	22.6±3.8AB	19.1±3.0A	67.0±4.9DE	52.1±4.5CD
	Tough	42.2±3.7CD	24.1±3.5AB	66.2±2.8E	46.6±4.0CD	9.6±1.0A	16.4±2.7A	14.4±2.2A	37.7±4.1BC	8.2±1.2A	20.3±4.7A	20.6±4.4A	54.1±5.0DE
	Sticky	62.7±4.0D	33.6±3.4BC	73.1±3.3D	38.0±3.4C	17.1±1.6A	14.5±2.0A	13.3±1.2A	18.1±2.2A	16.3±2.5A	21.8±3.7AB	15.1±1.5A	25.8±3.6ABC
	Elasticity	22.8±3.1ABC	36.8±3.7CD	28.5±4.1BC	56.6±3.5EF	11.8±1.4A	31.9±4.1C	11.3±1.1A	50.5±4.1DE	10.4±1.6A	34.0±4.9CD	15.1±2.0AB	67.1±5.3F
	Slippery	16.5±2.2A	53.4±4.2CD	15.1±2.2A	42.9±4.1BC	46.1±3.9BC	85.3±2.1F	29.4±3.9AB	79.6±2.7EF	48.3±5.9C	74.5±3.5EF	30.8±4.9DE	66.1±4.1
	Moist	15.2±1.7AB	45.4±4.5DE	11.1±1.4A	36.3±4.5CD	59.7±4.0EF	76.6±3.5F	33.5±3.8BCD	60.9±4.3EF	63.4±4.9EF	61.3±4.5EF	22.8±3.9ABC	37.9±4.6CD
	Rough	40.3±3.6BC	22.9±3.3A	47.2±3.6C	24.7±3.4AB	20.7±3.0A	17.3±3.1A	20.5±2.5A	14.8±2.2A	24.9±4.8AB	21.1±4.0A	25.4±3.7AB	18.0±3.4A
	Spreadable	70.9±3.6E	64.7±4.1DE	59.0±4.7CDE	50.4±4.0BCD	48.7±3.5BCD	46.0±4.8BCD	19.6±2.7A	34.3±3.7AB	43.4±5.2BC	61.4±4.4CDE	23.6±3.3A	23.7±4.3A
	Creamy	50.2±4.3DE	56.6±3.4E	48.8±4.8DE	54.0±3.9E	20.9±2.7AB	35.4±3.7BCD	14.2±1.6A	35.2±3.5BCD	22.3±3.6AB	47.4±5.1CDE	13.8±1.9A	31.2±4.2ABC
	Fatty	41.2±3.6D	30.0±3.7BCD	40.5±3.8D	35.8±4.4CD	20.4±2.3AB	16.8±2.0AB	15.4±2.3AB	17.5±2.2AB	15.9±2.8AB	23.3±3.4ABC	13.4±1.7A	15.9±2.6AB
	Melting	40.9±3.9CDE	73.4±4.7G	32.0±3.6BC	62.1±4.7FG	36.5±3.6BCD	56.9±4.1EFG	13.9±1.6A	35.6±3.7BCD	41.0±4.4CDE	52.6±4.0DEF	11.9±1.5AB	21.4±3.1
	Powdery	57.4±4.9B	20.7±3.8A	56.7±5.0B	20.7±3.3A	24.3±3.1A	15.9±2.4A	18.1±2.3A	11.6±1.2A	17.1±2.4A	16.5±4.5A	18.0±2.3A	15.8±3.3A
	Crumbly	25.8±2.9AB	21.7±3.1A	24.8±3.1A	34.4±3.9ABC	73.4±3.0FG	45.9±4.0CDE	85±1.7G	55.3±3.9DE	73.9±3.6FG	42.2±5.2BCD	82.7±3.0G	61.2±4.3EF
	Refreshing	18.0±2.9AB	47.1±4.5CDEF	14.9±2.1A	44.0±3.8CDE	45.4±3.8CDE	65.3±4.4F	32.4±3.8ABC	56±3.9EF	53.4±4.9DEF	49.7±4.8CDEF	34.4±5.3BCD	38.9±5.7CDE
	Clean mouth	52.2±4.2CDE	16.5±2.6A	69.0±3.9DE	23.3±2.9AB	51.9±3.0C	25.9±3.3AB	70.2±3.7E	38.6±3.9BC	48.6±5.2C	26.9±3.5AB	68.5±4.7DE	48.9±5.6C
After taste	Sweet	35.0±3.4ABC	51.8±4.2C	30.8±3.6AB	47.9±4.1BC	33.8±3.2AB	37.3±3.8ABC	30.4±3A	33.8±3.2AB	38.2±4.3ABC	37.0±4.3ABC	26.2±3.4A	29.3±3.5A
	Bitter	44.1±3.8AB	41.4±3.9A	40.4±3.8AB	34.1±3.3A	42.0±3.9AB	39.6±4.2AB	37.6±3.9B	28.9±3.5AB	36.8±4.5AB	33.3±5.0ABC	33.3±4.6AB	26.1±3.2AB
	Liquorice	24.9±3.0AB	18.7±1.9A	26.4±3.4AB	18.3±2.6A	34.2±4.2AB	27.0±3.2AB	36.6±4.7B	21.4±2.6AB	28.3±4.2AB	27.9±4.9AB	23.4±3.7AB	24.6±4.8AB
After-feel	Creamy	32.4±3.4CDE	40.4±4.5E	36.7±4.0DE	34.4±4.0DE	18.3±2.2ABC	26.7±2.8ABCDE	11.7±1.4A	25.2±2.8ABCDE	17.2±2.2ABC	28.1±4.3BCDE	12.9±2.3AB	21.7±3.3ABCD
	Fatty	30.3±3.2B	25.6±3.5AB	30.7±3.4B	30.0±3.1B	19.8±2.1AB	16.1±2.0A	15.3±1.5A	17.3±2.2AB	19.2±2.7AB	27.6±4.0AB	14.9±1.9A	18.7±2.9AB
	Dry	53.8±4.2C	38.4±4.4ABC	51.1±4.3BC	32.2±3.2AB	33.6±3.7AB	33.3±3.9AB	40.1±4.2ABC	31.3±3.4AB	30.9±4.6A	34.7±4.1ABC	40.7±5.6ABC	32.1±4.6AB
	Pepper	23.0±2.9	17.0±2.1	21.6±3.4	16.8±2.0	25.0±3.1	14.7±1.5	21.4±2.4	15.2±1.7	19.5±2.3	17.0±2.5	19.5±2.5	15.5±2.9
	Residue	22.7±3.0ABC	8.3±1.2A	28.5±4.1BC	9.8±1.4A	31.1±4.0BCD	9.2±1.0A	57.6±4.2E	11.5±1.1A	34.2±4.7CD	10.1±1.2A	43.3±5.6DE	18.0±2.2AB

Appendix 4.4 Pearson correlations between gels mechanical and bolus properties and sensory properties.

Sensory properties		Gel properties									Oral processing							
											Overall		Bolus fragments after 5 s			Bolus fragments at swallow		
Type	Attribute	Fracture stress	Fracture strain	Modulus	Fracture energy	syneresis	Serum release	Recoverable energy	Friction 22°C	Friction 37°C	Eating time	Saliva content	Number	Diameter	Roundness	Number	Diameter	Roundness
Taste	Intensity							.666*					.837**	-.856**	.831**		-.787**	.852**
	Sweet				-.592*				.612*									
	Vanilla								.712**									
	Bitter							.621*					.838**	-.867**	.869**		-.780**	.868**
After taste	Sweet																	
	Bitter	-.671*			-.679*								.669*	-.593*	.692*			.679*
	Liquorice		-.654*															
First bites	Sticky						-.762**	.645*	.756**	.595*		.611*			.718**			
	Firm	.719**			.686*	-.740**					.909**	.919**					-.584*	
	Elasticity		.878**	-.762**														
	Brittle						.811**		-.633*									
Chew down	Firm	.757**		.726**		-.688*					.931**	.892**						
	Tough						-.733**				.640*							
	Sticky						-.669*		.677*	.619*		.714**			.778**			
	Elastic		.889**	-.769**												-.598*		
	Slippery		.711**	-.707*		.749**		-.613*			-.646*	-.906**	-.735**	.896**	-.795**	-.742**	.870**	-.851**
	Moist					.766**	.638*	-.640*			-.882**	-.914**		.652*	-.611*		.660*	-.603*
	Rough									.580*		.856**		-.664*	.839**		-.614*	.725**
	Powdery									.681*		.748**		-.592*	.873**			
	Spreadable	-.748**			-.780**				.688*	.777**								
	Creamy			-.604*			-.666*		.799**									
	Fatty						-.708**	.625*	.737**	.639*					.718**			
	Melting	-.676*		-.677*	-.722**													
	Crumbly						.644*		-.760**									
	Refreshing					.648*	.580*	-.624*			-.810**	-.919**		.651*	-.740**		.648*	-.675*
	Clean mouth		-.694*	.834**								.721**						
After-feel	Creamy						-.611*		.781**									
	Fatty						-.687*	.640*	.845**	.687*					.613*			
	Dry									.596*		.793**		-.616*	.790**		-.585*	.676*
	Pepper		-.864**	.634*									.747**	-.732**	.763**	.690*	-.713**	.751**
	Residue		-.767**	.898**												.762**		

CHAPTER 5

Dynamic texture perception, oral processing behaviour and bolus properties of emulsion-filled gels with and without contrasting mechanical properties.

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Abstract
Many highly palatable foods are composed of multiple components which can have considerably different mechanical properties leading to contrasting texture sensations. The aim of this study was to better understand the impact of contrasting mechanical properties in semi-solid gels on oral processing behaviour and dynamic texture perception. Four reference layered emulsion-filled gels without mechanical contrast were prepared using agar (1 or 2 wt%) or gelatine (2.5 or 5.5wt%). Combining two different gel layers, 6 layered emulsion-filled gels with contrasting mechanical properties were obtained. Agar reference gels, displaying low fracture strain, produced boli with many small particles and were perceived as grainy. Gelatine reference gels, displaying high fracture strain, produced boli with few large particles which melted in mouth and were perceived as creamy. Reference gels with large fracture stress were masticated for long times with a high chewing muscle activity and were perceived as firm and grainy. Bolus properties, oral processing behaviour and dynamic sensory perception of the 6 contrasting gels were compared to the 4 reference gels using Principal Component Analysis. The presence of an agar layer in contrasting gels dominated bolus properties which contained many small particles and did not mix readily in mouth. Overall, the temporal sensory profiles and sensory trajectories of contrasting gels fell between the temporal sensory profiles and sensory trajectories of the two gel layers which they were composed of. We conclude that distinct features of dynamic texture perception in emulsion-filled gels with mechanical contrast are perceived separately in mouth.

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5.1. Introduction

Texture perception is complex and dynamic as it depends on food properties such as composition, structure and changes thereof during oral processing (Hutchings and Lillford, 1988). The structure of many composite foods is macroscopically inhomogeneous. Many foods that are highly palatable and highly liked are composed of multiple components with considerably different mechanical properties, for example in cookies often dry and crispy biscuits are combined with soft and creamy fillings. The mechanical contrast might lead to contrasting texture sensations which have been suggested to enhance palatability of foods (Hyde and Witherly, 1994). Texture perception has been shown to be an important factor contributing to consumer acceptance and food palatability. Texture contrast has been hypothesized to make generally well liked foods even more palatable. Texture contrasts are considered a desirable product property both within a meal and within a single bite (Szczesniak and Khan, 1984). Such texture contrasts can be caused by inhomogeneity in food structure or changes of structure over eating time, the second being considered as dynamic contrasts. The concept of dynamic texture contrast has been proposed as a concept to enhance the palatability of foods (Hyde and Witherly, 1994).

Dynamic texture contrast leads to continuous changes in intensity and quality of perceived texture as the food structure is broken down in the mouth. The combination of macroscopic components with contrasting mechanical properties in composite foods results in complex oral food breakdown behaviour in mouth and dynamic texture perception. Dynamic texture perception of foods with mechanical contrast depends on the mechanical properties of each compartment of the food as well as the oral processing of the compartments and their mixing behaviour in mouth. For example, bread, consisting of a crispy crust and soft crumb can be considered as a food product with different compartments which cause contrasting texture sensations. Methods of bolus analyses of breads have been proposed to determine the level of mixing between the different compartment (crust and crumb) in mouth during mastication (Tournier et al. 2012). The bolus properties of another inhomogeneous food, peanuts embedded in different food matrices, have been investigated. It was observed that the oral breakdown behaviour of the peanuts depended on the matrix they were embedded in (Hutchings et al. 2011 and 2012). However, eating behaviour, e.g. number of chews, was not significantly influenced by the properties of the matrices. It has not been investigated whether changes of matrices influence dynamic texture perception of the peanuts. Chewing behaviour which can be monitored by Electromyography (EMG) provides additional insights into texture perception of semi-solid and solid foods (Çakır et al. 2012). Texture perception can be monitored dynamically by sensory methods, such as Temporal Dominance of Sensations (TDS). Albert et al. (2012) concluded that TDS can be used to analyse dynamic texture perception over time of complex inhomogeneous foods consisting of two different structures.

Model foods allow to control the structure and mechanical properties of the foods and to vary specific parameters individually. Therefore, model foods are often used to gain fundamental understanding of the factors contributing to texture perception (Stieger and van de Velde, 2013). Emulsion-filled gels are frequently used as models for semi-solid foods. Mechanical properties of model gels such as fracture stress and fracture strain have been related to specific perceived textural properties such as hardness and brittleness (Foegeding et al. 2011). Agar and gelatine are commonly used gelling agents in many food preparations and have often been used as the main ingredient to prepare model foods. Gels made with agar or gelatine as gelling agents are well characterised. An emulsion can be added to the gel matrix to engineer the fracture behaviour and to investigate sensory perception of fat related attributes (Sala et al. 2007b). Both agar and gelatine emulsion-filled gels are often used as model foods. The use of agar or gelatine provides different structural properties to gels resulting in different behaviours during oral processing leading to different textural sensations. Model gels made from gelatine are characterised by a high fracture strain which increases together with fracture stress with increasing gelatine concentration. Gelatine gels are perceived as elastic compared to other gels and perceived firmness increases with increasing fracture stress (Muñoz et al. 1986a; Muñoz et al. 1986b). Upon mastication gelatine gels break down into a small number of large particles (Muñoz et al. 1986b). When semi-solid gelatine gels are masticated in mouth longer, the gelatine matrix melts and a liquid bolus is formed before swallowing (Inoue et al. 2009). Gelatine gels are therefore perceived as melting in mouth (Hayakawa et al. 2014) which is thought to be a desirable property to deliver flavours and provide a pleasant mouth-feel (Koliandris et al. 2008). Emulsion-filled gelatine gels are perceived as creamy compared to other non-melting emulsion-filled gels suggesting that melting positively influence creaminess perception (Sala et al. 2008). Agar gels are often used as model foods due to their low complexity. With increasing agar concentration, fracture stress increases accompanied by an increase in perceived firmness. With increasing agar concentration fracture strain decreases slightly (Barrangou et al. 2006a). Agar gels display considerably lower fracture strains than gelatine gels (Ikeda et al. 2003). Agar gels display strain hardening behaviour and brittle fracture (Sharma and Bhattacharya, 2014). Contrary to gelatine gels, agar gels do not melt in mouth but break down into several small particles. At the end of oral processing, agar gels are swallowed as a bolus of small, broken down particles which are adhering to each other by saliva (Inoue et al. 2009). The breakdown of agar gels during oral processing is perceived in mouth and can be characterized by a rate of breakdown (Barrangou et al. 2006a). The fracture properties of model gels can correlate with perceived chew down texture attributes (Barrangou et al. 2006a; Melito et al. 2013). The model gels described above have homogenous structures without mechanical contrast. In comparison to the several studies of gels without mechanical contrast, little is known about the oral break down behaviour, in mouth mixing behaviour and dynamic sensory perception of multicomponent foods displaying mechanical contrast.

The aim of this study was to better understand the impact of contrasting mechanical properties in foods on oral processing behaviour and dynamic texture perception of semi-solid model gels. We hypothesize that the composition of the emulsion-filled gel layers influences oral processing behaviour, breakdown behaviour in mouth and dynamic texture perception. We hypothesize that gel layers with high fracture stress dominate the oral processing behaviour and dynamic texture perception in emulsion-filled gel with contrasting mechanical properties when layers with high fracture stress are combined with layers with low fracture stress. The presence of an agar emulsion-filled gel layer is hypothesized to dominate the oral processing behaviour and dynamic texture perception in emulsion-filled gels with contrasting mechanical properties when agar layers are combined with gelatine layers. Indeed, agar gels do not melt in mouth and are expected to represent the bulk of the bolus once gelatine is molten into a liquid during oral processing.

5.2. Materials and Methods

As reference stimuli, four layered emulsion-filled gels displaying no mechanical contrast were prepared using 1 and 2wt% agar (denoted as LA+LA and HA+HA) or 2.5 and 5.5wt% gelatine (denoted as LG+LG and HG+HG). Two layers of emulsion-filled gels varying in mechanical properties were combined to yield six layered emulsion-filled gels with contrasting mechanical properties (LA+HA, LA+LG, LA+HG, HA+LG, HA+HG, LG+HG). For all emulsion-filled gels, the oral processing behaviour was determined by measurements of the eating time and determination of muscle activity by EMG , the bolus properties were characterized (number, size and roundness of particles as well as rheological bolus properties), the in mouth mixing behaviour was quantified using image analysis of expectorated boli and the dynamic sensory perception was quantified using TDS. The oral processing behaviour, bolus properties and dynamic sensory perception of the emulsion-filled gels with contrasting mechanical properties were compared to the emulsion-filled gels without mechanical contrast using Principal Component Analysis (PCA).

5.1.1. Ingredients

Pig skin gelatine (Bloom 240-260, Rousselot B.V., Gent, Belgium) and Ferwo agar 700 (Caldic Ingredients B.V., Oudewater, The Netherlands) were used. Whey Protein Isolate (WPI) (Davisco Foods International, Inc., Le Sueur, USA), bourbon vanilla VLB concentrate (Pomona Aroma B.V., Hedel, The Netherlands) and carbon black (Tefco EuroIngredients B.V., Bodegraven, The Netherlands) were used. Sunflower oil and sugar were purchased at a local retailer and used without further purification. Demineralized water was used for all recipes.

5.1.2. Preparation of emulsion-filled gels

The composition of all emulsion-filled gels is summarized in Table 5.1. O/w emulsions and gelling agent solutions were prepared separately. For the o/w emulsions, a solution of 2 wt % WPI in demineralised water was stirred for at least 1 h. Typically, 1200 g of sunflower oil were added to 1800 g of WPI solution and premixed for 1 min using an Ultra Turrax (T50 basic Ultra Turrax, IKA, Staufen, Germany) before being passed through a two-stage homogeniser (Panda NS1001L 2K, GEA Niro Soavi, Parma, Italy) at 500/50 bar. The Sauter diameter D[3,2] of the oil droplets was 0.60±0.09 µm as measured by light scattering (Mastersizer 2000, Malvern Instruments Ltd, Malvern, UK). After homogenisation, 0.03 wt % vanilla flavour was added to the emulsion. Gelling agent solutions of typically 500 g were prepared. Gelling agents (agar or gelatine), sugar, water and carbon black were mixed at room temperature and hydrated for 30 min. Agar and sugar solutions were heated in a water bath at 90°C and subsequently heated on heating plates while stirring

Table 5.1 Composition of all gel layers used. All gel layers contained 20 wt% sunflower oil, 10 wt% sucrose and 0.03 wt% vanilla flavour. To obtain black gels, 3 wt% of water was replaced by 3 wt% of carbon black solution.

Gel layer name	Gel layer property	Agar (wt %)	Gelatine (wt %)	Water (wt %)
LG	Low gelatine concentration	0	2.5	67.47
HG	High gelatine concentration	0	5.5	64.47
LA	Low agar concentration	1.0	0	68.97
HA	High agar concentration	2.0	0	67.97

until complete dissolution of agar. Solutions of agar were cooled in a water bath to 60°C. Gelatine and sugar solutions were heated in a water bath to 60°C while stirring for 20 min. The emulsions and the gelling agent solutions were then mixed in a 1 : 1 ratio to obtain emulsion-filled gels. For each gel, 500 g of emulsion were heated to 60 °C in a water bath and mixed with the gelling agent solution to obtain a 20% oil in water emulsion-filled gel. The obtained mixtures were poured into plastic syringes (28 mm diameter), sealed and kept in a cooling room at 5°C for 20-24 hours.

Table 5.2 Composition of all layered gels with and without mechanical contrast.

Gel name	Layer 1	Layer 2	Black layer	Contrast
LG+LG	Low gelatine	Low gelatine	LG	No
HG+HG	High gelatine	High gelatine	HG	No
LA+LA	Low agar	Low agar	LA	No
HA+HA	High agar	High agar	HA	No
LG+HG	Low gelatine	High gelatine	HG	L/H fracture stress (gelatine)
LG+LA	Low gelatine	Low agar	LA	Gelatine/agar (low fracture stress)
LG+HA	Low gelatine	High agar	HA	L/H fracture stress and gelatine/agar
HG+LA	High gelatine	Low agar	LA	H/L fracture stress and gelatine/agar
HG+HA	High gelatine	High agar	HA	Gelatine/agar (high fracture stress)
LA+HA	Low agar	High agar	HA	L/H fracture stress (agar)

The gels for sensory evaluations were sliced into cylindrical pieces of 5 mm height and 26 mm diameter. Two slices were placed on top of each to obtain layered gels of 10 mm height and 26 mm diameter as outlined in Table 5.2. Layered gels were stored at 4 °C for maximum 4 h and served at room temperature (20 °C). For the collection of bolus used in the particle size analysis and mixing analysis, carbon black was added to one of the layers (see Figure 5.1).

5.1.3. Determination of fracture properties of gels by uniaxial compression tests

Gels were cut into cylinders of 26 mm diameter and 20 mm height. Uniaxial single compression tests were performed at room temperature using a Texture Analyser with a 50 kg load cell (TA.XT Plus, Stable Micro Systems Ltd., Godalming, UK). The gels were lubricated with a thin layer of paraffin oil and compressed with a cylindrical probe (100 mm diameter) with a constant deformation speed of 1 mm/s to a target strain of 80%. The mean values of fracture stress, fracture strain, Young's modulus and fracture energy were calculated from triplicate measurements of seven batches of gels prepared on different days. Fracture stress, fracture strain, fracture energy and Young's modulus data were statistically analysed in SPSS (SPSS software, V19, SPSS Inc., Chicago, USA). A multifactorial ANOVA with gelling agent (agar/gelatine), gelling agent concentration (low/high) and colour (white/black) as factors was performed. A significance level of $p<0.05$ was chosen.

5.1.4. Characterization of oral processing behaviour and eating duration using electromyography (EMG)

The oral processing behaviour of subjects (n=10) was measured in triplicate in individually randomised order during two sessions of 45 min using surface electromyography (EMG) following the method described by Devezeaux de Lavergne et al. (2015c). Four electrodes were placed on the left and right masseter and left and right temporalis muscles. Three reference electrodes were included with the DRL on the left cheek, the CMS and an extra electrode on the mastoid bone behind the left and right ear, respectively.

Subjects were instructed to chew and to swallow the gels, as they would naturally do. The instructions were presented on a computer screen generated with a protocol prepared in the software E-Prime® (Version 2.0, Psychology Software Tools, Inc., Sharpsburg, US). Subjects started eating when indicated on the screen and EMG data were collected for 60 s per sample on the monitoring computer with the software ActiView (LabView 8.2, National Instruments Corporation, Austin, US). Subjects pressed a button to indicate the time of swallowing. EMG measures were later down-sampled to 256 Hz (Decimeter, BioSemi, Amsterdam, NL) and exported to MatLab® (Version R2012a 7.14, The Mathworks Inc., Natick, US) and processed using EEGLab (Version 10.2, open source toolbox). Area under the curve (AUC) was determined which is in the following referred to as muscle activity. The averaged muscle activities of the four muscles were calculated over 7 s intervals.

A repeated measure ANOVA on the homogeneous gels following a 2x2x3 factorial design gelling agent (agar/gelatine), concentration (high/low) and oral processing time (33, 66 and 100 %) as factors was made in SPSS (SPSS software, V19, SPSS Inc., Chicago, USA). A significance level of $p<0.05$ was chosen.

5.1.5. Bolus collection

Subjects (n=10) participated in 4 sessions to collect gel boli. Subjects were Dutch women (n=10) with an average age of 50.0 ± 13.6 years. The boli collected in first session were used for particle size and number analysis, the boli collected in the second session were used for boli image analysis to quantify in mouth mixing behaviour and the boli collected in the third and fourth sessions were used to analyse the mechanical properties of the boli. In all sessions subjects received the emulsion-filled gels in random order. Subjects were asked to expectorate the bolus at specified time points corresponding to 33, 66 and 100% of the total mastication time. The total mastication time corresponded to the mean time required by all subjects (n=10) to form a bolus that is ready for swallowing of a gel piece (26 mm diameter, 10mm height). The mean mastication time was determined by averaging the individual masticatory times of all subject determined from preliminary experiments. Subjects had previously participated in similar studies and were therefore familiar with this procedure. All bolus collection sessions lasted 1 h. Within one session, 30 pieces (26 mm diameter, 10 mm height) of emulsion-filled gels (10 gels x 3 oral processing times) were served per subject, except for the third and fourth sessions during which 60 pieces were served (5 gels x 3 oral processing times x 4 replicates). Panellists were instructed to rinse their mouth with water between each gel pieces.

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5.1.6. Characterization of number, size and roundness of bolus fragments

Boli were collected in plastic cups (screw cap urinary cup 120 ml, VWR) which were immediately filled with cold tap water to stop the melting of gelatine containing gels. The boli were passed through a sieve (335 µm mesh size) to remove the smallest particles and oil droplets. The boli fragments larger than 335 µm were collected from the sieve and dispersed in cold tap water and filled into 4 petri dishes. A colour picture of the petri dishes was taken with a Canoscan 9950F scanner (Canon Inc., Tokyo, Japan) at a resolution of 800 dpi with a yellow background (Figure 5.1 C1.). The images were analysed by ImageJ® (Version 1.48r, National Institute of Health, Bethesda, USA). A colour threshold was applied to discriminate gel particles from the background. Particle size analysis was conducted on binary images. The area and roundness of particles was determined using ImageJ®. The diameter of each particle was calculated assuming that the area of the particles was the disc projection of a sphere. Consequently, the total number of particles, particle volumetric diameter, cumulative area of all particles and average particle roundness were obtained.

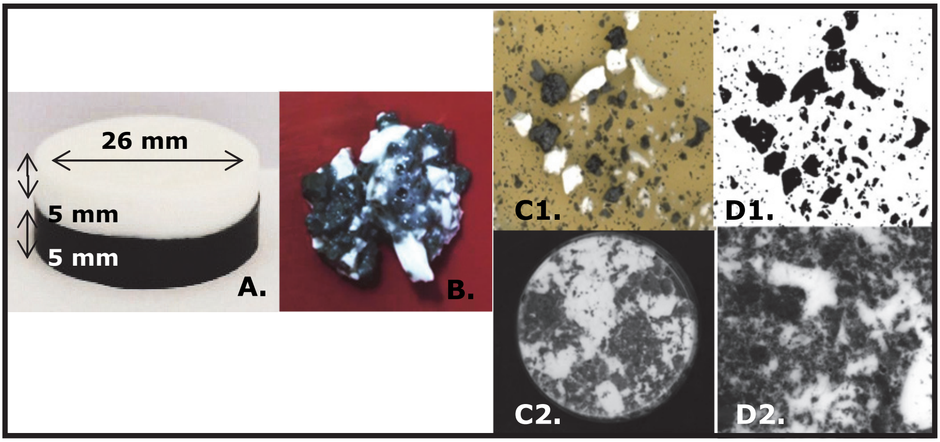

Figure 5.1 A. Gels consisting of two layers exhibiting a white (no colorant added) and black layer (carbon black added). B. Expectorated bolus of a gel from one subject after 7 s of oral processing. C1. Separated fragments of bolus dispersed in water in petri dish. D1. Binary image obtained from Figure C1. used for particle size analysis. C2. Bolus gently flattened in a glass petri dish. D2. Picture taken from the petri dish and used for further image analysis to determine mixing.

5.1.7. Characterization of the mixing behaviour between gel layers : image texture analysis

Previously, Tournier et al. 2012 demonstrated that image texture analysis using the grey-level co-occurrence matrix method (GLCM; Haralick et al. 1973) can be applied to discriminate between bread boli. More specifically, the texture feature "contrast" calculated from the matrix was reliably used as a marker of food breakdown during oral processing. This procedure of image analysis was used in the current study in order to characterize in-mouth breakdown of gels and the mixing of two gel layers differing in colour (black and white) during oral processing. Image acquisition and data analysis procedure were adapted from Tournier et al. 2012. Gel boli were collected in the lid of a glass petri dish (60 mm diameter). The boli were flattened by covering the boli with the bottom of the petri dish container, turned upside-down, and by pushing gently. Images were acquired on a red background with an IEEE 1394 C-Mount multi-megapixel camera equipped with CCD sensors (Oscar F-810C, Allied Vision Technologies, Stadtroda, Germany) with a KOWA lens (35 mm). The camera was positioned at a distance of 15 cm from the boli. The boli were lightened using a light/stand combination system (RS1, Kaiser Fototechnik, Buchen, Germany). The angle between the camera lens and the lighting source axis was around 45°. This set-up made it possible to capture a surface of 36 x 36 mm digitised to 820 x 820 pixels. Four images (2 from above and 2 from below the glass petri dish) were acquired for each bolus.

For some images, the bolus was not covering the total surface of the image. Therefore, the first step of image analysis was to isolate the red background from the bolus. Original RGB images were coded in the Y-Cb-Cr format; the Cr channel emphasizing the red hue. The Region Of Interest (ROI, i.e. the bolus) had a Cr value lower than a threshold fixed at 130. Images were transformed into grey level images and the Grey Level Co-occurrence Matrix (GLCM) was determined from extracted ROI (diagonal displacement direction (=45°) and a distance of 1 pixel). The GLCM describes the second-order statistics in the images. From each GLCM, the textural feature contrast was determined (Eq. 1). This feature represents the amount of local variation of grey level presents in the image.

$$f_2 = \sum_{n=0}^{n_g-1} n^2 \left[\sum_{i=1}^{n_g} \sum_{j=1}^{n_g} p_{(i,j)} \right] \quad |i-j| = n \qquad \text{(Eq.1)}$$

(*i* and *j*: row and column number in the GLCM matrix, μ: means, σ: standard deviation, $p_{(i,j)}$: (*i,j*)th entry in a normalized grey-level co-occurrence matrix (Haralick et al. 1973))

5.1.8. Characterization of mechanical bolus properties using two cycle penetration tests (TCPT)

Boli were collected in quadruplicate in one cup (screw cap urinary cup 120 ml, VWR) to obtain a cylindrical mass of approximately 20 mm height and 43 mm diameter. Boli were analysed using a two cycle penetration test (TCPT). After bolus collection, the surface of the boli in the cup was gently evened with a spoon. A double penetration test was made with a Texture Analyser with a 5 kg load cell (TA.XT Plus, Stable Micro Systems Ltd., Godalming, Surrey, UK). A cylindrical probe of 20 mm in diameter was used to perform two successive uniaxial penetrations to 75% strain (approximately 15 mm) at a constant speed of 5 mm/s. Retrieval of the probe was at a speed of 5.0 mm/s and the resting time between two penetrations was 5 s. The first peak force, resilience, adhesiveness and flowability were determined from the TCPT force-time curves as described in Devezeaux de Lavergne et al. 2015b.

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5.1.9. Statistical data analysis of bolus properties

Repeated measure ANOVA of the bolus properties of the gels without contrast following a 2x2x3 factorial design with gelling agent (agar/gelatine), concentration (high/low) and oral processing time (33, 66 and100 % of mastication time) as factors was conducted in SPSS (SPSS software, V19, SPSS Inc., Chicago, USA). Data was exported into Unscrambler (The Unscrambler® X software V10.2, CAMO software, Norway) to perform a PCA based on the oral processing parameters (EMG outputs and bolus properties).

5.1.10. Characterization of dynamic texture perception using Temporal Dominance of Sensations (TDS)

A panel consisting of Dutch women (n=10) with an average age of 50.0 ± 13.6 years was selected based on their discriminative abilities. All subject had extensive previous experience in sensory assessment of semi-solid model food gels using TDS and Quantitative Descriptive Analysis (QDA). Ten emulsions filled gels (Table 5.2) were evaluated in triplicate and presented in a balanced, monadic sequential design, split over two sessions of 1 h each. Each sample was coded with a random three digit number and served in plastic cups with a lid. The order of the top and bottom layer was randomised over samples. Panellists were instructed to put both gel layers in their mouth without turning the sample around.

Table 5.3 Texture attributes used in TDS evaluation together with definitions of attributes.

Texture attribute	Definition
Firm	The force needed to compress/chew the sample
Elastic	Springiness of the samples
Sticky	Sample sticks to the palate and teeth during tasting
Moist	Watery, the amount of perceived water
Refreshing	Cooling sensation in the mouth
Melting	Loss of structure in the mouth, like ice cream
Grainy	From crumbly to granular particles in the mouth
Powdery	Dusty to fine particles on the palate
Creamy	Creamy as well as fatty, smooth sensation

The panellists (n=10) assessed all gels using temporal dominance of sensation (TDS). Training took place during three sessions of 2 h. In the first training session, the notion of the temporality of sensations was explained and the term ‘dominance’ of an attribute was defined as “the attribute that attracts the most attention at a given time point”. Sensory attributes were determined by introducing the samples in the second training session using an attribute lists from previous studies (Devezeaux de Lavergne et al. 2015a)(Table 5.3). During the third training session the panellists trained using the software EyeQuestion (Version 3.9.7, Logic8 B.V., Elst, The Netherlands). During two test sessions of 1.5 h panellists assessed all gels in a balanced randomized design. After clicking the “start” button, panellists were free to chew the gels as they would normally do and as long as they wanted to. Panellists indicated which attributes were perceived as dominant at the moment they perceived a difference by selecting the attributes from a list. The list of attributes was presented on a computer screen in a randomized order between each assessor and each session, but not between samples. Panellists were allowed to select as many attributes as they wanted and to select attributes several times. At the point they would normally swallow the samples the recording was stopped by clicking the “stop” button. The bolus was expectorated and the assessor was asked to cleanse the palate with water and to eat an unsalted cracker. The dominance rates were computed from the proportion of panellists perceiving an attribute as dominant. Dominance rates were time normalized according to individual mastication times on a scale from 0 (start of mastication) to 100 (expectoration of the stimulus). The chance level (P_0=1/9) and significance level at α<0.05 (P=0.205) were included in the temporal dominance rate curves (Pineau et al. 2009). TDS scores were calculated as the average duration of dominance of an attribute over total assessment duration:

$$\text{Attribute Score} = \sum\left(\frac{\sum Duration\ attribute\ dominance}{Total\ assessment\ duration}\right) \times \frac{100}{Number\ of\ assessments}$$

Principal component analysis (PCA) was performed to obtain the sensory trajectories of all gels following the procedure described by Lenfant et al. 2009. Gels were plotted over their dominance rate at ten equally spaced time points corresponding to 10%, 20%, .. , 99% of the standardised mastication times using Unscrambler (The Unscrambler® X software V10.2, CAMO software, Norway). A PCA plot of all samples based on the TDS scores was also obtained.

5.2. Results and discussion

5.2.1. Characterisation of gel layers

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Section 5.3.1. discusses the mechanical properties of the gel layers used and the oral processing and dynamic texture perception of the four reference gels without texture contrast. Section 5.3.2. discusses the oral processing and dynamic texture perception of gels with contrasting mechanical properties.

5.3.1.1. Mechanical properties of gel layers

Fracture properties of gels are given in Table 5.4. Fracture stress of gelatine and agar gels with high concentrations of gelling agent (HG and HA) was significantly higher than fracture stress of gels with low concentrations of gelling agent (LG and LA) (p<0.001). Fracture stress of gelatine gels (LG and HG) was significantly higher than fracture stress of the respective agar gels (LA and HA) (p<0.001). However, these differences in fracture stress were small (factor 1.2x) compared to the differences in fracture stress between low and high gelling agent concentrations (factor 2.7x). Fracture strain was significantly higher for gelatine gels (LG and HG) than for agar gels (LA and HA) (p<0.001) and significantly higher for HG compared to LG (p<0.001). This difference in fracture strain between HG and LG was small (factor 1.2x) compared to the differences in fracture strain between agar and gelatine gels (factor 2.7x). Fracture energy was significantly higher for gelatine gels (LG and HG) than for agar gels (LA and HA) (p<0.001) and higher for gels with higher concentrations of gelling agent (HG and HA) than gels with lower concentrations of gelling agent (LG and LA) ($p<0.001$). Young's modulus was significantly higher for agar gels ($p<0.001$) and significantly higher for gels with high concentrations of gelling agent ($p<0.001$). The mechanical properties of the emulsion-filled agar and gelatine gel layers are in agreement with previous studies of agar and gelatine gels (Ikeda et al. 2003; Barrangou et al. 2006a; Funami, 2011). The addition of carbon black to the emulsion-filled gels did not significantly influence the fracture stress ($p=0.23$), fracture energy ($p=0.69$) and Young's modulus ($p=0.88$) of the gels. Addition of carbon black had a significant influence on fracture strain ($p<0.05$) only for the LG gel, but this effect was small. We conclude that the addition of carbon black to dye the layers black does not to impact the mechanical properties of the gels. We conclude that the emulsion-filled gels reveal different mechanical properties such as fracture stress, fracture strain, fracture energy and Young's modulus. It has been shown that those differences in mechanical properties influence texture perception at first bite (Chen et al. 2012; Foegeding et al. 2011; Barrangou et al. 2006a) and suggested to influence texture perception of chew down attributes during oral processing.

Table 5.4 Mean fracture properties of agar and gelatine gel layers together with standard deviation. LG black, HG black, LA black and HA black are gels to which 3 wt% of carbon black was added and 3 wt% of water removed. The concentration of gelling agents is the same as for the LG, HG, LA and HA gels, respectively.

Sample	Fracture stress (KPa)	Fracture strain (True)	Fracture energy (mJ)	Modulus (KPa)
LG	21.1 ± 1.7	0.71 ± 0.03	9.4 ± 0.7	14.1 ± 0.7
LG black	22.5 ± 3.3	0.74 ± 0.06	9.3 ± 0.8	16.1 ± 0.5
HG	56.2 ± 5.2	0.90 ± 0.06	20.8 ± 2.2	43.5 ± 1.4
HG black	55.4 ± 3.9	0.89 ± 0.05	21.8 ± 1.9	49.9 ± 1.5
LA	17.4 ± 0.6	0.29 ± 0.01	2.4 ± 0.2	51.6 ± 1.6
LA black	17.5 ± 0.6	0.29 ± 0.01	2.5 ± 0.2	52.8 ± 12.6
HA	47.4 ± 1.9	0.32 ± 0.01	7.4 ± 0.5	145.9 ± 2.0
HA black	47.7 ± 2.5	0.32 ± 0.01	8.1 ± 0.6	147.6 ± 1.0

5.3.1.2. Oral processing behaviour

5.3.1.2.1. Oral processing duration

The time required for oral processing of a piece (26 mm diameter, 10 mm height) of emulsion-filled gels (n=10 subjects, triplicate) was determined for normal eating and during the EMG and TDS experiments (Figure 5.2). Eating time tended to increase from free eating to TDS, but this effect was not significant ($p=0.205$). Oral processing time was not significantly different between gelling agents ($p=0.977$), but was significantly higher for gels with high concentrations of gelling agent ($p<0.001$) compared to gels with low concentrations of gelling agent (Figure 5.2). The normal eating time of emulsion-filled gels with high concentrations of gelling agent was in average 23.9 ± 2.9 s compared to 15.6 ± 2.1 s for gels with low concentrations of gelling agent. The average normal eating time of all gels was 19.5 ± 4.6 s, therefore, 20 s was chosen as the maximum time for oral processing of the gels corresponding to 100% of mastication. Additional expectoration times at 7 s and 14 s were selected to represent 33% and 66% of oral processing, respectively.

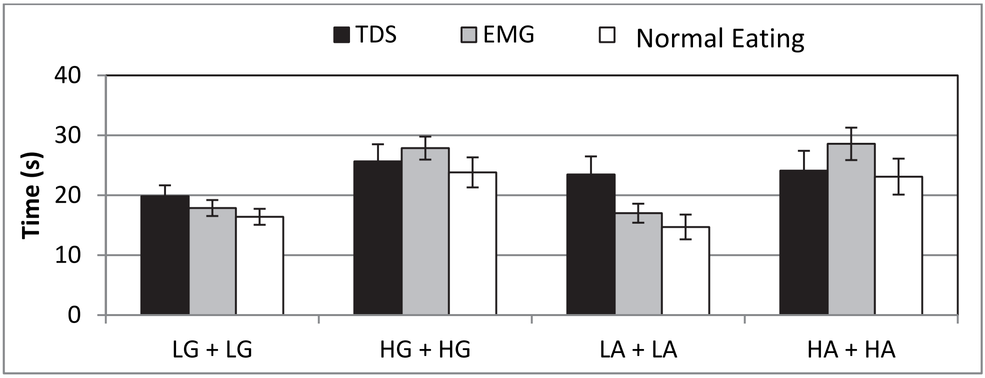

Figure 5.2 Eating times of the reference emulsion-filled gels without mechanical contrast while performing TDS, EMG and under a normal eating condition.

5.3.1.2.2. Chewing muscles activity (EMG)

The average muscle activity per second, averaged over the masseter and the temporalis muscles, while consuming the homogeneous gels is given in Figure 5.3. Muscle activity significantly decreased with increasing eating time after 13 s of oral processing time ($p<0.001$). This suggests that, while the gels are broken down by oral processing, oral processing behaviour is adaptive and the activity of the muscles is reduced since lower muscle activity is required to break down the gel fragments further. Muscle activity was significantly higher for gels with high concentrations of gelling agent than for gels with low concentrations of gelling agent ($p<0.001$). Type of gelling agent (gelatine vs agar) did not significantly influence muscle activity ($p=0.390$). These results suggest that emulsion-filled gels with a higher fracture stress (HA+HA and HG+HG) require a higher muscle activity in order to obtain a bolus that is safe to swallow. Other fracture properties, such as fracture strain, Young's modulus and fracture energy, and differences in melting properties in mouth between the gels (gelatine vs agar) did not have a significant impact on muscle activity. Koç et al. (2013a) found that an increase in deformability in k-carrageenan and locust bean gum mixed gels increased total muscle activity which was not found here for agar (low deformability) and gelatine (high deformability) gels. As gelatine is expected to melt in mouth, the effect of an increase in deformability on muscle activity might be overruled by the effect of melting. We conclude from the eating time measurements and the determination of muscle activity during oral processing that the gelling agent concentration is the main factor influencing oral processing behaviour of the subjects.

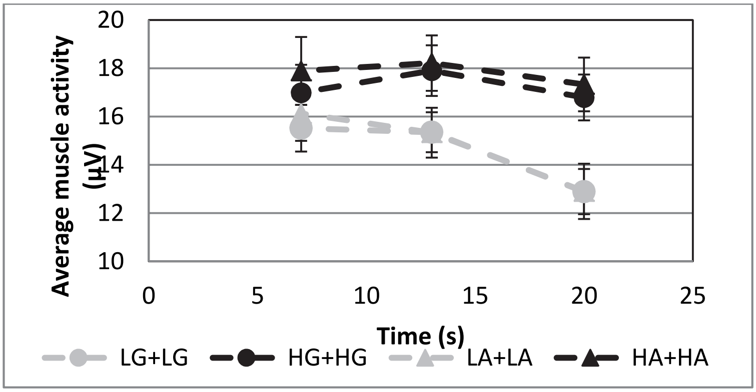

Figure 5.3 Average muscle activities while consuming the reference emulsion-filled gels without contrast. Error bars represent the standard error to the mean (n=10, triplicate).

5.3.1.3. Bolus properties

5.3.1.3.1. Particle size of bolus fragments

The particle size of boli as a function of oral processing time is given in Figure 5.4. The number of fragments in the boli increased significantly with eating time ($p<0.001$), was

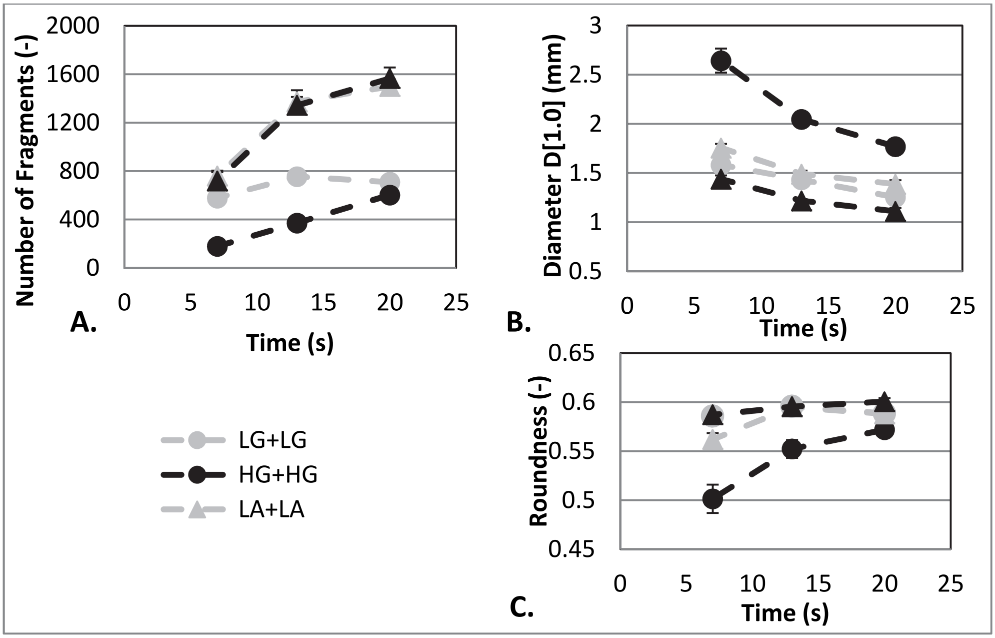

Figure 5.4 Number (A.), diameter (B.) and roundness (C.) of gel fragments of boli of the reference emulsion-filled gels without mechanical contrast over oral processing time. Error bars represent the standard error to the mean (n=10).

higher in gels containing agar than in gels containing gelatine ($p<0.001$) and was higher in gels with lower gelling agent concentrations for gelatine gels ($p<0.001$). The diameter of the gel fragments in the boli decreased significantly over oral processing time ($p<0.001$). Diameter of fragments in the boli was higher in HG than in other gels. Roundness of gel fragments increased significantly over oral processing time ($p<0.001$) to reach a plateau at 14 s. Roundness was lower in boli of HG gels. These results showed that gels are broken down by oral processing and form boli with more, smaller and rounder fragments over chewing time. Gels containing gelatine broke down in fewer, larger and less round fragments which could be due to a higher fracture strain of gelatine gels. Such behaviour of gelatine gels after a few chews has been reported in literature before (Muñoz et al. 1985b). The small number of fragments in boli of gelatine gels together with small particle sizes at the end of oral processing (especially for LG) could be explained by the in mouth melting of the gelatine gels which mix with saliva and was eliminated through the sieving step. The accumulation of many small particles in boli of agar gels could be explained by a low fracture strain (Devezeaux de Lavergne et al. 2015b) together with the absence of melting of these particles.

5.3.1.3.2. Mixing of layers

The image texture feature contrast is presented in Figure 5.5, together with a few typical examples of corresponding images. Contrast is a measure of the local variations in grey level present in the image. Pictures with higher contrast contain numerous local grey level transitions and therefore indicate a textural heterogeneity of the image. Picture with lower contrast contain few grey level transitions suggesting that pixels neighbouring each other have closer grey levels. Contrast was significantly higher in gels containing agar than in gels containing gelatine ($p<0.0001$). Within gelatine gels contrast was significantly lower for lower gelling agent concentrations. The impact of eating duration on contrast depended on the gel composition ($p<0.0001$). Contrast tended to increase for agar gels while it significantly decreased for gelatine gels through the oral processing sequence.

The image textural properties of boli and their evolution during eating time depend on the type of gelling agent. At 7 s of oral processing, agar gel boli are composed of small black and white particles. At the end of oral processing, images become more contrasted with smaller black and white areas indicating a better mixing of the particles with increasing oral processing time. These results demonstrate that agar gels, independent of concentration of gelling agent, are already well broken down in small particles after 7 s of oral processing and further break down is observed with prolonged oral processing. A different behaviour was observed for gelatine gels. After 7 s of oral processing, images are less contrasted than in the corresponding images of agar gels, which is explained by bigger black and white areas (particles) in the images. These results are well in line with previous studies. During oral processing the contrast of gelatine gels decreased, i.e. the local variation between grey levels decreased. In other words, black and white areas in the images are transformed to closer grey levels. This suggests that during oral processing gelatine gels are melting and that both layers are mixing. The melting is more important for low gelatine concentration. In a previous study, the GLCM method was found to reliably discriminate breads submitted to different chewing cycles (Tournier et al. 2012). In the current study, this method allowed discriminating of gels boluses as a function of their composition. Moreover it allowed estimating the melting / mixing of layers during oral processing.

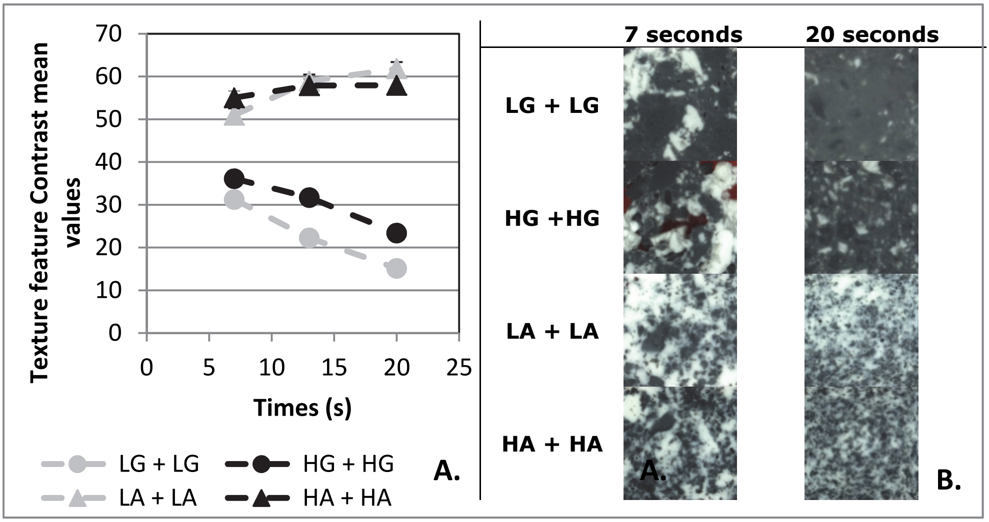

Figure 5.5 Image texture contrast of boli of the reference emulsion-filled gels without mechanical contrast over oral processing time (A.). Error bars represent the standard error to the mean (n=10). Example of images collected from the boli from one subject (B.).

5.3.1.3.3. Mechanical properties of boli

Mechanical properties of the expectorated boli of the reference gels without mechanical contrast are shown in Figure 5.6. First peak force of the boli significantly decreased with increasing oral processing time ($p<0.001$), was significantly higher for high gelling agent concentrations ($p<0.001$) and significantly higher for gels containing agar ($p<0.001$). Flowability increased significantly with increasing oral processing time ($p<0.001$), was significantly lower for high gelling agent concentrations ($p<0.001$) and was significantly lower in agar gels ($p<0.001$). Adhesiveness (data not shown) did not vary significantly with oral processing time and resilience (data not shown) was higher for gelatine gels ($p<0.001$).

These results suggest that as gels are broken down by oral processing, first peak force of boli decreases and flowabilty of boli increases. Boli from gels with high concentrations of

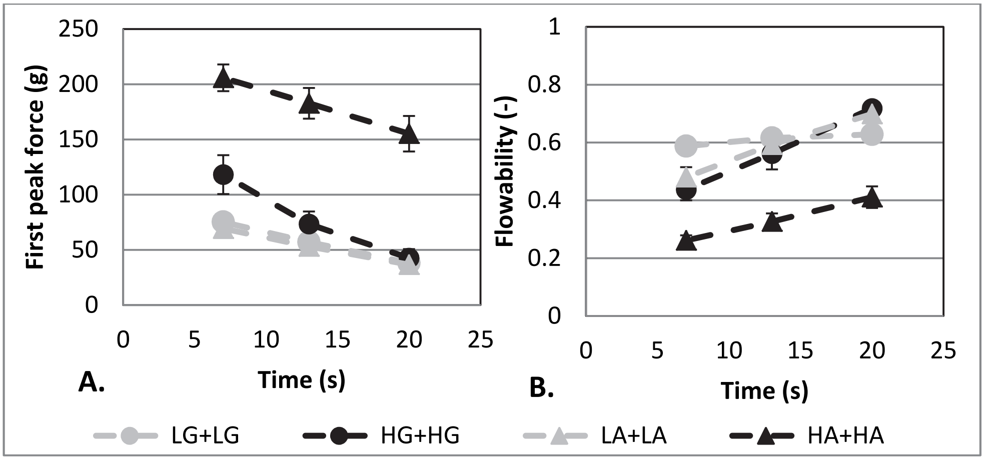

Figure 5.6 TCPT first peak force (A.) and flowability (B.) of the boli of the reference emulsion-filled gels without mechanical contrast over oral processing time. Error bars represent the standard error to the mean (n=10).

gelling agent are less broken down than boli from gels with low concentrations of gelling agent despite the higher muscle activity used to break down the gels (see section 5.3.1.2.2.). The mechanical properties of boli of gelatine gels suggest that the boli are more broken down, however the fragment size and number suggest that the boli are less broken down. Such apparent contradictory results could be explained by the in mouth melting of gelatine gels as observed in image texture analysis, which creates a liquid phase surrounding the gel fragments resulting in softer and more flowable boli.

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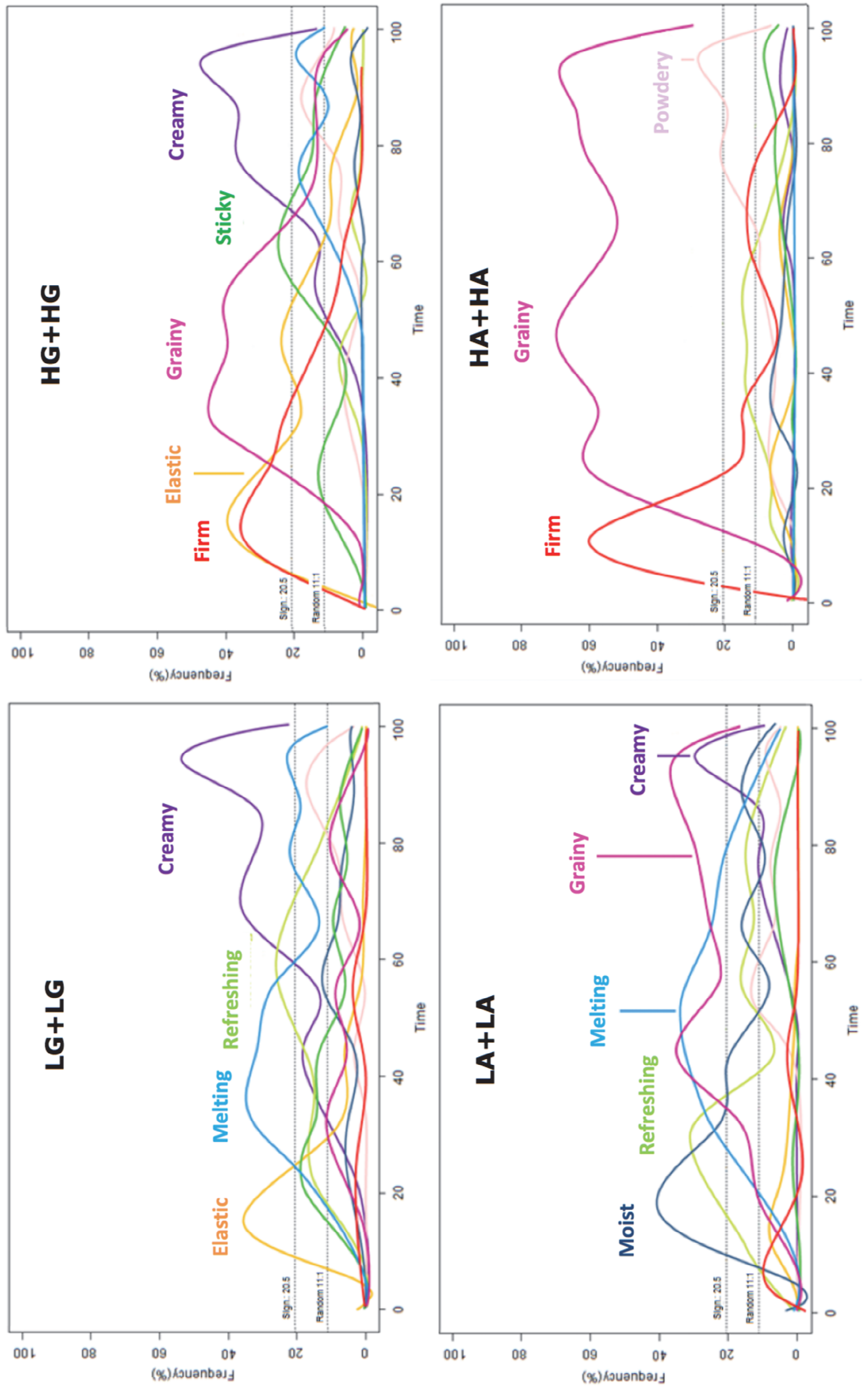
Bolus fragments analysis, image texture analysis and mechanical boli properties suggest that gels are broken down differently during oral processing depending on the gelling agent and concentration used. Gels with a high concentration of gelling agent broke down slower than gels with a low concentration of gelling agent. Gels containing gelatine broke down faster than agar gels due to in mouth melting.

5.3.1.4. Dynamic texture perception of emulsion-filled gels without mechanical contrast (TDS)

TDS profiles of the layered, homogeneous gels without mechanical contrast are shown in Figure 5.7. Both gelatine gels (LG+LG and HG+HG) were perceived as elastic in the beginning of oral processing and as creamy towards the end of oral processing. Both agar gels (LA+LA and HA+HA) were perceived dominantly as grainy from around 1/3 of oral processing time until the time of swallow. Gels with low concentrations of gelling agents (LG+LG and LA+LA) were perceived as melting and refreshing in the middle of oral processing and creamy at the end of oral processing. Gels with a high concentrations of gelling agents (HG+HG and HA+HA) were perceived as firm in the beginning of oral

Figure 5.7 TDS dominance curves of the reference emulsion-filled gels without mechanical contrast (n=10, triplicate).



processing time and grainy in the middle of oral processing time. We conclude that the perception of texture of the emulsion-filled gels was dynamic with a succession of attributes. Perception of gel texture was mainly influenced by the type of gelling agent used as well as by the concentration used. The most complex gels were HG+HG and LA+LA with 5 different texture attributes perceived as dominant sensations followed by LG+LG with 4 attributes perceived as dominant followed by HA+HA, which was dominantly grainy with a high consensus of the panellists, with only 3 attributes. We conclude that the four reference emulsion-filled gels reveal different dynamic texture profiles.

5.3.2. Impact of mechanical contrast on oral processing and dynamic texture perception of emulsion-filled gels

When two different homogenous gel layers are combined in samples, the gel becomes heterogeneous with respect to its mechanical properties i.e. displays mechanical contrast. Knowing the properties of each homogenous layers (see section 5.3.1.), in terms of mechanical properties, dynamic texture perception and oral processing parameters, the dynamic texture perception and oral processing of gels with contrasting mechanical properties can be better understood. All oral processing parameters (time and muscles activities), bolus properties and dynamic texture perception (TDS) obtained for all emulsion-filled gels with mechanical contrast (LA+HA, LA+LG, LA+HG, HA+LG, HA+HG, LG+HG) are summarized in appendices 5.1-5.7.

5.3.2.1. Oral processing of emulsion-filled gels with contrasting mechanical properties

In Figure 5.8, a PCA bi-plot of the 10 gels over the oral processing parameters is given. PC1 and PC2 account for a total of 79% of the variance between the gels. It can be seen that PC2 (X axis) accounts for the difference in gelling agent concentration with HA+HA and HG+HG being masticated for a long duration and a high muscle activity. HG+HG and HA+HA are located on the right side of PC2 while LA+LA and LG+LG are located on the left side. PC1 (X axis) accounts for the difference in gelling agent used with agar gels having boli with many, small and round particles and low mixing (high image contrast features) and gelatine gels having boli with high resilience and adhesiveness, gel fragments and lower image textural contrast, as a result of melting. LA+LA and HA+HA are located on the top side of PC1 while LG+LG and HG+HG are located on the bottom side of PC1. The four reference emulsion-filled gels without mechanical contrast form a reference trapezoid (blue lines in Figure 5.8). It can be seen that gels with mechanical contrast are positioned within or close to the lines of the trapezoid. Gels with contrasting mechanical properties combining hard and soft layers of the same gelling agent (LG+HG and HA+LA), are positioned in between their respective homogeneous layers indicating that their oral processing parameters were close to the average of the two respective homogeneous gels. However, when two gelling agents are combined, the contrasting gel was positioned

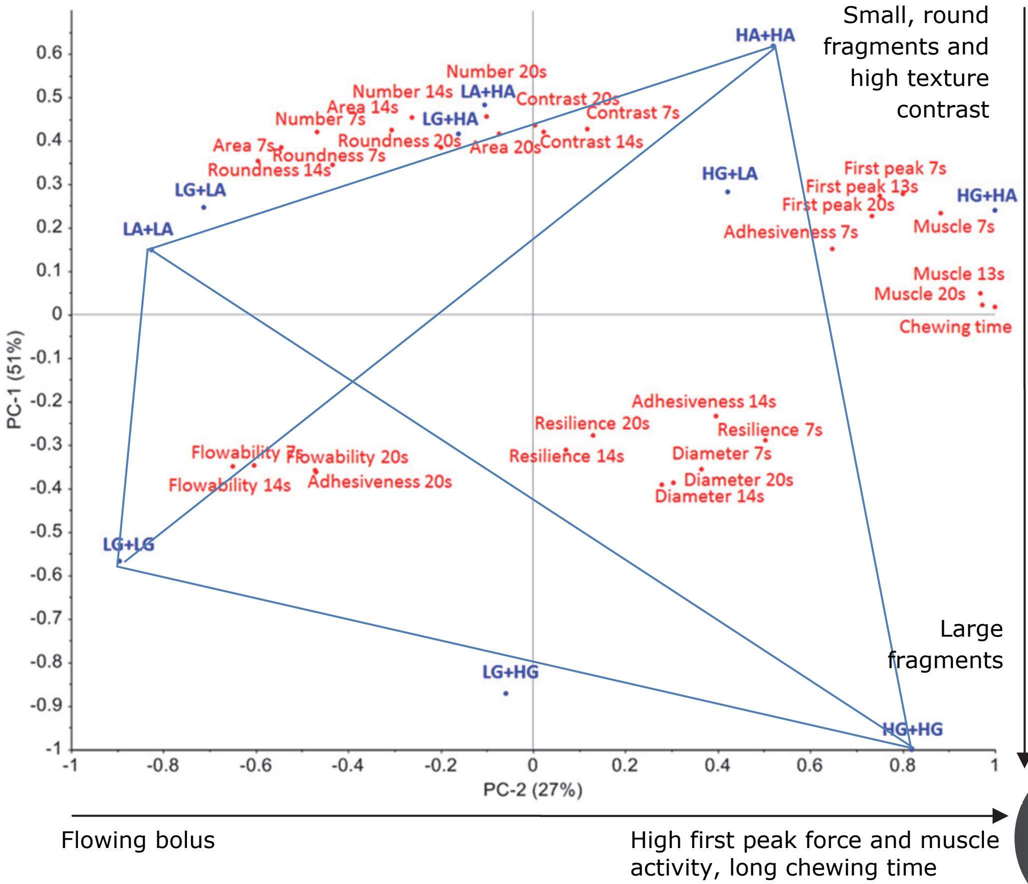


Figure 5.8 Principal Component Analysis (PCA). The bi-plot represents the scores and loading of the 10 gels over muscle activity, eating time, bolus mechanical properties and bolus fragments analysis at 3 times: 7 s, 14 s and 20 s, corresponding to 33%, 66% and 100% of oral processing. Diameter, number, area and roundness refer to parameters measured on bolus fragments by image analysis. Muscle refers to the muscle activity measured by EMG. Flowability, adhesiveness, resilience and first peak refer to parameters measured by TCPT. Blue lines were drawn between the reference emulsion-filled gels without mechanical contrast to help comparison with emulsion-filled gels with mechanical contrast.

towards the top of PC2, indicating that the oral processing parameters of agar layers had a higher impact over the gelatine layers with gels producing a powdery bolus. When layers of gels with a high concentration of gelling agent (high fracture stress) and a gel with a low concentration of gelling agent (low fracture stress) are combined, the high fracture stress gel layer seem to influence more the oral processing parameters with a slightly higher muscle activity. We conclude that gels with mechanical contrasting layers are broken down and masticated with parameters influenced by the properties of both gel layers. However, agar layers dominate the chewing behaviour and represent the bulk of the bolus. Moreover, a hard layer influence the mastication pattern more than a soft layer. It is expected that agar layers and hard layers would dominate the sensory perception as a results of changes in oral processing and breakdown.

5.3.2.2. Dynamic texture perception of emulsion-filled gels with contrasting mechanical properties

A PCA plot of all emulsion-filled gels with and without mechanical contrast over the TDS scores is shown in Figure 5.9. It can be seen that PC1 and PC2 account for 87% of the variance of the dataset (TDS scores are given in Appendix 5.7). It can be seen that similarly to Figure 5.8, PC1 (X axis) accounts for the differences in gelling agent concentration with a high concentration being perceived as firm and a low concentration as melting. HG+HG and HA+HA are located on the right end side of PC1 while LA+LA and LG+LG are located on the left end side. PC2 (Y axis) accounts for the difference in type of gelling agent used with agar gels being grainy and powdery or moist and refreshing, depending on the concentration, and gelatine gels being creamy, elastic and sticky. LA+LA and HA+HA are located on the top of PC2 while LG+LG and HG+HG are located on the bottom of PC2. Similarly to Figure 5.8, the four reference emulsion-filled gels without mechanical contrast form a reference trapezoid (blue lines in Figure 5.9). It can be seen that gels with contrast are positioned within this trapezoid. More specifically, inhomogeneous gels are positioned between the TDS scores of the two gel layers they are composed of (e.g. HG+HA is positioned between HA+HA and HG+HG). Overall, these results suggest that a combination of gels with distinctly different textures in one bite is perceived as an average of the two gels sensory properties and the perceptual properties of one gel layer do not necessarily dominate the other, with the exception of HG+LA and LG+HA. For HG+LA and LG+HA, the profile of the gel layer with high concentration of gelling agent, HG and HA respectively, seem to slightly dominate dynamic texture perception compared to the gel layer with low concentration of gelling agent as their position on the bi-plot is closer. Therefore, the hypothesized effect that a hard gel layer would dominate the texture perception of a soft gel layer is valid only when two different gelling agents are combined and this effect is small. The presence of agar gel layers did not dominate the sensory profile over the presence of a gelatine gel layer as it was shown for oral processing behaviour (Figure 5.8). We conclude that even though gelatine gels melted in mouth and agar gels composed the bulk of the bolus, melted gelatine was perceived in mouth and contributed to the sensory profile.

No effect on creaminess perception by contrasting effects of more and less creamy layers was found. Mosca et al. (2012) controlled breakdown properties of gels and differences in creaminess perception between layers were due to different fat contents in the layers. The contrast of breakdown properties in our study did not impact creaminess perception which could suggest that enhancement of fat perception cannot be achieved by contrasts in breakdown properties. However, due to the large difference in mechanical properties of the gels used in the current study, other changes in texture perception than creaminess due to contrast are introduced. As the current study uses TDS which is based on changes in dynamic perception, texture contrast resulted in the perception of many dominant attributes which limited to focus on creaminess perception solely.

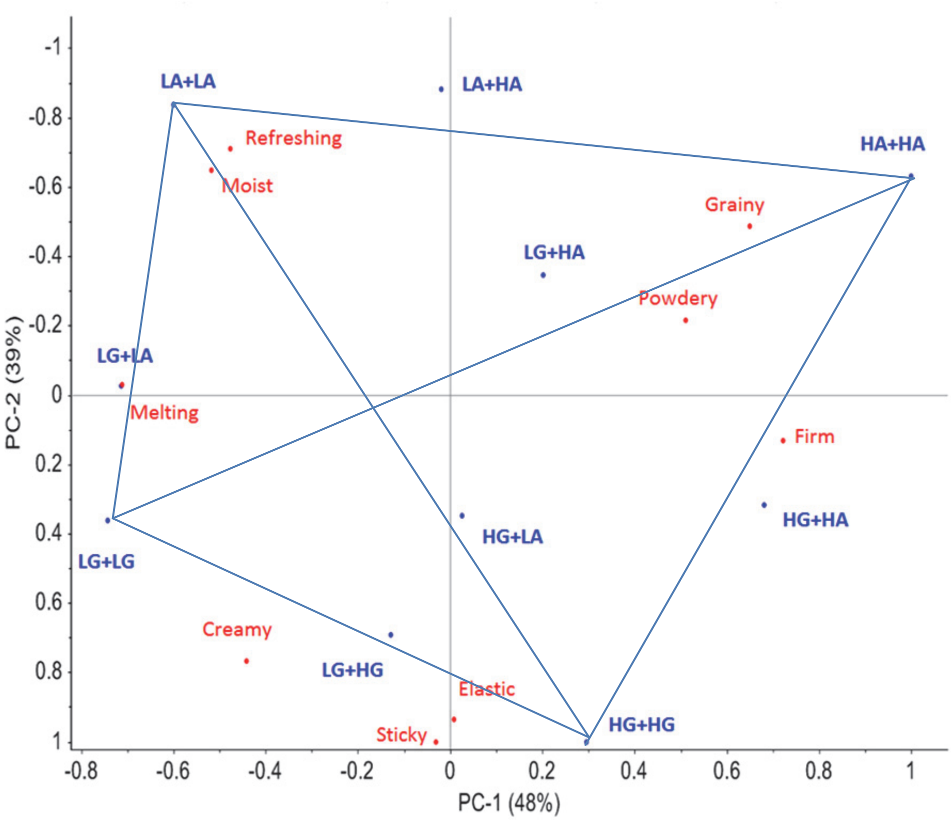


Figure 5.9 Principal Component Analysis (PCA). The bi-plot represents the scores and loading of the 10 gels over the TDS scores. Blue lines were drawn between the reference emulsion-filled gels without mechanical contrast to help comparison with emulsion-filled gels with mechanical contrast.

5.3.2.3. Sensory trajectories of emulsion-filled gels with contrasting mechanical properties

In Figure 5.10, the sensory trajectories, calculated as described by Lefant et al. (2009), are shown. PC1 and PC2 account for 67% of the variance between points. The trajectories of HA+HA and LG+LG are located at the extremes on the PCA plot and trajectories of other gels are located in between. Sensory trajectories of all gels start near to the attributes elastic and/or firm. Trajectories end towards grainy or powdery for agar gels and creamy and melting for gelatine gels. Attributes moist sticky and refreshing are mainly close to the middle of the trajectories and do not correlate highly with components. The effect of

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concentration of gelling agent seems high in the beginning of the trajectories with LG+LG and LA+LA on one side, and HG+HG and HA+HA on another side being near to each other's. Whereas, toward the end of oral processing, the effect of the gelling agent used seem to be higher with LG+LG and HG+HG on one side and HA+HA and LA+LA on another side getting closer to each other's. The concentration effect for between HA+HA and LA+LA is still important at the end of oral processing as even though closer, they remain far from each other's. It can be seen that the sensory trajectories of gels containing a combination of two gel layers with different mechanical properties are in between the sensory trajectories of the two gels they are composed of. Both layers seem to influence the dynamic texture perception of the combined gels during the total duration of oral processing, with a slight domination of HG in HG+LA and HA in HA+LG, respectively. Similar conclusions can be drawn from sensory trajectories compared to TDS scores with an additional time dimension.

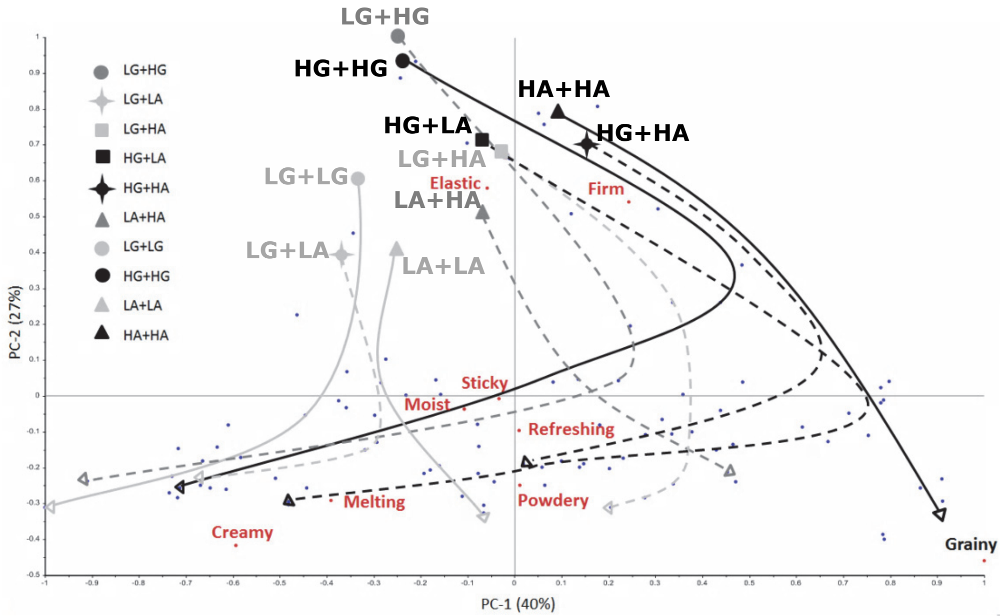


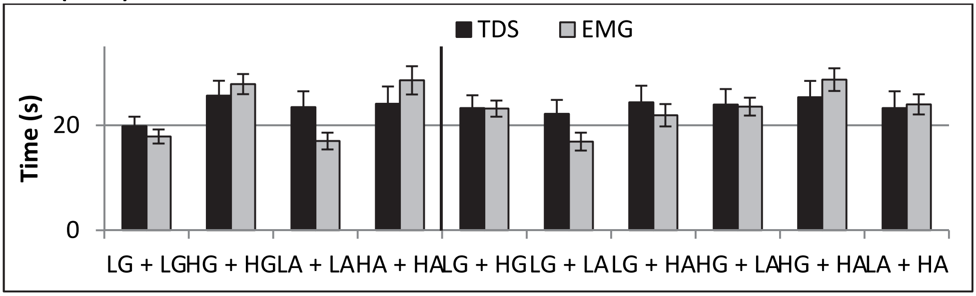
Figure 5.10 Principal Component Analysis (PCA). The bi-plot represents the sensory trajectories of the 10 gels during oral processing. Dominance rates were taken at 10% time intervals for the nine texture attributes. The lines are a simplified representation of the successive order over time and are merely to guide the eye.

5.4. Conclusions

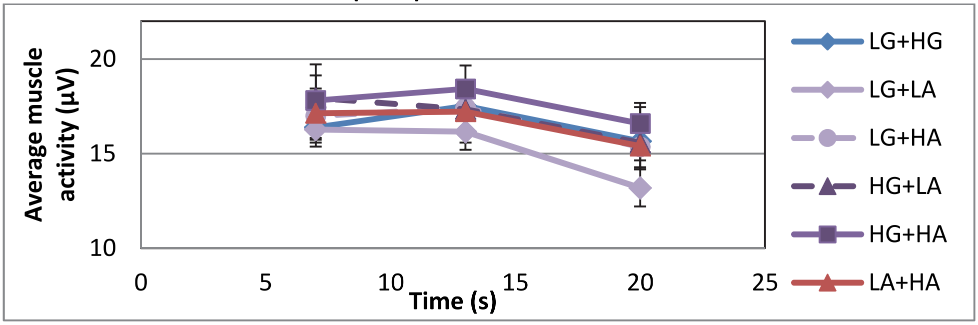
The composition of emulsion-filled gels in terms of gelling agent (agar/gelatine), concentration (high/low) and combination of layers has an impact on mechanical properties, oral processing parameters and dynamic texture perception of emulsion-filled gels. Gel layers made with high concentrations of gelling agent display a higher fracture stress than gel layers with lower concentrations of gelling agent. Gelatine gel layers have a higher fracture strain than agar gel layers. Dynamic texture perception and oral processing parameters of emulsion-filled gels differed due to both gelling agent type and gelling agent concentration. Gelatine gels were perceived as elastic and creamy while agar gels were perceived grainy. Gels with low concentration of gelling agent were perceived melting, refreshing and creamy, while gels with a high concentration of gelling agent were perceived firm and grainy. Oral processing parameters also varied depending on the gels composition. Gels with high concentrations of gelling agent, as they were hard, are masticated for a long time, with high muscle activity, and produce boli containing large gel fragments, having a high first peak force and a low flowability. Gelatine gels, as they melt in mouth during oral processing, produce boli containing few large gels fragments, having a low image textural contrast and a high flowability, while agar gels, as they do not melt, and produce boli containing many small particles, having a high image textural contrast and a high first peak force and low flowability.

When two gel layers differing in mechanical properties are combined in one sample, eaten in one bite, perception and oral processing parameters depend on both layers present. Dynamic texture perception of the combined gels was in between the perception of the two gel layers present. Similar considerations hold for the sensory trajectories. Agar gel layers and gel layers with high concentrations of gelling agent dominated slightly the oral processing of the gels with mechanical contrast. However, this effect is only found in the texture perception of HG+LA and HA+LG. We conclude that when two contrasting textures are present in one bite, subjects perceive texture over time close to an average of both textures. Foods with complex textures can be evaluated with TDS. This approach could be used to investigate perception of foods with larger mechanical contrasts in further studies, such as a dry biscuits combined with a soft creamy filling in a cookie.

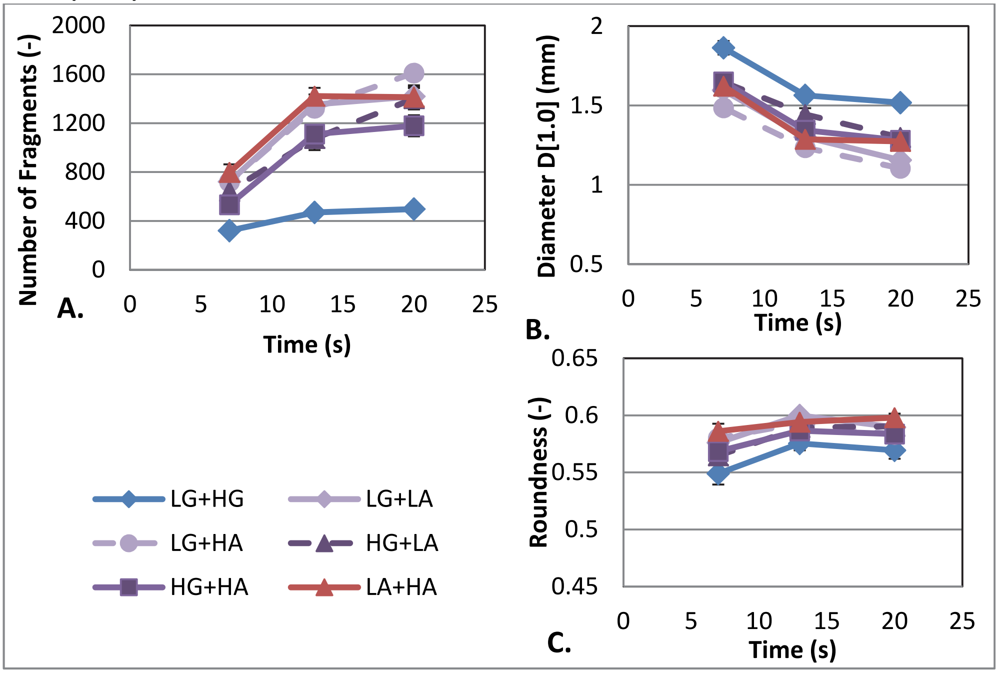
Appendix 5.1 Eating time of the reference and contrasting gels while performing TDS or EMG (n=10).



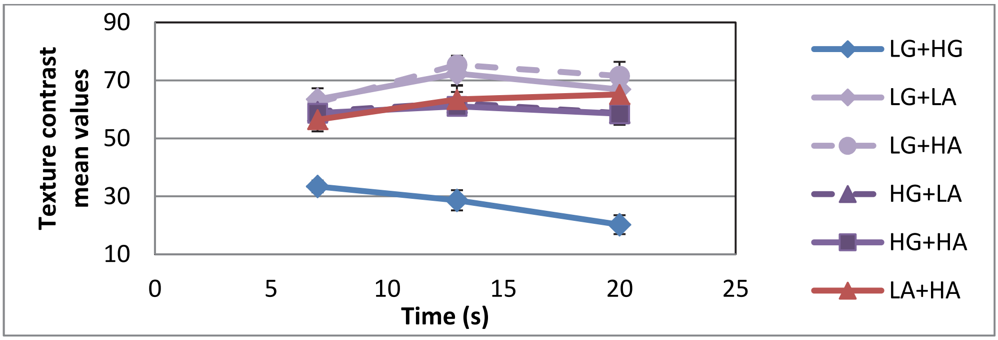
Appendix 5.2 Muscle activity while consuming the combined gels. Error bars represent the standard error to the mean (n=10).



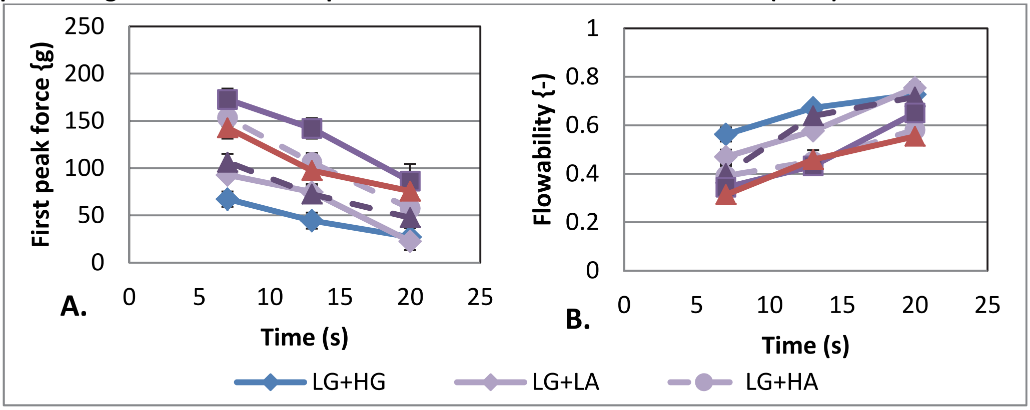
Appendix 5.3 A. Number of gel fragments in the boli from the combined gels over oral processing time. B. Diameter of the gels fragments in the boli from the combined gels over oral processing time. C. Roundness of the gels fragments in the boli from the combined gels over oral processing time. Error bars represent the standard error to the mean (n=10).



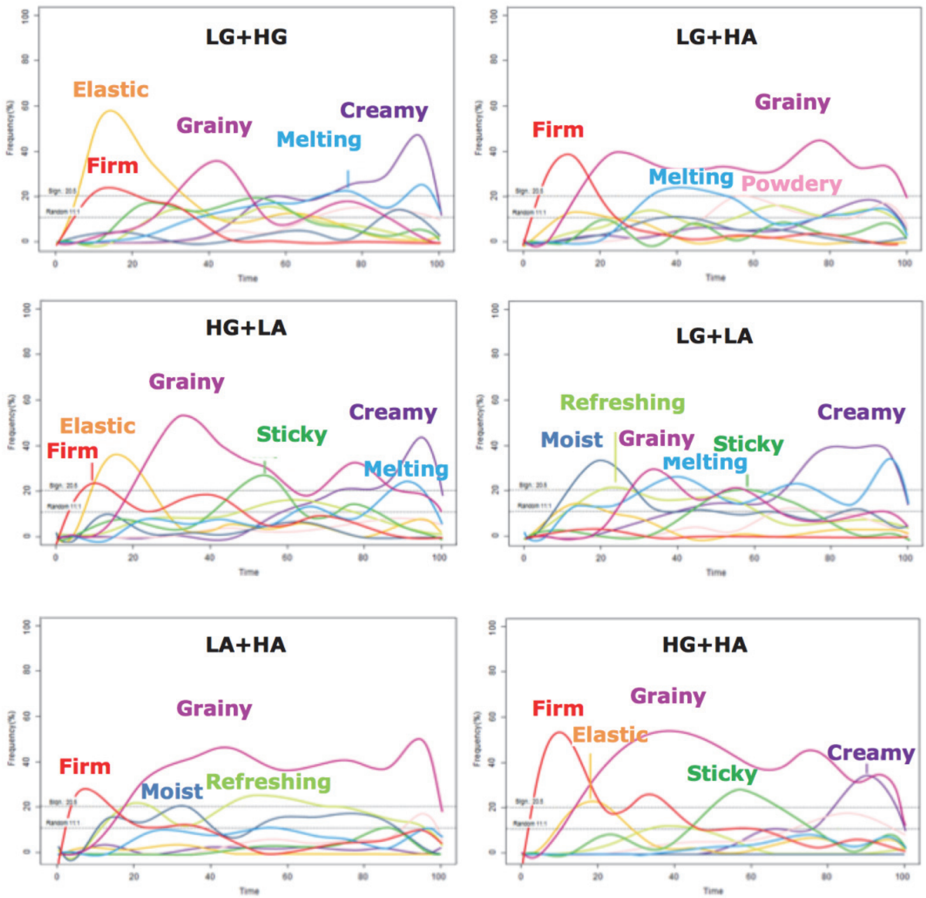
Appendix 5.4 Texture contrast of the boli from the combined gels over oral processing time. Error bars represent the standard error to the mean (n=10).



Appendix 5.5 A. TCPT first peak force of the boli from the combined gels over oral processing time. B. TCPT flowability of the boli from the combined gels over oral processing time. Error bars represent the standard error to the mean (n=10).



Appendix 5.6 TDS curves of the contrasting gels (n=10).



Appendix 5.7 TDS scores ± standard error of the mean

	Firm	Elastic	Sticky	Moist	Refreshing	Melting	Grainy	Powdery	Creamy
LG + HG	6.9 ± 2.1	17.4 ± 3.5	10 .0± 3.0	4.1 ± 2.8	7.9 ± 3.8	11.5 ± 3.0	13.2 ± 2.8	6.5 ± 2.7	14.4 ± 3.8
LG + LA	0.7 ± 0.6	4.4 ± 2.6	7.2 ± 3.3	13.2 ± 3	11.7 ± 3.4	18.2 ± 3.7	12 ± 4.5	4.5 ± 2.4	16.8 ± 5.4
LG + HA	8.4 ± 2.3	3.9 ± 2.3	4.5 ± 2.1	4.7 ± 2.5	10.2 ± 3.5	11.8 ± 3.5	30.9 ± 6.1	9.1 ± 4.5	6.8 ± 2.8
HG + LA	9.9 ± 3.2	8.9 ± 2.7	9.7 ± 3.4	2.9 ± 1.9	8.4 ± 3.9	8.4 ± 2.8	25.2 ± 4.9	3.1 ± 2.1	10.3 ± 3.5
HG + HA	16.8 ± 4.1	6.9 ± 2.6	9.7 ± 4.2	0.0 ± 0.0	3.7 ± 2.3	3.1 ± 2.4	37 .0± 6.3	6.9 ± 3.2	8 .0± 3.1
LA + HA	9.2 ± 3.0	1 ± 1.3	2.6 ± 1.9	12.5 ± 4.1	16.9 ± 4.1	6.8 ± 2.7	34.1 ± 5.9	4.2 ± 2.5	1.8 ± 1.5
LG	1.2 ± 1.2	7.6 ± 2.6	9.2 ± 3.2	5.5 ± 2.8	13.7 ± 3.5	20 ± 3	5.5 ± 2.9	4.6 ± 2.1	19.8 ± 4.2
HG	12.7 ± 3.0	16.9 ± 3.1	11.8 ± 3.4	0.5 ± 0.6	1.1 ± 0.9	6.2 ± 2.2	22.2 ± 3.4	5.3 ± 2.6	14.5 ± 3.8
LA	1.4 ± 1.0	1.9 ± 1.6	1.9 ± 1.7	17.9 ± 4.3	15.1 ± 3.6	19.1 ± 4	22 ± 6	4.8 ± 2.3	5.7 ± 2.6
HA	15.8 ± 4.6	1.8 ± 1.8	2.3 ± 2.1	1.8 ± 1.3	7.3 ± 3.0	0.0 ± 0.0	52.5 ± 7.7	10.7 ± 4.7	1 ± 1.1

CHAPTER 6

Eating behaviour explains differences between individuals in dynamic texture perception of sausages.

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Abstract

Texture perception of foods has been demonstrated to be influenced by age, dental health and oral processing behaviour. Eating duration is a significant factor contributing to and determining food oral processing behaviour. The influence of eating duration on dynamic texture perception, oral processing behaviour and properties of the food bolus has not been investigated extensively. The aims of this study are i) to determine the influence of naturally preferred eating duration on dynamic texture perception of sausages and ii) to explain differences in dynamic texture perception between short and long duration eaters by chewing behaviour and bolus properties. Two groups of subjects were selected based on their natural eating duration for a controlled portion size of two sausages. The group of “long duration eaters” (n=11) took on average twice as long to consume a piece of sausage compared to the group of “short duration eaters” (n=12). Independent of eating duration, short and long eating duration subjects chewed sausages with the same chewing frequency ($p=0.57$) and muscle effort rate ($p=0.15$) during oral processing. Total muscle effort and total number of chews were significantly higher ($p<0.05$ for both)for long duration eaters mainly due to the longer eating time compared to short duration eaters. Bolus properties showed that short duration eaters did not break down the boli as much as long duration eaters resulting in fewer ($p<0.001$) and larger ($p<0.05$) sausage bolus fragments, firmer ($p<0.001$) and less adhesive ($p<0.001$) boli with lower fat content ($p<0.05$) and less saliva incorporation ($p<0.001$) at swallow compared to the bolus properties of long duration eaters. These differences in bolus properties influenced dynamic texture perception of the sausages as the bolus of short duration eaters revealed different properties than the bolus of long duration eaters. Temporal dominance of sensations (TDS) showed that short and long duration eaters perceived the same sausage similarly in the early stages of oral processing, but started to perceive the texture of the same sausage differently from the middle of oral processing towards the end. We conclude that short duration eaters did not compensate for their shorter eating duration by chewing more efficiently but were comfortable swallowing a less broken down bolus than long duration eaters. Moreover, we conclude that differences in eating behaviour between subjects can lead to differences in bolus properties of sausages causing differences in dynamic texture perception of the same sausage.

6.1. Introduction

Texture perception changes over oral processing time as food is broken down by mastication and is lubricated by saliva incorporation (Hutchings and Lillford, 1988). Several factors were found to influence texture perception including food structure and physiological and behavioural aspects of oral processes (Wilkinson et al. 2000). Szczesniak (2002) hypothesized that differences in texture perception between individuals could depend on differences in age, hunger state, relaxation state and eating behaviour such as slow/passive eaters compared to fast/nervous eaters.

Of the factors influencing texture perception between individuals suggested by Szczesniak, the impact of age on sensory and texture perception has been studied the most. Variation in age can be considered as a variation of a physiological aspect of oral processing that influences oral processing behaviour and perception. For instance, with increasing age the sensitivity to taste, olfactory and trigeminal stimuli generally decreased (Hummel et al. 1998; Stevens et al. 1982; Kremer et al. 2007a). However, decrease in tactile sensitivity was hardly related to differences in sensory perception in elderly subjects (Kremer et al. 2007b). The influence of age on dynamic texture perception was studied by Hutchings et al. (2013, 2014) using temporal dominance of sensations (TDS). Hutchings et al. (2013, 2014) found that dynamic texture perception of a range of foods varied only slightly between young and older consumers. The effect of age on eating behaviour was studied using Electromyography (EMG) by Kohyama et al. (2002). They found that elderly subjects apply less force per chew and apply more chewing cycles before swallowing foods than younger subjects. Mioche (2004) suggested that elderly adapt their eating duration (i.e. chew for a longer time) to compensate for a lower chewing efficiency resulting in a similar texture perception compared to younger subjects.

According to Szczesniak (2002), besides age, additional factors can influence texture perception such as oral physiology and oral behaviour parameters. It was shown that elderly wearing dentures perceived the texture of the same foods differently compared to elderly without dentures (Kremer et al. 2007b). Furthermore, it was suggested that properties of the food bolus, such as saliva incorporation, should be measured when investigating the effect of differences in eating behaviour on food breakdown (Yven et al. 2012). Several bolus properties were related to texture perception in several studies (de Wijk et al. 2006b; Young et al. 2013). Saliva composition was found to have an impact on sensory perception (Salles et al. 2010). Moreover, total protein concentration and α-amylase activity were correlated to texture perception (Engelen et al. 2007). Oral behaviour was found to influence texture perception as well. Brown et al. (1994) used EMG on young and healthy subjects consuming foods varying in hardness and showed that individuals can be grouped according to eating behaviour. Using hierarchal linked cluster analysis on fifty-two subjects they distinguished five groups differing in eating behaviour. The main factors varying between groups were chewing time and muscle work rate. They also demonstrated that the obtained groups showed differences in texture perception determined using a visual analogue scale, for example eaters with a short eating time perceived firmness higher than groups with longer eating times (Brown et al. 1994). This suggests that differences in eating strategies could be a key factor contributing to inter-individual differences in texture perception.

To the best of our knowledge, the influence of differences in eating behaviour, such as slow versus fast eaters, on texture perception has not been studied extensively. The aims of this study are i) to determine the influence of naturally preferred eating duration on dynamic texture perception of sausages and ii) to explain differences in dynamic texture perception between subjects having a different eating duration by their chewing behaviour and bolus properties. In this study, two groups of healthy subjects were selected based on their natural eating duration for a controlled portion size of sausages representing short and long duration eaters. To achieve the aims, three hypotheses are tested:

Hypothesis 1: We hypothesise that subjects with a shorter eating duration of a given portion size of a sausage compensate for their shorter eating duration by applying a higher chewing frequency (number of chews per time) and/or a higher muscle effort resulting in a higher chewing efficiency (as defined by Slagter et al. 1992) during mastication in comparison to subjects with a longer eating duration.

Hypothesis 2: We hypothesize that short and long duration eaters swallow a bolus with similar properties at the end of mastication as a result of compensational oral behaviour.

Hypothesis 3: We hypothesise that dynamic texture perception varies between groups differing in eating duration as a result of differences in eating behaviour (compensation by chewing frequency and efficiency) rather than differences in bolus properties.

6.2. Materials and methods

Participants were selected on their natural eating time of sausages. Eating behaviour was measured by surface EMG. Surface EMG monitors the electrical activity of skeletal muscles. The electrical potential of muscle cells (voltages) when they are active is recorded by EMG electrodes which are placed on the skin surface overlaying a muscle group. Expectorated bolus were analysed for particle size, saliva and fat content and rheological properties. Dynamic texture perception was measured by TDS.

6.2.1. Sausages

Two commercial meat products manufactured by Encebe Vleeswaren (VION Food Nederland B.V., Boxtel, The Netherlands) were used: Berliner and Ardenner sausages. The two sausages were selected based on their differences in mechanical properties. The Ardenner sausage exhibits a fracture force (190.0 ± 15.4 KPa) nearly four times higher than the Berliner sausage (50.2 ± 5.8 KPa). The fracture force was determined in 5 replicates using a uni-axial compression test at a constant speed of 5.0 mm/s to a compression of 80% with a texture analyser (TA.XT plus, Stable Micro Systems-SMS) on a 1 x 2 x 2 cm piece positioned to a 1 cm height. In the following, the Ardenner sausage is referred to as hard sausage and the Berliner sausage as soft sausage. The hard sausage contained 54.7% water, 28 % fat, 12 % proteins, 3 % carbohydrates, 2 % salt and 0.3 % fibres. The soft sausage contained 50.8 % water, 32 % fat, 12 % proteins, 3.5 % carbohydrates and 1.7 % salt.

6.2.2. Screening of consumer groups for natural eating time

Sixty-seven participants were recruited for a screening session based on criteria of having no swallowing or mastication disorders, good dental health and non-smoking habits. A faster eating style is often correlated to a higher body weight (Hill and McCutcheon, 1984; Llewellyn et al. 2008). Therefore, all subjects participating in our study had a healthy BMI below 25. During the screening session subjects were asked to time their natural eating time of sausage cubes (1 x 1 x 2 cm) from the moment they put the cube into their mouth to the moment they swallow the bolus. The screening was done for the soft and hard sausages. Twenty-three participants were selected to join further sessions based on their individual eating times. In the following screening session, subjects were asked again to time their eating time of soft and hard sausage cubes of larger dimensions (1 x 2 x 2 cm) to confirm their individual eating time. The selected participants were divided into two groups varying in natural eating time, a group of short duration eaters (n=12, age 22.8 ± 2.6 years, 8 female) and long duration eaters (n=11, age 24.4 ± 2.5 years, 6 female) (see section 6.3.1). Short and long duration eaters groups were composed of respectively 7 and 6 different nationalities. Subjects were unaware of the selection criteria during the whole experiment. All subjects gave written informed consent prior to the study. All subjects were paid for their participation. The study was conducted in line with the medical ethical guidelines of the Wageningen University, The Netherlands.

6.2.3. Electromyography (EMG)

6.2.3.1. Placement of electrodes

At sensor locations, subject’s skin was cleansed with ethanol swaps. Four active EMG electrode sensors (Biosemi Active 2, Biosemi b.v., Amsterdam, The Netherlands) were placed on the so called Temporalis (left, right) and Masseter (left, right) muscle. In addition, CMS and DRL reference electrodes were placed on the cheek and behind the right ear on the mastoid bone, respectively. Two extra electrodes were placed centrally above the right eyebrow and on the mastoid bone behind the left ear. These electrodes were added to monitor artefacts due to eye blinks and eye movements and as optional reference electrodes. The electrodes were located by palpation. EMG recordings were amplified with a BIOSEMI ActiveTwo amplifier in DC mode and sampled at 2048 Hz.

6.2.3.2. Experimental procedure

Subjects were seated in a comfortable chair with a computer screen approximately 40 cm in front of their eyes. Instructions were presented on the screen generated by a protocol prepared with EyeQuestion Version 3.9.7 (Logic8 BV, Elst, The Netherlands). The EMG session consisted of two parts. During the first part, EMG recordings were made during natural consumption of the sausages. During the second part, simultaneously to the EMG recordings subjects assessed the texture perception of the sausages using TDS. At the start of all sessions subjects received a short introduction about the session. In the first part of the session subjects were asked to masticate and swallow seven samples (one warm up sausage and, at random, three replicates of the soft and hard sausages). Subjects were instructed to eat freely with no specific instructions regarding the oral processing of the sausages. Subjects were prompted on the computer screen which sausage to place in their mouth. Then, following a subsequent start-sign from the researcher, subjects started eating while EMG data were collected for 60 s. When subjects finished eating the sausage, they raised their hand to indicate to the researcher that they had finished eating. These events were collected (eating on and off set) by the researcher with E-prime® stimulus presentation software (E-prime Sharpsburg, USA). The second part of session was following a similar procedure, the only differences was that the subjects were instructed to conduct the TDS assessment of the sausages simultaneous to the EMG recordings (TDS is described in section 6.2.6). All sessions lasted less than one hour. Subjects could pause at will between the sausages and an extra break was taken half way through the session. Sausages were evaluated in individually randomised order. Sausages were presented at room temperature as cubes (1 x 2 x 2 cm corresponding to 4.24 ± 0.25 g) in a cup coded with 3 digits.

6.2.3.3. EMG data analysis

EMG data pre-processing: EMG measures were down-sampled to 256 Hz (Decimeter, BioSemi, Amsterdam, NL). Subsequent EMG data analyses were performed with the EEGlab (9_0_8_6b) (Delorme and Makeig, 2004) toolbox running under Matlab R2011a (The Mathworks, Natick, MA). EMG data were band-filtered (2 Hz - 64Hz), notch filtered (45 - 55Hz) and epoched (-100 ms pre-eating to +59000 ms post-eating onset). Artefacts due to eye-blinks and eye-movement were removed after component extraction with independent-component analysis (ICA) and subsequent identification of the components containing the typical ocular artefact spindles with the expected topographic distributions in the light of the signal source. Subsequently, data were converted to absolute voltages. For the EMG recordings of the Masseter (left and right) the total Area Under the Curve (AUC) were calculated for the TDS and no TDS conditions over the whole recording (60 s). Furthermore, the total AUC, the average AUC per second, total number of chews and chewing frequency over oral processing times corresponding to 33%, 66% and 100% of the total eating time (see Table 6.2) were calculated for the no TDS condition (first part of the session).

EMG statistical data analysis: The total AUC, AUC per second, number of chews and chewing frequency were subjected to a repeated measures ANOVA in SPSS (IBM SPSS statistics v19.0, Chicago IL, 2010) with sausage type (hard and soft), expectoration time (33%, 66% and 100% of oral processing time), replicate (3) and eating duration group (short and long) as between subjects factor. Post-hoc pairwise comparison test were performed with Bonferroni correction. The degrees of freedom were adjusted with Greenhouse-Geiser in case of a significant ($p<0.05$) outcome in the Mauchly's Test of Sphericity.

6.2.4. Bolus collection

Subjects (n=23) joined three sessions of 45 minutes for bolus collection. During each session, subjects were instructed for 10 min and placed in sensory booths where they received cups in random order containing 3 sausage cubes (1 x 2 x 2 cm) coded with 3-digits. Subjects were instructed to put one cube in their mouth and chew as naturally as possible and expectorate the sausage bolus when a timer gives a signal. At the end of the given time, panellists spat out the bolus as a whole in a coded, sealable plastic cup (screw cap urinary cup 120 ml, VWR). The sausage boli were expectorated at different time intervals corresponding to 33%, 66% and 100% of the averaged oral processing time (see Table 6.2). All collected sealable cups were stored overnight in a fridge at 4 °C before further analysis.

6.2.5. Characterization of bolus properties

6.2.5.1. Gravimetrical determination of saliva content of boli

Boli collected for measuring saliva content were placed on aluminium dishes, weighed and dried in a convection oven (Binder, Tuttlingen, Germany) for a minimum of 24 hours at 102°C. Dry weight of boli was measured after cooling the boli in a desiccator for 20 min. Dry matter of the sausage was measured following the same protocol but using mashed cubes (1 x 2 x 2 cm) of sausage in triplicate. Saliva content (wt%) was calculated by subtracting the water content of the sausage (wt%) from the water content of the expectorated boli (wt%).

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6.2.5.2. Determination of fat content released from sausages boli

A solution of distilled water containing 4 wt% of liquid dishwashing soap (purchased at a local retailer) was added to each collected bolus to reach approximately a 1:4 dilution. The obtained mixture was mixed with a Vortex mixer VV3 (VWR International Ltd, Lutterworth, England) for around 30 s and filtered with a micro sieve of 125 µm mesh. The oil content of the filtrate was determined using the Rose-Gottlieb method (ISO 1211) by Qlip (Leusden, The Netherlands). This method was adapted from Sala et al. (2007b).

6.2.5.3. Determination of particle size, number and roundness of bolus fragments

Each boli were placed in one plastic petri dish (plastic 94/16 mm, Greiner) containing distilled water and fragments were gently separated with a spatula. When necessary, fragments were distributed on more petri dishes to avoid contact between them. Boli of the soft sausage could not be dispersed properly as separation of the soft and highly sticky fragments involved applying a small pressure on the spatula which broke and deformed the fragments. Therefore, only the hard sausage dispersed boli were used for data analysis of particle size, number and roundness. For each bolus of the hard sausage, the petri dishes containing one bolus were placed on a 9950F scanner (Canon Inc., JP) and two grayscale pictures at a resolution of 800 dpi were taken. Fragments were re-dispersed by mixing with a spatula between the two pictures. Pictures were analysed for particle size after applying a black and white threshold in ImageJ (National Institutes of Health, Version 1.45 K) which provided, for each picture, the number of fragments and the area and roundness of each fragment. Results from image analysis were exported to Excel (Microsoft, 2010) where the volumetric diameter (D[4,3]) was calculated, assuming that fragments are a disc projection of a sphere. Average roundness, average volumetric diameter (D[4,3]) and average number of fragments were calculated for combination of eating times (33, 66 and 100 %) and each eater group (short and long duration eaters).

6.2.5.4. Two cycle penetration test (TCPT) of expectorated sausage boli

For two cycle penetration test (TCPT) analysis, panellists chewed subsequently 4 pieces of sausage, for each duration (33, 66 and 100 %), and spat them out in the same sealable cup. After collecting each bolus in quadruplicate in one cup, the surface was gently smoothed with the back of a spoon. Boli were kept at 20°C until being analysed within a few hours after collection. A TCPT was performed consisting of two successive uniaxial penetrations of a 20 mm diameter cylindrical steel probe into the boli mass using a Texture Analyser (TA.XT plus, Stable Micro Systems-SMS). The probe penetrated twice the bolus until 75% strain at a constant speed of 5 mm/s. The probe was retrieved at a speed of 5 mm/s. A resting time of 5 s between the two compressions was applied. Data acquisition was carried out using a 5 kg load cell at a sample frequency of 40 Hz. From the TCPT, the peak force of the first penetration cycle and the negative area under the force-time curve after the first retrieval defined as adhesiveness were obtained. Flowability (defined as the area under the force-time curve during the second penetration cycle divided by the area under the force-time curve during the first penetration cycle) was determined for all boli of the soft and hard sausages. Flowability did not differ significantly between sausage types or eater groups and is not discussed further.

6.2.5.5. Statistical data analysis

All bolus parameters were checked for normality of the distribution of the data and transformed when needed: square root transformation of saliva content, inverse transformation of fat content released from bolus and square root transformation of the positive value of adhesiveness were applied to normalise the data. Normalised data was analysed in SPSS for repeated measures ANOVA where the effect of sausage type (soft and hard) and expectoration time (33, 66 and 100%) were analysed as within subject factors and eater group (short and long duration eaters) was analysed as a between subjects effect. A Bonferronni Post-Hoc test was conducted between the three expectoration times when applicable. A significance level of $p<0.05$ was chosen.

6.2.6. Temporal dominance of sensations (TDS)

Subjects (n=23) were invited to join 3 training sessions for the TDS assessment. The first session of 1.5 hours consisted of explaining the principle of TDS and the definition of dominance according to Pineau et al. (2009). After the explanation, subjects could taste three commercial meat products (cooked ham, gebraden gehakt (meatloaf) and boterhamworst (luncheon meat) manufactured by Vion Food (The Netherlands) which were not used in the TDS assessment sessions. This procedure was followed to discuss and illustrate the texture attributes of a predetermined list from internal unpublished reports in agreement with literature (Jimenez et al. 1995; Xiong et al. 2006). Reformulation of the name of attributes or removal of attributes from the list was discussed until agreement was reached between the subjects. The two following training sessions of 30 minutes each were conducted in sensory booths to train panellist on the use of the TDS software of EyeQuestion Version 3.9.7 (Logic8 BV, Elst, The Netherlands) on the soft and hard sausages. No further training was conducted as TDS is known to be suitable for use by untrained consumers (Meillon et al. 2010; Bouteille et al. 2013). For the test session, 8 texture attributes were used for the TDS scoring (Table 6.1). The appearance order of attributes was randomized between panellists but maintained for each panellist between samples. Panellists were instructed to put a cube of sausage (1 x 2 x 2 cm) into their mouth and press the 'start' button. Then, they were instructed to rate dominance while eating as they would normally do and push the button 'end' at the time of swallowing. After swallow, panellists rated 3 texture after-feel attributes (Table 6.1) on a 100 mm line scale (anchored with "very low" at the left end and with "very high" at the right end). In a single test session of 45 minutes, panellists tested a warm up sample followed by two sausage samples (hard and soft sausage) in quadruplicate in a random design. Therefore, each sausage (soft and hard) was assessed by n=12 subjects of the short duration eater group and n=11 subjects of the long duration eater group in quadruplicate. During each run, dominance of each attribute was recorded at each time point. Each run was standardized according to individual mastication duration. Chance level, significance level and dominance rates were calculated and visualized in dominance curves according to Pineau et al. (2009).

Table 6.1 List of sensory attributes and definitions used for the TDS assessment of soft and hard sausages

Attribute	Definition
Chew down:	
Hard	Effort or force required to bite through the sample
Grainy	Presence of particles in the mouth, inhomogeneity
Dry	Dry and rough feeling on the tongue and oral cavity
Smooth	Smooth feeling, homogeneity of the product in the mouth
Sticky	Product sticks to oral cavity and teeth. Difficulty to get the teeth off from each other
Fatty	Perception of fatty, oily, greasy feeling
Slippery	Easiness to move the sample in the mouth
Juicy	Presence of liquids in the mouth
After-feel:	
Fatty	The product leaves a fatty layer/film after consumption.
Residue	The remaining lumps of the product after consumption
Dry	The dry, rough feeling on your tongue the product leaves after consumption

6.3. Results

6.3.1. Characterization of subjects according to eating time

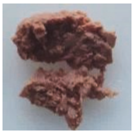
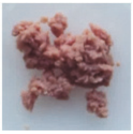
Out of the 67 participants who participated in the screening sessions, two groups were selected based on their natural eating duration of pieces of the soft and hard sausage (portion size 1x1x2 cm and 1x2x2 cm). The results from the mastication of the 1x2x2 cm pieces are reported in Table 6.2.

One group consisted of n=12 short duration eaters, the second group of n=11 long duration eaters. For both types of sausage, long duration eaters orally processed the sausages on average by a factor of 2.3x longer than short duration eaters ($F(1, 20) = 73.6$, $p<0.001$). Eating times of the hard sausage were slightly higher than eating times of the soft sausage for both eater groups ($F(1, 20) = 54.2$, $p<0.001$). The mastication times corresponding to 33, 66 and 100% of oral processing given in Table 6.2 were calculated from the eating durations of each group and sausage. Typical boli pictures are shown in Table 6.2 to illustrate the appearance of collected boli and are not discussed further.

Long and short duration eaters recorded the dominance of their perception using TDS. While performing the test, they increased their eating duration ($F(2, 19) = 13.5$, $p<0.001$) on average by 7 s for the long duration and 9 s for the short duration eaters compared to the normal eating condition (Table 6.2). Long duration eaters still took a longer time (1.7x) to eat the sausages than the short duration eaters during TDS ($F(1, 20) = 24.9$, $p<0.001$).

Results from EMG showed that the effort of eating the sausages increased slightly, but not significantly, while performing the TDS assessment (p=0.42).

Table 6.2 Characteristics of the two groups of subjects varying in their normal eating time of pieces of sausages (short and long eating duration). Normal, TDS and EMG eating time (± standard error of the mean) are summarized for the soft and hard sausage. Bolus collection times are reported for each group and sausage type. Representative pictures of expectorated boli are shown.

Group	**Short duration eaters** n = 12 (8 female)		**Long duration eaters** n = 11 (6 female)	
Age (±SD)	22.8 ± 2.6		24.4 ± 2.5	
Sausage	Hard sausage	Soft sausage	Hard sausage	Soft sausage
Code	**Sh/Ha**	**Sh/So**	**Lo/Ha**	**Lo/So**
Normal eating time (s)	14.5 ± 0.8	10.0 ± 0.6	32.1 ± 2.2	25.3 ± 1.4
TDS eating time (s)	23.0 ± 3.1	19.7 ± 2.8	39.7 ± 3.8	32.6 ± 3.5
EMG eating time(s)	15.1 ± 1.6	14.0 ± 1.4	34.6 ± 3.2	33.2 ± 2.9
AUC (µV) No Instruction Right Masseter	465.7 ± 58.7	465.8 ± 60.1	846.9 ± 61.3	818.6 ± 62.8
AUC (µV) TDS Right Masseter	544.1 ± 67.4	502.2 ± 64.2	989.9 ± 70.4	852.5 ± 67.1
Oral processing time **33%**	 5 s	 4 s	 11 s	 8 s
66%	 10 s	 7 s	 21 s	 17 s
100%	 15 s	 10 s	 32 s	 25 s

6.3.2. Characterization of oral processing behaviour

The total AUC of the right masseter and number of chews is given in Figure 6.1. Repeated measures Anova of total AUC of right and left Masseter activity showed significant effects for eater group [$F(1,21) = 68.12$ and $F(1,21) = 60.04$, $p<0.05$], product [$F(1,21) = 78.97$ and $F(1,21) = 202.09$, $p<0.05$] and expectoration time [$F(2,20) = 256.70$ and $F(2,20) = 168.14$, $p<0.05$]. Furthermore, significant interaction effects were found for product x eater group x expectoration time [F(2,20) = 22.96 and F(2,20) = 28.93, p<0.05]. The total number of chews showed significant effects for eater group [F(1,21) = 117.69, p<0.05], product [F(1,17) = 222.59, p<0.05] and expectoration time [F(2,16) = 47.93, p<0.05]. As illustrated in Figure 6.1, the long duration eaters had a significant larger total AUC and total number of chews compared to the short duration eater group. An increase in both parameters was observed for the hard sausage compared to the soft sausage.

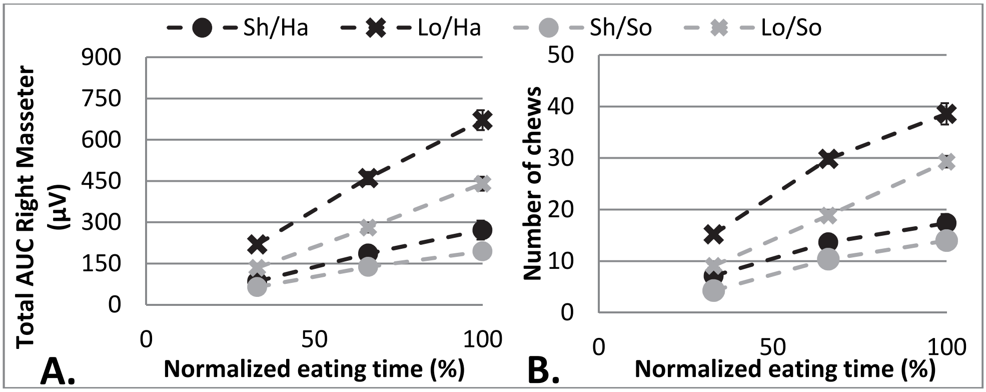


Figure 6.1 Total average AUC of EMG data of the Masseter right (A.) and Number of chews (B.) for short and long duration eater groups for the soft and hard sausage over normalized eating time. Error bars represent the standard error of the mean. The abbreviations used are explained in Table 6.2.

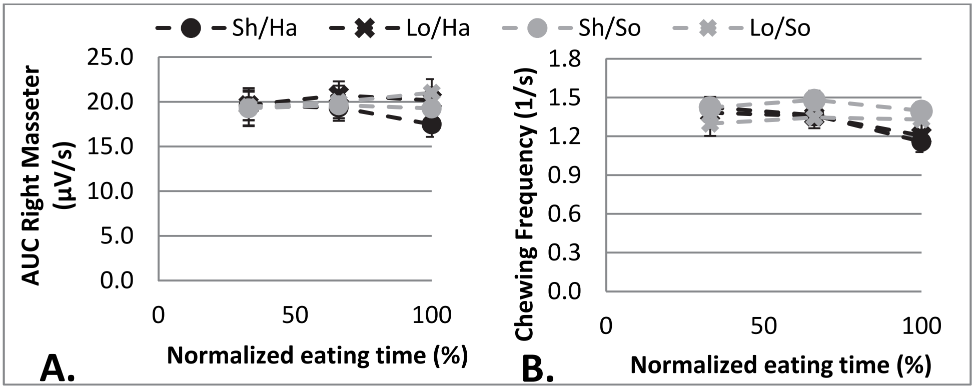


Figure 6.2 AUC per second of right Masseter (A.) and Chewing frequency (B.) for short and long duration eater groups for the soft and hard sausages over normalized eating time. Error bars represent the standard error of the mean. The abbreviations used are explained in Table 6.2.

The average AUC per second of the right masseter and chewing frequency are given in Figure 6.2. Chewing frequency showed a significant effect for expectoration time [F(2,34) = 9.5, p<0.05], but no significant differences were found for AUC per second of the right and left Masseter [F(2,20) = 0.77, p=0.47 and F(2,20) = 3.04 p=0.06]. No significant differences were found for chewing frequency and right and left Masseter AUC per second between eater groups [F(1,17) = 0.34, p=0.57, F(1,21) = 0.23, p=0.67 and F(1,21) = 2.29, p=0.15] and sausage types [F(1,17) = 3.66, p=0.07, F(1,21) = 0.59, p=0.45 and F(1,21) = 0.11, p=0.74]. As illustrated in Figure 6.2, long and short duration eaters did not differ significantly in AUC per second and chewing frequency, except the chewing frequency after 100% of oral processing time which is significantly lower compared to the chewing frequency after 33 and 66% of oral processing time.

6.3.3. Characterisation of bolus properties

6.3.3.1. Saliva content of boli and fat content released from sausages

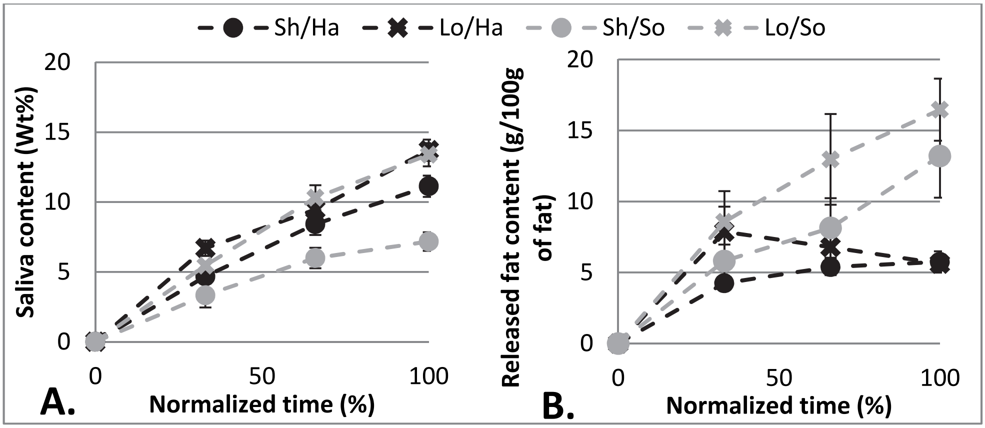


Figure 6.3 Saliva content (A.) and fat content released from the sausage into the bolus (B.) of short and long duration eater groups for the soft and hard sausages over normalized eating time. Error bars represent the standard error to the mean. The abbreviations used are explained in Table 6.2.

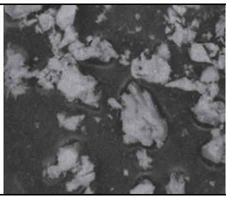
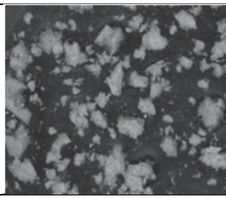
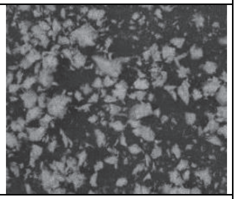
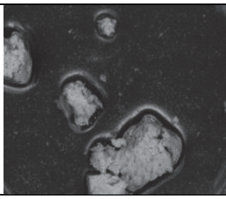
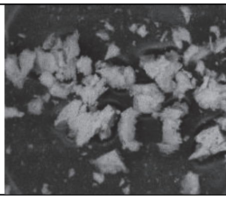
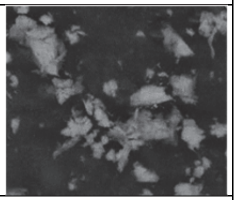
The saliva content of the bolus and the amount of fat released from the sausages into the bolus are shown in Figure 6.3 A. and 3 B. Saliva content in the boli increased significantly with eating time [F(2, 19) = 172.15, p<0.001], was higher for the hard sausage than the soft sausage [F(1, 20) = 15.68, p<0.001] and was higher in the long duration eaters group than the short duration eaters group [F(1, 20) = 20.61, p<0.001]. There was a significant interaction effect between saliva content and eater group [F(1, 20) = 10.25, p<0.05]. A post-hoc analysis showed that saliva content was higher in the hard sausage for the short duration eaters group (p<0.001) but not for the slow eaters group (p=0.675). Fat release from the sausage into the bolus significantly increased with eating time [F(1, 20) = 0.88, p<0.05], was significantly higher in the soft sausage than in the hard sausage [F(1, 20) = 26.00, p<0.001] and was not significantly different between eaters groups (p=0.102).

6.3.3.2. Particle size, number and roundness of bolus fragments of the hard sausage

In Table 6.3, pictures of hard sausage bolus show qualitative differences in sausage fragments between the short and long duration eater at different mastication times. Hard

6

Table 6.3 Analysis of bolus fragments of the hard sausage for short and long duration eater groups. An example picture is given together with the average volumetric diameter D[3,0], the average number and roundness of sausage fragments (± standard error to the mean) averaged over each group at each spit out times.

Group		Oral processing time 33%	66%	100%
Lo/Ha	Pictures from one slow eater panellist			
	D[4,3] (mm)	4.28 ± 0.22	4.05 ± 0.21	3.84 ± 0.23
	Number (-)	325 ± 28	441 ± 51	586 ± 83
	Roundness (-)	0.62±0.01	0.63±0.01	0.63±0.00
Sh/Ha	Pictures from one fast eater panellist			
	D[4,3] (mm)	4.96 ± 0.27	4.8 ± 0.12	4.35 ± 0.17
	Number (-)	193 ± 28	206 ± 20	310 ± 30
	Roundness (-)	0.57±0.01	0.61±0.01	0.62±0.01

sausage fragments were analysed for fragments size, number and roundness (reported in Table 6.3). Fragment size significantly decreased with eating time [$F(2, 19) = 15.26$, $p<0.05$] and was significantly lower for boli of long duration eaters than for boli of short duration eaters [$F(1, 20) = 23.63$, $p<0.05$]. The number of hard sausage fragments significantly increased with eating time [$F(2, 19) = 12.10$, $p<0.001$] and was significantly higher for boli of long duration eaters compared to those of short duration eaters [$F(1, 20) = 23.63$, $p<0.001$]. Roundness of the hard sausage fragments significantly increased with eating time [$F(2, 19) = 12.10$, $p<0.001$] and was significantly higher for boli of long duration eaters compared to short duration eaters [$F(1, 20) = 10.84$, $p<0.05$]. A significant interaction effect was found for roundness between eating time and eater group [$F(1, 20) = 5.01$, $p<0.05$]. A post-hoc analysis showed that short duration eaters had significantly less round boli fragments than long duration eaters at 33 and 66% of mastication time. No significant differences in roundness were found at 100% of eating time.

6.3.3.3. TCPT of sausage boli

First peak force and adhesiveness of sausage boli are reported in Figure 6.4. A significant decrease of first peak force over eating time was observed [$F(2, 20)=55.92$, $p<0.001$]. No significant differences between the two sausages ($p=0.052$). Boli of short duration eaters had a significantly higher first peak force than boli of long duration eaters [F(1, 21)=16.45, p<0.05] Interaction effects between eater groups and time were significant [F(2,20)=12.75, p< 0.001 and F(1, 21)=16.12, p<0.05]. A post-hoc analysis showed that the differences between eater groups were only significant at 33 and 100% eating time. Adhesiveness results showed that boli became more adhesive over eating time [F(2, 20)=37.08, p<0.001]. Boli of the hard sausages were less adhesive than boli of the soft sausages [F(1, 21)=203.76, p<0.001]. Long duration eaters had a significantly more adhesive boli than short duration eaters [F(1, 21)=121.93, p<0.001].

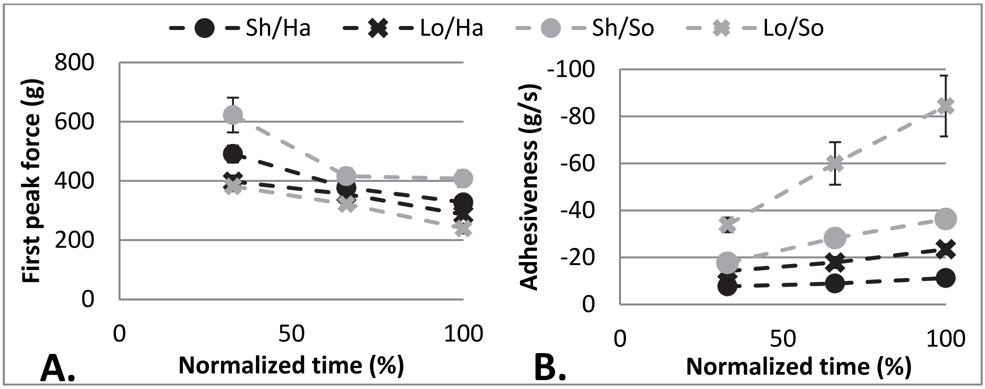


Figure 6.4 First peak force (A.) and Adhesiveness (B.) of the sausage bolus of short and long duration eater groups for the soft and hard sausages over normalized eating time. Error bars represent the standard error to the mean. The abbreviations used are explained in Table 6.2.

6.3.3.4. Correlations between oral processing behaviour and bolus properties

Bolus properties such as bolus fragments size, saliva and fat content were positively correlated to eating duration while first peak force of the bolus was negatively correlated with eating duration (Appendix 6.1). For all sausages, eater groups and oral processing times, EMG parameters were correlated with eating duration and between each other's. In addition, EMG parameters and eating time correlated negatively with fragment size of the bolus and bolus first peak force and positively with fragment number. Saliva content of the bolus was positively correlated with eating time, number of chews and muscle activity (Appendix 6.1).

6.3.4. Dynamic texture perception of sausages

While performing TDS, both groups of eaters rated on average the same number of attributes as dominant sensations regardless of the differences in eating duration (3.8 ± 1.3 attributes for the short duration and 3.9 ± 2.2 attributes for the long duration eaters, averaged on the two sausages). The TDS profiles of the soft sausage are reported in Figure 6.5 A. and 5 B. For both eater groups, the sausage was perceived as smooth in the

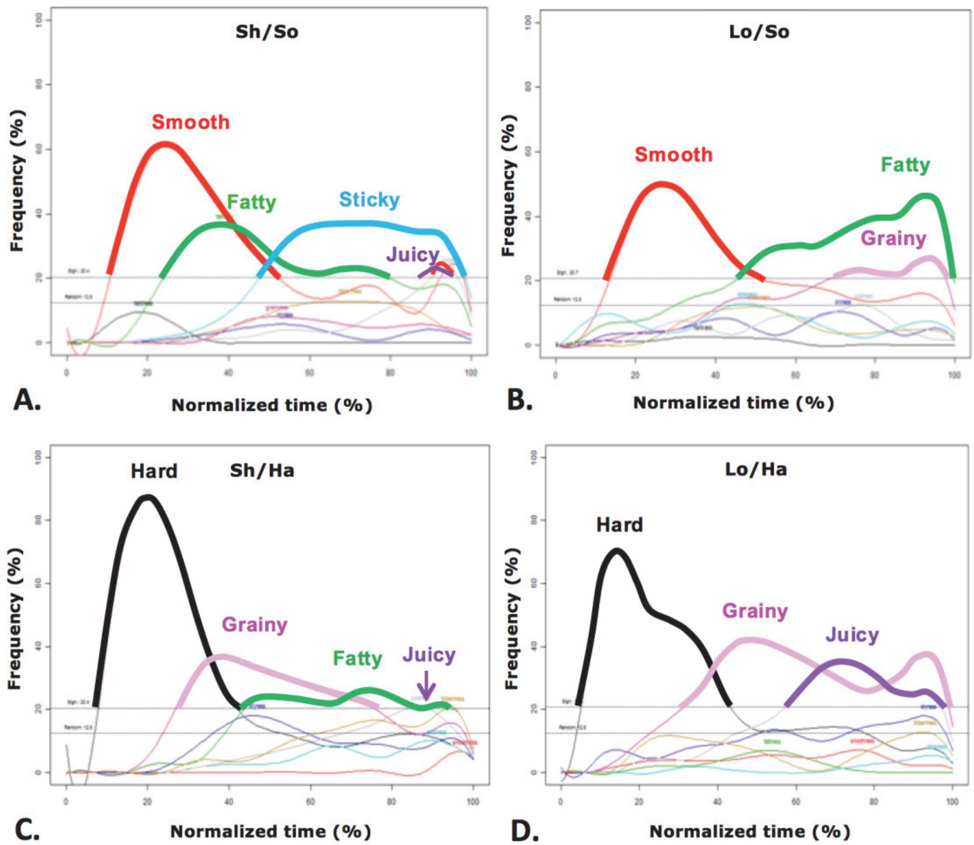


Figure 6.5 TDS curves of soft sausage of short eating duration group (A.), soft sausage of long eating duration group (B.); hard sausage of short eating duration group (C.) and hard sausage of long eating duration group (D.) over normalized eating time. The lower dotted line indicates chance level and the higher dotted line the significance level. The abbreviations used are explained in Table 6.2.

beginning of oral processing. Short duration eaters perceived fatty as the dominant sensation in the middle of eating and sticky and slightly juicy and smooth at the end of eating time. In contrast, long duration eaters perceived fatty as the dominant sensation during the entire second half of eating time and grainy as the dominant sensation towards the end of eating. Juiciness rose above chance level but did not become significant for the long duration eaters towards the middle of eating time. The TDS profiles of the hard sausage are shown in Figure 6.5 C. and 5 D. Similarly, both groups perceived the same attributes in the beginning of oral processing with hard being the dominant sensation followed by grainy. Towards the end of oral processing, short duration eaters perceived the hard sausage fatty and slightly juicy whereas the long duration eaters perceived juicy and grainy as the dominant sensation during the last third of eating time. After swallowing, panellist rated the intensity of 3 after-feel attributes (Figure 6.6). After-feel dryness was not significantly different between eater groups (p=0.279) and sausages (p=0.496). The soft sausage was significantly fattier in after-feel than the hard sausage [F(1, 90)= 59.62, p<0.001]. Short duration eaters perceived significantly less residue after-feel than long duration eaters [F(1, 90)=9.79, p<0.05].

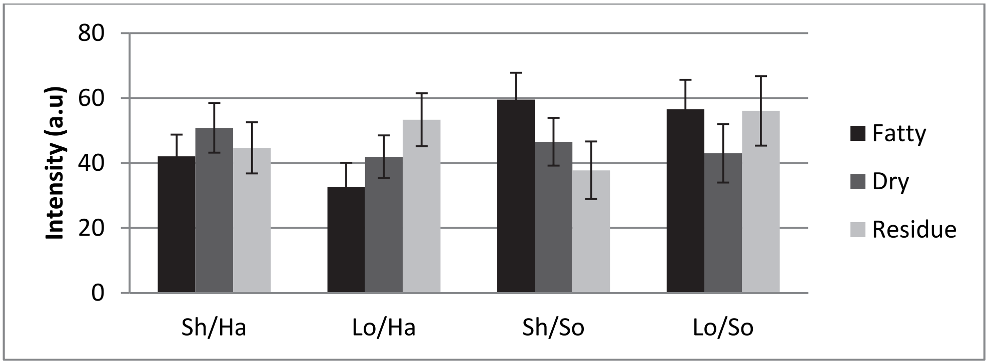


Figure 6.6 After-feel intensity of fatty, dry and residue assessed after the TDS evaluation (± standard error of the mean). n=12 for Sh and n=11 for Lo subjects in 4 replicates. The abbreviations used are explained in Table 6.2.

6.4. Discussion

6.4.1. Characterization of oral processing behaviour

We hypothesized that short duration eaters compensate for their short eating time by an increase in chewing frequency or chewing efficiency (hypothesis 1). The EMG results, reported in Figure 6.1 and Figure 6.2, demonstrate that the oral processing behaviour between the groups of short and long duration eaters differs considerably with respect to eating duration. Short and long duration eaters chewed with the same chewing rate and the same AUC per second for both sausages. In contradiction to hypothesis 1, no compensation for a shorter eating time of the short duration eaters by applying a higher chewing frequency or an increased muscle effort was observed.

6.4.2. Characterisation of bolus properties

We hypothesised that bolus properties are the same between the short and long duration eaters especially at the end of mastication as a result of compensational oral processing behaviour (hypothesis 2). However, EMG results revealed that the two groups of eaters chewed for different durations but did not vary in chewing frequency and muscle effort rate. Bolus properties were compared at mastication times of 33, 66 and 100% of eating time between groups differing in eating duration. Major modifications of the sausages in mouth are incorporation of saliva, release of fat from the sausage matrix, fragment size reduction and changes in rheological properties of the sausage bolus that result in the formation of a safe-to-swallow bolus.

This study shows that a longer eating duration results in more saliva incorporation into the bolus (Figure 6.3.A). This was in agreement with Tarrega et al. (2011) who observed that increased eating time of hard products was accompanied by an increase in saliva content of the bolus. However, for the hard sausage, the long duration eaters seem to not incorporate saliva constantly in the bolus which could be due to a lower saliva production with time, intermediate swallowing of saliva or saliva remaining in the mouth as coating after bolus expectoration. Fat release into the bolus was measured (Figure 6.3.B). For the soft sausage more fat is released into the bolus with longer eating time. Long duration eaters release more fat due to a longer eating time compared to the short duration eaters. For the hard sausage, there is a trend of increasing fat release for the short duration eaters while released fat content seems to be decreasing for the long duration eaters. This decrease of fat released into the bolus could be due to either the fat and saliva being intermediately swallowed or remaining in the mouth as a residual coating after spitting the bolus by the long duration eaters. It is known that solid foods usually require several swallows (Hiiemae et al. 1996), however subjects were instructed to not swallow during the spit out sessions.

Furthermore, analysis of fragments in the hard sausage bolus show that with increasing eating time the size of hard sausage fragments constantly decreases and number of sausage fragments constantly increases (Table 6.3). Fragment roundness changed mainly before 33% eating time of long duration eaters and before 66% of eating time of short duration eaters. We conclude that short duration eaters generate less broken down hard sausage boli containing fewer and larger fragments at all eating times than long duration eaters. However, roundness of fragments was similar at the moment of swallowing.

TCPT results gave insight on mechanical properties of the bolus (Figure 6.4). The results of first peak force, which might represent the force needed to bite into the bolus, show that for each eater group the firmness of the boli decreased over oral processing time. This suggested that long duration eaters reduced the firmness of the sausage bolus more than short duration eaters at any stage of mastication. This is supported by results shown in Appendix 6.2 A. showing that over absolute eating time, fast and long duration eaters seem to decrease boli first peak force at the same rate. Results on bolus adhesiveness, in Figure 6.4, suggest that the more a sausage boli was orally processed the more adhesive the boli became which could be due to addition of saliva together with increased release of fat. We conclude that the boli of short duration eaters were less processed resulting in a higher first peak force and lower adhesiveness.

Breakdown of the bolus over mastication time by reducing fragment size accompanied by increasing saliva and fat content of the bolus and therefore lowering mechanical firmness was highly correlated to increasing eating duration, number of chew and muscle activity (Appendix 6.1). These results imply that even if not measured *per se* as the amount of which particle size is broken down after a given number of chews (Slagter et al. 1992), chewing efficiency did not vary between eaters groups. We conclude that eaters naturally preferring a short or a long eating duration chewed in the same way over time and differed only in the total chewing time, thus the moment when they decide to safely swallow the sausage bolus. Eaters swallowing the bolus after a short duration swallowed a less comminuted bolus without compensating by increasing chewing efficiency, than eaters preferring a longer eating duration. The two eater groups can be considered to have different swallowing thresholds. Swallowing threshold is often measured by particle size (Fontijn-Tekamp et al. 2004) or saliva content (James et al. 2011) in the bolus or bolus mechanical properties (Chen and Lolivret, 2011; Peyron et al. 2011) at swallowing time. However, the factors triggering swallowing that could explain the differences in natural eating time between the two groups are not known. The reason for a later swallow for the long eating duration group might be caused by other factors, such as eating habits than bolus properties alone.

Our hypothesis 2 is rejected as bolus properties are different between both groups at the end of mastication. As hypothesis 1 was rejected, the absence of compensation in eating behaviour for a shorter eating duration by increasing the chewing efficiency resulted in varying bolus properties at the moment of swallowing.

6.4.3. Dynamic texture perception of sausages

We demonstrated that chewing rate and efficiency did not vary between short and long duration eaters. We hypothesized that chewing rate and efficiency are related to dynamic texture perception (hypothesis 3). However, as a result of different eating time, most of the bolus properties differed between the two eater groups at 100% of normalized mastication time which corresponds to the moment of swallowing. Hence, when the bolus properties at the moment of swallowing differ considerably between the short and long duration eaters, the texture perception of the same sausage might differ as well.

The characterisation of the selected groups of eaters suggests that the separation in short and long duration groups was maintained during the TDS in terms of eating duration despite a slight increase in eating time. Such an increase in eating time while performing TDS due to adding an analytical task to the normal eating condition was already observed in literature (Devezeaux de Lavergne et al. 2015a). Moreover, the behaviour of panellists while doing TDS is not considered to change considerably based on EMG activity recorded during the sensory test as the ratio of activity between eaters groups remained constant. Results of TDS show that the differences in eating duration have an impact on texture perception of the sausages especially towards the end of the mastication cycle. Short and long duration eaters perceive the texture of the sausages similarly in the beginning of mastication but start perceiving different texture attributes as dominant sensations at the middle of eating time, while the product is broken down by oral processing. As the two groups display similar oral processing behaviour (the two groups differed in eating time but chewed with the same chewing frequency and muscle effort rate) it is expected that texture perception of the long duration eaters in the second half of their mastication time would be different from the short duration eaters, reflecting the more degraded bolus of the long duration eaters. Moreover, both groups rated on average around 3.8 attributes per assessment as dominant sensations which suggests that short duration eaters rate a higher number of dominant perceptions during a shorter eating time and maybe detect more subtle differences in dynamic texture perception in this short duration. Differences in bolus properties on normalized eating time can explain the observed differences in dynamic texture perception towards the end of mastication. For both sausages, short duration eaters perceive significantly less residue after-feel than long duration eaters. For the hard sausage, short duration eaters swallow a bolus containing fewer and larger fragments. These fragments might be removed in the oral cavity more easily explaining the decreased perception of residue after-feel in comparison to the long duration eaters. Similarly, the long duration eaters perceive grainy as dominant sensation as opposed to sticky for the short duration eaters for the soft sausage. Unfortunately, particle size of the broken down fragments could not be measured for the soft sausage. However, we speculate that the soft sausage behaves in a similar way as the hard sausage. Therefore, the small fragments might be perceived as grainy by the long duration eaters while the short duration eaters perceive more subtle changes in texture in a shorter eating time and sticky as dominant sensation. For the hard sausage, long duration eaters perceive the sausage more grainy and juicy than the short duration eaters that perceive it fattier and slightly juicy at the end of mastication. Juiciness just starts to be the dominant sensation for the short duration eaters before swallowing while it lasts for the long duration eaters supposedly due to an increase in saliva content, release of fat and, eventually, intermediate swallows or increase of oral coating. Short duration eaters perceive fatty as dominant sensation due to a slight, non-significant, increase in fat release in the bolus while long duration eaters do not perceive these small changes and their perception is dominated by the attribute juiciness.

Hypothesis 3 is rejected, as different eating durations resulted in differences in dynamic texture perception as a result of different bolus properties rather than differences in behaviour. Other factors such as liking of the product, different eating patterns or different eating environment could be investigated in a similar way. Such differences in eating duration may be of particular interest for studies linking oral processing behaviour to satiety as a longer oral exposure time and a higher eating effort has been associated with a higher satiation (de Wijk et al. 2008).

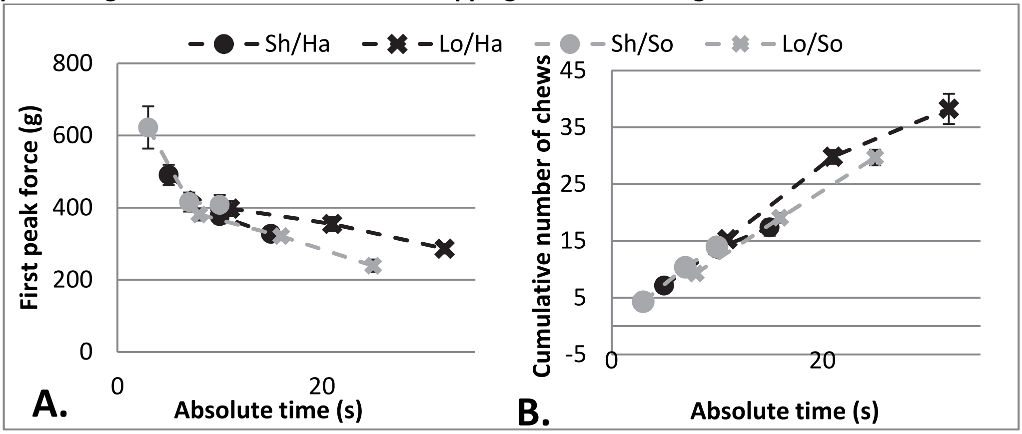
6.5. Conclusions

Short and long duration eaters perceived the same sausage similarly in the early stages of oral processing, but started to perceive the texture of the same sausage differently from the middle towards the end of oral processing. Independent of eating duration, subjects of both eating durations chewed with the same chewing frequency and muscle effort rate during oral processing. Total muscle effort and total number of chews was higher for long duration eaters mainly due to the longer eating time compared to short duration eaters. Bolus properties showed that short duration eaters did not break down the boli as much as long duration eaters resulting in fewer and larger sausage bolus fragments at the end of oral processing time, firmer and less adhesive boli with lower fat release and saliva incorporation compared to the bolus properties of long duration eaters. Therefore, short duration eaters did not compensate for their shorter eating duration by chewing more efficiently but are comfortable swallowing a less broken down bolus revealing that the swallowing trigger is different between the short and long duration eaters. These differences in bolus properties influenced dynamic texture perception of the sausages as the bolus of short duration eaters was different than the bolus of long duration eaters during the normalized eating time. We conclude that differences in eating behaviour between subjects can lead to differences in bolus properties of sausages causing differences in dynamic texture perception of the same sausage.

Appendix 6.1 Pearson correlation between eating duration, mastication parameters from EMG and bolus properties.

	Eating Time	Right Masseter	Left Masseter	Right Temporalis	Left Temporalis	Number of chews
Right Masseter	.985**	1	.998**	.998**	.999**	.995**
Left Masseter	.986**	.998**	1	.998**	.998**	.992**
Right Temporalis	.990**	.998**	.998**	1	.999**	.996**
Left Temporalis	.991**	.999**	.998**	.999**	1	.997**
Number of Chews	.987**	.995**	.992**	.996**	.997**	1
Fat Release						
Saliva Content	.931**	.880**	.873**	.888**	.896**	.899**
Adhesiveness						
First peak force	-.794**	-.747**	-.737**	-.765**	-.767**	-.783**
Number of fragments	.972**	.978**	.984**	.984**	.980**	.976**
Roundness						
Diameter of fragments	-.897*	-.888*	-.887*	-.902*	-.898*	-.908*

Appendix 6.2 First peak force of boli (A.) and cumulative number of chews (B.) over eating time in seconds shows that fast and long duration eaters have a similar oral processing with short duration eaters stopping earlier than long duration eaters.



CHAPTER 7

General discussion and implications

7

7.1. Introduction

In the past decades, food oral processing developed as a discipline linking food science to the physiology of the eating process. Food oral processing is considered to be key for understanding food sensorial perception over eating time (Chen, 2009). This PhD Thesis focuses on the impact of food breakdown on dynamic texture perception. Texture is an important quality attribute of food and food oral processing is considered of major importance for understanding food texture perception (Koç et al. 2013a). A multidisciplinary approach to study texture perception is advised in literature. Moreover, the use of model foods with controlled physical-chemical properties is expected to provide a fundamental understanding of texture perception (Pascua et al. 2013; Foegeding et al. 2015).

In this Thesis, gaining a better understanding of food dynamic texture perception was approached by quantifying food oral breakdown of model gels. The first step was to identify which sensory methods were appropriate for investigating dynamic texture perception (**Chapter 2**). The second step was to understand which properties of the food control bolus formation and which bolus properties would explain the perception of chew down texture attributes (**Chapters 3-5**). In **Chapter 3**, the impacts of fracture properties on bolus formation and subsequent texture perception were investigated. In addition to fracture properties, composition of gels was expected to impact food breakdown and texture perception. Therefore, **chapter 4** aimed to uncouple the effect of fracture properties from gel composition on dynamic texture perception. In **Chapter 5**, the effect of food structure inhomogeneity on dynamic texture perception was investigated. Finally, the impact of human oral processing behaviour such as eating time on dynamic texture perception was demonstrated in **Chapter 6**. The present chapter contains a summary of the main findings from this Thesis. First methodological considerations are discussed, then the interpretation of obtained results. Finally, the future prospects and main conclusions are stated.

7.2. Main findings

In **Chapter 2**, it was found that fracture properties of agar/gelatine mixed emulsion-filled gels could be controlled in parallel to oil binding properties. Using these gels, three sensory techniques were used and compared. Qualitative descriptive analysis (QDA) was a comprehensive method, providing complementary information about texture, taste and flavour. QDA enabled the incorporation of a time dimension by rating texture attributes perceived at first bite, during chew down or after swallowing. However, the evolution of attributes perception over time was not obtained from this method. Dynamic methods, such as progressive profiling and temporal dominance of sensations (TDS), provided useful insights on changes of texture perception over time. Especially, TDS sensory trajectories showed that major differences in texture perception were perceived at the end of chew down and depended on the fracture strain of the gels mainly. It was concluded that the use of sensory methods for the evaluation of food texture depended mainly of the aim of a study. However, dynamic methods and QDA should be used in combination to obtain a complete texture profile of food. Next to comparing the sensory methods, the impact of gel properties on perception was analysed. As expected, fracture properties impacted first bite texture attributes firmness and brittleness. Moreover, fracture properties could relate to chew down texture attributes. Mainly fracture strain was related to late perception of chew down attributes, with a high fracture strain relating to high creaminess intensity and a low fracture strain relating to high graininess intensity, as shown by the sensory trajectories. Fracture stress also impacted creaminess perception, with a low fracture stress relating to high creaminess intensity. The effect of oil droplets binding (bound or unbound) on texture perception was negligible compared to the effect of fracture properties.

In **Chapter 3**, the same gels as in **Chapter 2** were used for a characterisation of bolus properties at different time points in order to better understand the dynamic texture perception of the gels. It was found that fracture properties of gels greatly impacted breakdown of the gels. Fracture stress did not impact particle breakdown, but the bolus was harder and therefore, longer mastication duration was observed. Fracture strain impacted mainly the particle breakdown with low fracture strain gels breaking in many small particles and high fracture strain gels breaking in a few large fragments. Having bound or unbound oil droplets in the gel matrix influenced the release of oil droplets during breakdown of the gels. However, this did not impact perception. Bolus properties could be related to texture attributes perceived in the beginning, the middle and the end of oral processing. For instance, a high number of gel fragments in the bolus was related to perception of graininess at the end of oral processing and a high flowability of the bolus was related to perception of creaminess at the end, melting in the middle and low firmness in the beginning of oral processing. Therefore, knowing the oral breakdown of the bolus enabled to understand better the perception of chew down texture attributes. However, information on surface properties and melting of the gels, as a result of gel composition, was not considered in this chapter although it could have an influence on perception.

In **Chapter 4**, gels varying in fracture properties were designed using different gelling agent combination. These gels enabled to account for differences in serum release or melting caused by changes in composition while having similar fracture properties. This resulted in 12 gels varying in fracture stress (high/low), fracture strain (high/low) and gelling agents' composition (agar/gelatine, k-carrageenan/LBG or high/low acyl gellans).

Principal component analysis showed that half of the variation in sensory perception between gels depended on the gelling agents used (PC1) and the other half depended on the fracture properties of the gels (PC2 and PC3). Similar results on fracture properties and texture perception were found as in **Chapter 2** and similar impact of fracture properties on bolus properties and subsequent perception as in **Chapter 3.** In addition, it was found that serum release from the gel matrix was related to high perception of moist related texture attributes and that melting of gels at mouth temperature increased the perception of fat related texture attributes. Surface properties of the gels impacted stickiness perception. It is therefore important to consider other physical and structural properties of food when controlling fracture properties.

The gels used in the above mentioned chapters were all homogeneous in terms of structure. In **Chapter 5**, inhomogeneous gels were designed by combining two macroscopic layers of gels with different mechanical and breakdown properties. It was found that food breakdown and eating behaviour was influenced by structural inhomogeneity. Emulsion-filled agar gels did not melt and dominated the mixing properties and the particle size distribution of the boli when mixed with an emulsion-filled gelatine gel layer. However, the perception measured by TDS showed that subjects were able to perceive the two gel layers equally. Only a hard gel layer would dominate slightly the sensory profile when combined with a soft layer made from a different gelling agent.

Besides mechanical properties of food, oral behaviour is known to influence texture perception. In **Chapter 6**, subjects were selected based on varying eating duration of a piece of sausage. It was found that subjects with a naturally long eating duration chewed at the same rate and with same muscle activity than subjects with naturally short eating durations. Consequently, the swallowed bolus differed in particle size, saliva incorporation and mechanical properties due to the difference in chewing time. These changes in bolus properties resulted in the two groups of subjects perceiving the same food differently towards the end of mastication. Such results confirmed that food breakdown is key in texture perception.

The main findings related to gels breakdown as the link between food mechanical properties and texture perception are summarized in Figure 7.1.

7.3. Methodological considerations

7.3.1. Choice of sensory methods

The first consideration when designing food texture is an effective assessment of texture perception. Depending on the food and on the aim of the sensory test, different methods can be used and were discussed in **Chapter 2**. QDA, TDS and progressive profiling can similarly discriminate between samples. The major differences between these techniques

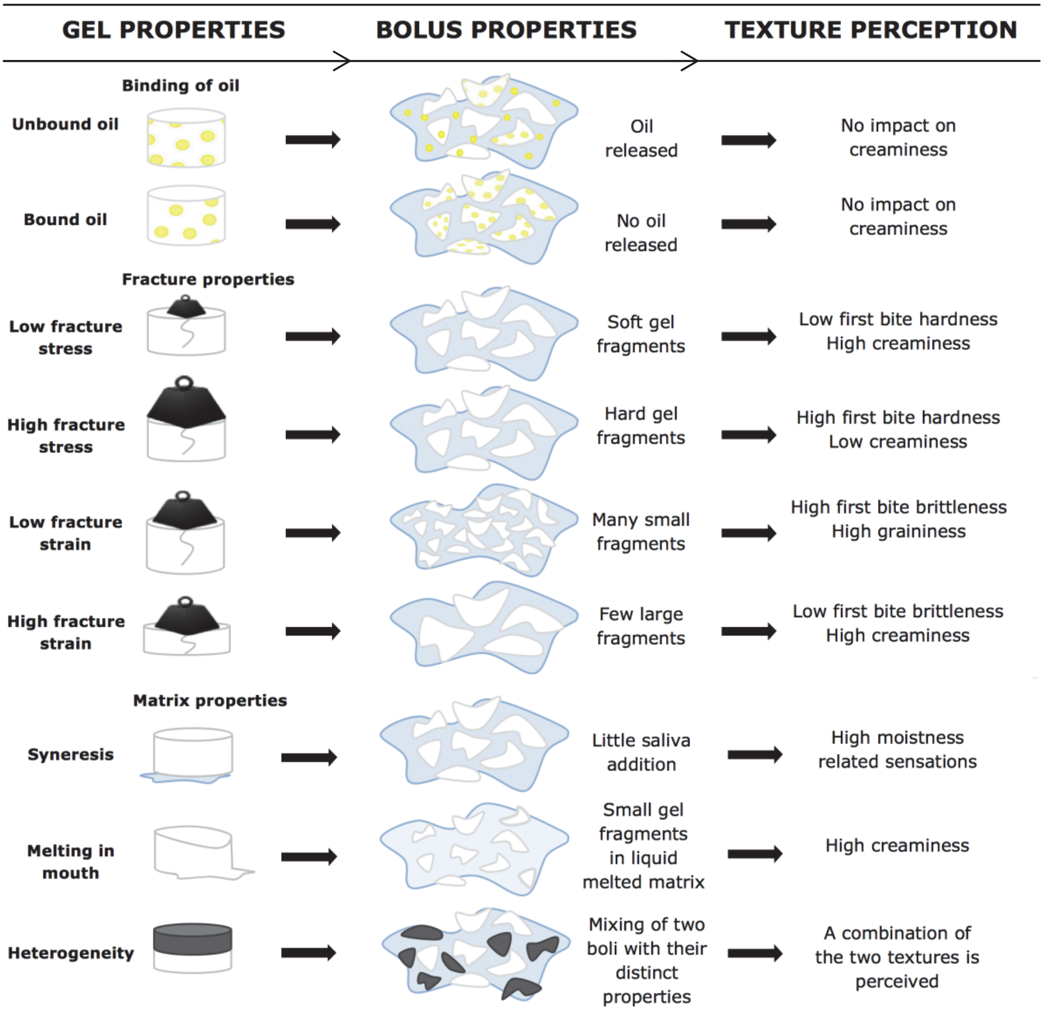


Figure 7.1 Main results on the impact of gel properties on breakdown and subsequent texture perception.

are the number or attributes and the time dimension. QDA uses the largest number of attributes and describes samples in a comprehensive manner, including odor, taste and texture perception. Texture attributes' intensities are rated at different time points corresponding to first bite, chew down and after-feel. TDS requires little training, alters only slightly the eating behavior of subjects and monitors perception continuously over the whole eating duration. However, TDS can rate only up to 10 attributes and is based on attributes dominance, and not intensity (Pineau et al. 2012; Cheong et al. 2014). In order to monitor intensity over time, TI (Cliff and Heymann, 1993; Larson-Powers and Pangborn, 1978; Pineau et al. 2009) or progressive profiling (Jack et al. 1994) can be used but require more training. Therefore, the choice of sensory method depends on the type of research. QDA was preferred in **Chapter 4** as many texture attributes were of interest in this chapter and TDS might not have enabled to rate all relevant differences between samples. However, TDS was preferred in **Chapter 5**, where differences in dynamic texture perception were important and, more specifically, the dominance of attributes was considered relevant for oral processing of gels with texture contrasts. In **Chapter 6**, TDS was preferred as it required no training and enabled to preserve the differences in eating behavior between subjects. Overall, TDS has a high potential in oral processing studies (Cheong et al. 2014). This illustrates the possibilities of using different methods. A combination of integrated methods, such as QDA, together with a dynamic sensory method, such as TDS, remains the most informative alternative.

7.3.2. Choice of sensory attributes when assessing texture perception

In studies related to texture perception of food, texture sensory terms are often used with different definitions or different terms might have the same definition. Such inconsistencies in texture vocabulary make it difficult to compare studies from literature. A list of commonly used texture attributes have been described by Pascua et al. (2013) and show the lack of current consensus in the texture lexicon. In our studies, QDA was used in **Chapter 2** and **Chapter 4**. QDA consists of training a panel in sensory evaluation following a strict method (Stone & Sidel, 1985). Part of the training consists of developing a list of attributes, which is generated and agreed with the panellists. The implication of the panel in the definition of the attributes limits the use of terms and definitions compared to literature. In addition, the extensive training required for QDA, including the development of sensory attributes, is not described fully in most publications, and sensory terms and scales might be developed differently depending on the studies. Moreover, texture terms depend widely on the food product being assessed and some attributes that were used in **Chapter 2** did not apply to the gels assessed in **Chapter 4**. For instance, the term grainy, which was an important attribute in **Chapters 2 & 3**, was not used in **Chapter 4** even though the gels in these chapters were very similar. Consistency in the terms used could be achieved in these studies by using previous lists of attributes when starting the generation and discussion of attributes that will be used in the QDA together with the panel. However, the choice of these attributes and their exact definition still depended on the panel. Reaching consistency in the texture vocabulary used was difficult due to differences that are specific to the food products assessed. It would be recommended to follow the texture profiling method for the texture terms of a QDA or use the Spectrum Method. The Spectrum Method involves the use of reference products and intensive training on scale rating, which enables to compare results from different studies. A limitation of this method could be biasing the response of panellists by introducing technical language (Murray et al. 2001). Moreover, it was highlighted by Pascua et al.

(2013) that the most variation in the definition of sensory terms was observed for terms lead by complex mechanisms, such as adhesiveness or creaminess, which depend on the bulk properties of the forming bolus. For instance, adhesiveness measured after a few chews or after efficient lubrication by saliva is expected to be different. Therefore, the use of dynamic sensory methods might be of help to better evaluate those terms.

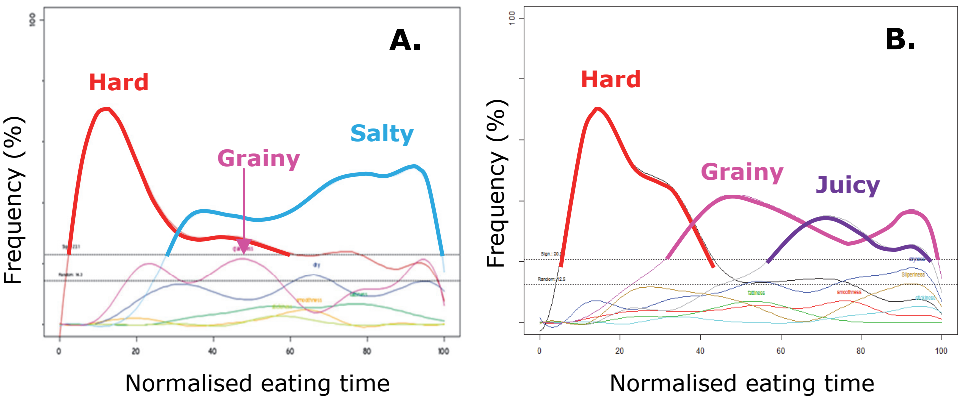


Figure 7.2. TDS curves of the hard sausage by the short duration eaters when the term "Salty" was included in the attribute list (A.) and when the term "Salty" was replaced by "Slippery" in the attribute list (B.).

In TDS assessments, lists of attributes from previous QDA tests were used in **Chapter 2** and **Chapter 5**. The highly trained panel was familiar with these terms and could easily use them to assess the products. In **Chapter 6**, the panel was untrained and only received training during 3 sessions. Therefore the choice of texture terms used was more difficult. A list of terms to describe processed meat products was used from the literature and discussed with the panel. The main challenge was to select terms that were understandable to the panellists so that they would use the terms as dominant and not discard them during the test. In TDS, a maximum of ten attributes can be used, which limits the choice of attributes and gives a high impact to the selection of attributes on the outcome (Pineau et al. 2012). During a first TDS test, not reported in **Chapter 6**, the taste attribute salty was combined with texture attributes. Saltiness is an important dynamic sensory attribute that applies to processed meat and was expected to be relevant in this test. However, saltiness was easy to identify and to rate by the untrained panellists compared to complex texture attributes. The result of this first TDS test for the short duration eaters testing a hard sausage is given in Figure 7.2.A. In Figure 7.2.B. the TDS profile of the same panellists and same sausage is shown with the term salty being replaced by slippery in the attribute list. It can be seen that short duration eaters perceived the sausage dominantly hard in the beginning in both TDS profiles. Then grainy almost became significantly dominant in Figure 7.A, but mostly, salty was dominant during more than half of the eating duration, whereas grainy and juicy became dominant in Figure 7.B. Such a result of saltiness being the dominant sensation for the second half of the TDS recording was found for both short and long duration eaters and for both sausages during the first TDS. The clear dominance of the taste attribute salty over texture attributes can cause to omit important information on texture perception. Such results confirm the importance of the choice of attributes when conducting a TDS test. Even though this was not reported in literature (Pineau et al. 2012), our results suggest not to use taste and texture terms together in one TDS test. Two TDS could be conducted separately to assess taste and texture independently when required.

7.3.3. Model food design

7.3.3.1. Choice of gelling agents

One of the first challenges faced in this Thesis was to design a model food with varying fracture stress and fracture strain in a 2x2 full factorial design. In literature, several model foods showed variations in fracture properties due to changes in composition, such as agar/glycerol (Barrangou et al. 2006), agar/gelatine (Mosca et al. 2012), carrageenan/LBG (Chen et al. 2001; Koç et al. 2013b), whey proteins and polysaccharides (Jong and van de Velde, 2007; Çakır et al. 2012), high and low acyl gellan (Mao et al. 2000; Huang et al. 2003; Matsukawa and Watanabe, 2007). The challenge of developing a full factorial design with these model systems is that the composition of the gels has to be changed in order to vary fracture properties. Therefore, next to fracture properties, other properties of the gels might be modified, such as microstructure. A clear example of these changes is whey protein mixed polysaccharide gels. In whey protein isolate (WPI) gels, the addition of polysaccharides results in a change in fracture properties and in microstructure (de Jong and van de Velde, 2007). For instance, adding guar gum, gellan or locust bean gum (LBG) to WPI in sufficient ratios results in increasing the fracture stress and strain of the mixed gels. Such changes in fracture properties are due to micro-phase separation between the protein and polysaccharide phase. Differences in microstructure in phase separated mixed gels are known to influence breakdown and texture perception of these gels (van den Berg et al. 2007a). Therefore, it is difficult to uncouple the effect of microstructure and the effects of fracture properties. An ideal model system would be homogeneous. However, few homogeneous mixed gels are reported in literature and little variations of mechanical properties are observed in these systems (Harrington and Morris, 2009). In **Chapter 2**, agar/gelatine mixed gels were chosen as they enable to manipulate fracture stress and strain independently from each other. A limitation from this model system was the differences in melting properties of agar and gelatine. Agar is known not to melt at mouth temperature oppositely to gelatine (Muñoz et al. 1986a and 1986b; Inoue et al. 2009) and an increase in the gelatine ratio might impact the perception of gels during oral processing by partial melting of the gel matrix. It was found that an increase in gelatine ratio resulted in an increase in fracture strain, which coincided with an increase in creaminess perception. The effect of fracture strain could not be uncoupled from the composition of the gels in **Chapter 2**. To compensate these variations, three mixed gelling agent systems were used in **Chapter 4**, each gelling agents mixtures having specific changes in physical properties by manipulating the ratios and concentrations of the ingredients. This approach was a first step in uncoupling the effect of gels composition and fracture properties. Developing a full factorial design with varying fracture properties without the influence of any other physical-chemical properties of the gels is yet a challenge.

7.3.3.2. Measuring gels fracture properties

In order to design the fracture properties of gels, an effective method to measure fracture properties has to be used. In gels, plate to plate compression is often used in literature (Bourne, 2002; Chen et al. 2012). As gels are visco-elastic solids the speed of deformation is known to impact the outcome of such compression tests (Koç et al. 2013a). It was found that fracture properties of emulsion-filled gels measured at different compression speeds were different (Sala et al. 2009). Using several compression speeds might have described better the behaviour of gels during mastication. However, in order to design gels varying in fracture properties, one test speed had to be selected. Gelatine and kappa-carrageenan gels were shown to have a dominantly elastic behaviour (Sala et al. 2009), which were two of the gelling agents used in this Thesis. Therefore, a singular test speed, which is often used in literature, was conducted to describe and design gels in this Thesis. After selecting the speed and performing a compression test, fracture stress and strain can be calculated. Fracture stress and strain can be calculated in two ways, engineering and true fracture properties (van Vliet, 2014). Engineering stress and strain make the assumption that food does not expand during compression, whereas true stress and strain compensate for this extension and assure equal volume during the test. Material scientists usually use engineering stress and strain, however, the difference between true and engineering stress and strain becomes relevant at deformation close to breakages which are often not reached in material science. In food science, breakage of food is required for comminution. Therefore, the choice of using engineering or true stress and strain might become relevant. Often, true stress and strain are used to describe fracture properties of foods in literature (Gwartney et al. 2002; Gwartney et al. 2004; Barrangou et al. 2006a; Foegeding et al. 2011; Mosca et al. 2012). As fracture is obtained by chewing of the food, the compression surface is smaller than total surface of the sample and remains the same during the compression. The extension of the food may occur at a lower extent in mouth than in a plate to plate compression. Therefore, it could be expected that engineering stress and strain reflect the muscle force and jaw movement during biting, respectively. In this Thesis, the choice of using engineering stress and strain was made. As engineering and true fracture strain are mathematically related they might both predict equally brittleness perception. However, true fracture stress depends on fracture strain and samples were designed to fracture at low and high fracture strain. The difference between engineering and true fracture stress in predicting first bite firmness might be relevant. When comparing fracture properties with first bite attributes, firmness and brittleness were correlated to engineering fracture stress and strain respectively. As shown in Table 7.1, true fracture strain did not provide better correlation to brittleness than engineering fracture strain. Moreover, for the agar/gelatine gels used in **Chapter 2**, engineering fracture strain correlated better to brittleness than true fracture strain. In contrast, true fracture stress correlated better with first bite firmness than engineering fracture strain, especially for gellan gels and agar/gelatine gels from **Chapter 4**. However, for carrageenan/LBG gels, engineering fracture stress was significantly correlated to firmness whereas true fracture stress was not. Overall, these results suggest that using true fracture stress might describe better the perception of food deformation in the mouth than engineering fracture stress and that true and engineering fracture strain are similarly linked to brittleness perception. This suggests that firmness perception at first bite depends on the deformation applied when evaluating the force applied to break food. It is advised to use true stress and strain to design model foods with controlled fracture properties in the future. However, in agar/gelatine gels from **Chapter 4**, fracture strain and brittleness were not correlated. This suggests that other rheological properties such as the shape of the post-fracture curve are also involved in perception of first bite attributes.

Table 7.1 Correlation of first bite attributes firmness and brittleness, with engineering and true fracture stress and strain. NS stands for non-significant.

Gels	First bite firmness		Second bite brittleness	
	Engineering stress	True stress	Engineering strain	True strain
Agar/Gelatine (Chapter 2)	R^2=0.848; p<0.001	R^2=0.920; p<0.001	R^2=0.801; p<0.05	R^2=0.702; p<0.05
Agar/Gelatine (Chapter 4)	R^2=0.502; NS	R^2=0.819; NS	R^2=0.485; NS	R^2=0.416; NS
Carrageenan/LBG (Chapter 4)	R^2=0.936; p<0.05	R^2=0.891; NS	R^2=0.952; p<0.05	R^2=0.928; p<0.05
Gellan (Chapter 4)	R^2=0.658; NS	R^2=0.998; p<0.001	R^2=0.925; p<0.05	R^2=0.965; p<0.05

7.3.4. Oral processing studies

7.3.4.1. Choice of subjects in oral processing studies

The choice of a panel in oral processing studies can be difficult when a sensory study is related to an oral processing study. In **Chapter 3**, the same subjects as in **Chapter 2** were selected as panel to collect expectorated bolus, as they constituted the sensory panel of **Chapter 2**. However, sensory evaluation of food is known to influence behaviour as a specific analytical task is performed by the subjects (Mioche and Martin, 1998). For instance, the eating time increased while performing TDS for both trained and untrained panels (Chapters 2 & 6) as shown in Table 7.2. During the bolus collection sessions, subjects were not instructed to perform a product evaluation, but were instructed to chew as they would naturally do. Even though the panel remained the same in terms of physiological variability between subjects (e.g. size of the oral cavity, jaw strength, number of teeth), panellists did not have the same behaviour during the sensory test and the bolus collection sessions. The benefits of using the same panel in both bolus collection and sensory sessions are, therefore, not evident. Moreover, trained panellists were found to behave differently from untrained panellists when eating without instructions (Mioche and Martin, 1998; Gonzalez et al. 2002), having longer eating time and lower chewing frequency. Such differences are expected to be caused by the extensive knowledge trained panellists have of the samples. Using separate panels in the sensory study and the oral processing study would mitigate differences in behaviour due to training. In Chapter 4, different panellists were used for QDA evaluation and bolus collection and similar correlations between bolus properties and sensory perception were found as in Chapter 3. This suggests that using different panellists did not modify the output of the study in Chapter 4. Moreover, selecting a panel based on their eating duration on the gels, in order to get a homogeneous group of subjects, was an advantage of using different panels, one based on sensorial discrimination capacities and one based on eating behaviour. In Chapter 6, however, using a different panel for sensory evaluation and bolus collection would not enable to investigate the influence of eating behaviour on food breakdown and subsequent perception. It is necessary to use the same panel for bolus collection and sensory testing when interested in differences between subjects or groups of subjects. When interested in product differences only, it is possible to choose the same or different panels for sensory and oral processing studies. In the case of studies including TDS, which require little training, the same panel can easily be used (Cheong et al. 2014). For instance, Table 7.2 shows that the panel used in Chapter 5 had the same eating duration when performing TDS, EMG and a free eating condition. Such a consistency in behaviour was an advantage in this study. However, behaviour changed from the free eating condition during TDS assessment in Chapter 2 & 6. In the case of highly trained panels and tests that

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Table 7.2 Eating duration of the same subjects under different conditions ± standard deviation. Different subsequent letters indicate a significant difference at p<0.05.

Food product \ Eating duration	Natural eating (s)	TDS (s)	EMG (s)
Averaged over all gels (Chapter 2)	18.8 ± 9.7 ^{A}	37.5 ± 11.8 ^{B}	-
Averaged over all gels (Chapter 5)	19.5 ± 8.1	23.3 ± 8.2	22.9 ± 9.0
Averaged over hard sausage (Chapter 6) i.e. Short duration eaters	14.5 ± 2.8 ^{A}	23.0 ± 10.8 ^{B}	15.1 ± 5.6 ^{A}

modify extensively eating behaviour, such as QDA, using a different panel for the oral processing study is advised.

7.3.4.2. Protocols for bolus analyses

Bolus characterisation is often described in literature (Hutchings et al. 2011; Loret et al. 2011 ; Peyron et al. 2011 ; Mosca et al. 2012; Tournier et al. 2012 ; Guo et al. 2013; Chen, 2013; Rodrigues et al. 2014). Collecting the bolus as a whole cohesive mass is challenging during bolus formation as the cohesive forces holding the bolus together are still building. In addition, spitting out at a specific time after chewing as "naturally" as possible is not a natural behaviour for subjects. Expectorating boli has been reported to be disliked by some subjects, such as elderly people (Mowlana and Heath, 1993). In this Thesis, often a warm up sample, that was not analysed, was collected before collection of the boli used in analysis. However, no training was performed with the panel. Familiarization on bolus expectoration may have been beneficial to minimise variation between subjects. Alternative ways of bolus collection could be considered such as described by Mowlana & Heath (1993) or Tournier et al. (2015) using a plastic compartment to chew the food. However, lubrication of the bolus by saliva is discarded in such methods, which is not realistic when considering changes in texture perception. Moreover, gel samples can be soft and would be crushed differently in a compartment than chewed freely by the teeth. After effective collection, the second challenging aspect of bolus characterisation is direct analysis of the bolus. All tests performed in this Thesis were first tested on freshly collected boli and, subsequently, on boli collected a few hours prior to analysis. It was found that a few hours' time gap between collection and analysis did not influence the results of the analysis for most tests. However, for Two Cycle Penetration Tests (TCPT), gelatine that melted during oral processing could gel again and change mechanical properties of the bolus. In addition, particle size analysis was done with fragments suspended in water as previously done in literature (Bornhorst et al. 2013). The presence of water could eventually dissolve or swell gel particles. Therefore, the selection of a time gap between collection and analysis of bolus requires a high consideration of the physical-chemical changes that may occur in the boli and the impact of such changes on the test results. This is highly dependent on the food tested and the test itself. For instance, dry matter content did not change upon storage of the boli in a sealable cup.

A wide choice of possible bolus characterisation methods is available in literature. Methods such as particle size analysis or dry matter can be considered standard, whereas methods to analyse bolus mechanical properties are less defined and depend on the heterogeneity and properties of the boli. Boli properties have been tested by small deformation rheology (Le Bleis et al. 2013; Saint-Eve et al. 2015) but this method requires a relatively homogeneous bolus, which is not the case at early stages of mastication.

Mechanical properties of the boli were analysed by TPA in several studies (Peyron et al. 2011) and allowed to test boli at varied stages of oral processing. However TPA is a test mimicking two consecutive bites on an intact piece of food and specific parameters are derived from the properties of the food material (Bourne, 2002). Therefore, it was decided in this Thesis to develop a similar method as TPA on a boli placed in a cup, in order to control the height and shape of the boli. The test was named Two Cycle Penetration Test (TCPT). Due to the test conformation the parameters obtained from TCPT, calculated similarly as in TPA, needed to be defined in relation to their physical meaning (details are shown in **Chapter 3**). From this test, first peak force, adhesiveness and flowability were identified as the most relevant parameters to describe changes in bolus mechanical properties over eating time and between boli from different gels.

Another consideration in bolus characterisation studies is the number of boli replicates to be analysed. In this Thesis, for each analysis, one bolus was collected per sample, per participants, per collection time. The subjects, usually n=10, were considered as the replicates. Making replicates per subject would have doubled the costs of the analysis but would have enabled a discussion at the subject level. Discussing at the subject level could be more insightful than a discussion at the group level as individual variability might minimise differences between samples. However, intra-subject variability in bolus properties have been reported as small compared to physiological variability, such as electromyography activity (Peyron et al. 2004; Mishellany et al. 2006). To discuss at the subject level, several other considerations would need to be taken into account, mainly individual eating duration (Brown et al. 1994) and bite size of the stimuli (Wintergerst et al. 2008; Hutchings et al. 2009). This would mean that individuals could expectorate the boli at different times corresponding to a portion of their personal total eating duration and each individual could receive a different sample size according to their personal natural bite size (Hutchings et al. 2009). The use of an individual normalized eating time and bite size would introduce variations at the group level. Moreover, different bite size would introduce variability in boli analyses, which make it difficult to compare results from different subjects. As our studies focused on differences in oral processing and texture perception between samples in **Chapter 2 to 5** or between groups of individuals in **Chapter 6**, the comparison between subjects was discarded and no individual eating duration and bite size were used. Therefore, a replicate per subject was not required and, overall, results gave insightful significant differences between samples.

7.4. Discussion and interpretation of the results

7.4.1. Impact of gel design on texture perception

Several gel properties were modified during the research described in this Thesis in order to understand the impact of these properties on dynamic texture perception. The properties investigated were fracture stress and strain (**Chapter 2-4**), binding of oil droplets to the gel matrix (**Chapter 2 & 3**), properties related to the specific gelling agents used, such as melting or serum release (**Chapter 4**), and the presence of mechanical contrast (**Chapter 5**). The impact of these gel properties on dynamic texture perception are individually discussed in the following sections. The aim of this sub-chapter is to integrate the results from this research linking gel properties to dynamic texture perception, as shown in Figure 7.3. Oral processing, or the link between food properties and perception, is discussed in the next sub-chapters.

Figure 7.3 Linking food properties to texture perception

Fracture properties of model gels were found to impact first bite texture attribute as well as chew down texture attributes as described in **Chapters 2 & 4**. The fracture properties, fracture stress and strain, were expected to be related to first bite attributes perception in gels as extensively reported in literature (Barrangou et al. 2006; Foegeding, et al. 2011; Gwartney, et al. 2004). The relations between texture attributes and fracture properties obtained from **Chapters 2 & 4** are summarized in Figure 7.4. It can be seen that the relationships between fracture stress and firmness perception at first bite, and between fracture strain and brittleness perception at second bite were confirmed. However, correlation did not show for all gels in **Chapter 4**, suggesting that other rheological properties such as the shape of the post-fracture curve or surface properties of the gels are also involved in perception of first bite attributes. It was found that gels with a high fracture stress and strain were perceived as elastic at first bite. Agar/gelatine gels with a high fracture strain were perceived sticky at first bite in **Chapter 2**, which was more related to composition than to fracture properties. The relationship between fracture properties of model foods and texture perception during chew down was discussed previously in literature (Gwartney et al. 2004; Sala et al. 2008; Çakır et al. 2012) but remained unclear. As shown in Figure 7.4. gels with a high fracture stress were perceived as firm and not spreadable during chew down and gels with a low fracture strain were perceived powdery and grainy during chew down and with a high amount of residue after expectoration. Fracture stress and strain usually both influenced perception of chew down texture attributes. For instance, gels combining a high fracture stress and a high fracture strain were perceived elastic and tough, gels with a high fracture stress and a low fracture strain were perceived lumpy and crumbly, and gels combining a low fracture stress and a high fracture strain were perceived fatty, melting and creamy during chew down in both experiments. Some differences in texture perception could be seen between the two experiments as the gels differed between the studies. In Chapter 2, agar/gelatine gels

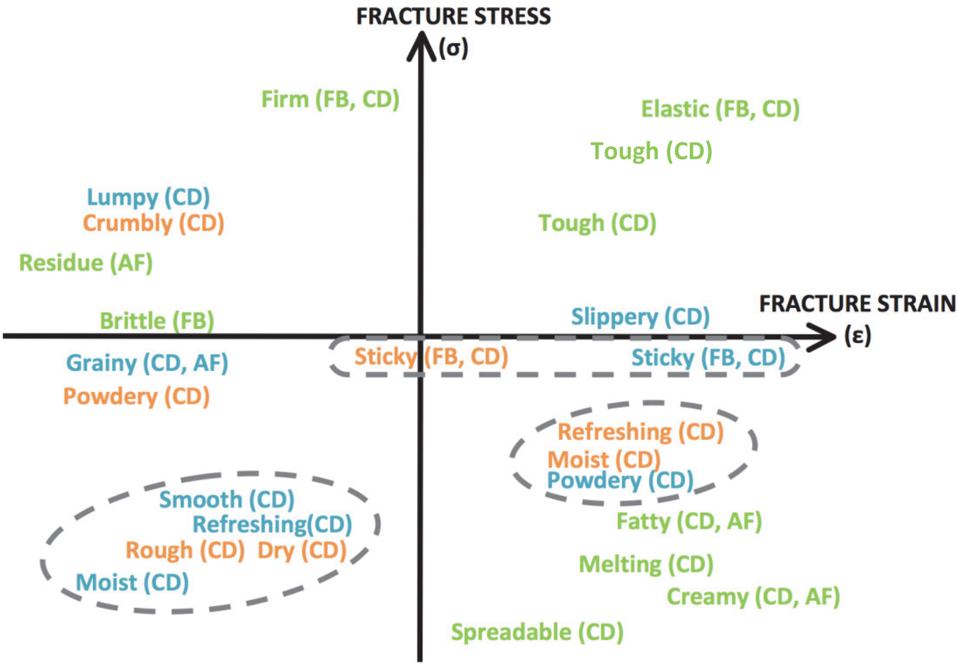


Figure 7.4 Relation between fracture properties and texture attributes perceived at first bites (FB), chew down (CD) and after-feel (AF). Texture attributes common from Chapter 2 and 4 are in green, attributes from Chapter 2 are in blue and from Chapter 4 are in orange. Circled with dotted lines are attributes used in chapter 2 and 4 that differed between the experiments.

were used, whereas in **Chapter 4**, three different gelling systems were used. In both experiments, gels with low fracture stress were perceived more refreshing and moist, however, the impact of fracture strain differed in the different gels and is explained in a next paragraph. In general, results were congruent between the two studies and confirmed the impact of fracture properties on chew down texture perception. Moreover, TDS sensory trajectories (**Chapter 2**) showed that fracture stress mainly impacted early chew down whereas fracture strain impacted late chew down with gels having a high fracture strain being perceived creamier and less grainy. In **Chapter 5**, fracture stress of agar and gelatine emulsion-filled gels were varied and TDS showed that gels with low fracture stress were perceived dominantly melting and refreshing in the middle of oral processing and creamy at the end of oral processing. Gels with a high fracture stress were perceived dominantly firm in the beginning of oral processing time and grainy in the middle of oral processing time. These results confirm that fracture stress is mainly impacting perception at the beginning and the middle, and have a slight impact at the end of oral processing. Fracture strain is expected to change breakdown of the gels to a greater extent than fracture stress. Indeed, a small movement in the mouth is sufficient to break gels with low fracture strain whereas changes in fracture stress can be compensated by a higher muscle force (Foster et al*.* 2006). The impact of fracture properties on bolus properties are discussed in the following sub-chapter. An interesting finding is the impact of fracture strain on creaminess perception, as creaminess is a fat related attribute highly relevant for fat reduction in foods. Such a result could be due to the high grainy perception of low fracture strain gels which would lower creaminess perception.

Creaminess was hypothesised to depend mainly on binding of oil droplets to the gel matrix (Sala et al. 2007b; Liu et al. 2015). Oil binding was varied in **Chapter 2**, for agar/gelatine mixed emulsion-filled gels. Oil binding to the gel matrix is known to affect fracture properties of gels. Unbound oil droplets act as inactive fillers and reduce the Young's modulus of gels, whereas bound oil droplets, which act as active fillers, increase the Young's modulus of gels with increasing oil concentration (Dickinson et al. 2012). In literature, binding is often varied by changing the emulsifier and maintaining the properties of the gel matrix, which result in unbound gels having different fracture properties than bound gels (Sala et al. 2007a). In **Chapter 2**, changes in gel matrix were compensated by adjusting the composition of the gels and obtain gels with bound and unbound droplets with similar fracture properties. Oil droplets being unbound to the gel matrix are hypothesized to increase creaminess perception, as the oil can be released upon fracture and coalesce on the contact with the oral tissue (Sala et al. 2007b; Liu et al. 2015). However, such results are not always shown (Sala et al. 2007b). Our results showed no significant differences in creaminess or in any other texture attribute between gels having bound and unbound droplets and similar fracture properties. In **Chapter 2**, variation in fracture properties between gels were large and overruled the effect of oil release. Moreover, fracture properties showed an impact on oil release (Sala et al. 2007b), which might also impact creaminess perception. The impact on fracture properties on oil release in the boli is discussed in the following sub-chapter.

Gel composition controls fracture properties and oil binding, but also other gel properties might be altered by a specific choice of ingredients. In **Chapter 4**, three different combination of gelling agents were used, agar/gelatine, carrageenan/LBG and low/high acyl gellan, to design emulsion-filled gels with similar fracture properties. In **Chapter 5**, pure agar and gelatine emulsion-filled gels were used with similar fracture stress but different fracture strains. Fracture strain depended on the gelling agent with agar gels having a low fracture strain and gelatine gels having a high fracture strain. In these two chapters, the effect of different gelling agents on texture perception could be discussed coupled (**Chapter 5**) and uncoupled (**Chapter 4**) from fracture properties, using TDS and QDA respectively. In **Chapter 5**, gelatine gels were perceived dominantly elastic in the beginning of oral processing and creamy towards the end of oral processing, whereas agar gels were perceived predominantly grainy from around 1/3 of oral processing time until the time of swallow. This result is in agreement with literature, which showed that different gelling agent in emulsion-filled gels impacted texture perception (Sala et al. 2008). A first difference between agar and gelatine gels is their melting behaviour. Agar melts at 85 °C whereas gelatine melts below mouth temperature (Inoue et al. 2009), which increases creaminess perception in emulsion-filled gels (Sala et al. 2008). A second difference between agar and gelatine gels is their fracture properties. Gelatine gels have a higher fracture strain than agar gels, which was associated to high creaminess perception in **Chapter 2**. In **Chapter 4**, fracture properties of gels were controlled using different gelling agent matrices. It was shown that composition accounted for 48% and fracture properties accounted for 47% of the variation in texture perception between the gels. This result suggests that the composition of gels is as relevant as their mechanical properties in relation to texture perception. However, the differences in perception due to composition were mainly perceived during chew down and fracture properties still dominated perception at first bites. The main variations caused by using different gelling agents were the serum release and syneresis in carrageenan/LBG gels and in gellan gels and melting and adhesiveness of the agar/gelatine gels. Serum release was previously reported in literature for carrageenan/LBG and gellan gels (Dunstan et al. 2001; Huang, et al. 2003) and is known to impact the perception of moist related texture attributes (Gwartney et al. 2004; van den Berg et al. 2008a; Çakır et al. 2012) which was confirmed in **Chapter 4**. The differences in serum release between gels from **Chapter 2 & 4**, namely agar/gelatine gels not showing serum release and other gelling system showing serum release at high fracture strain, could explain the differences in moist and refreshing perception between the experiments circled in Figure 7.4. In addition, tribology measurements showed that agar/gelatine gels generated more friction than other gels, which correlated to a higher sticky sensation, especially for gels at high fracture strain containing more gelatine. Finally, melting of agar/gelatine gels was related to a high creaminess perception in **Chapter 4**, independently from fracture properties.

In addition to comparing agar and gelatine emulsion-filled gels, in **Chapter 5,** gels were layered and layers with different mechanical properties could be combined to obtain gels with mechanical contrast. The presence of mechanical contrast on texture perception was limited. Overall, both layers were perceived equally as dominant during oral processing. A slight dominance of a hard gel layer was found in the texture profile when it was combined with a soft layer of gel from a different gelling agent.

It can be concluded that gel properties impact dynamic texture perception at first bite and during chew down. From these results, designing food structures for specific texture perception can be improved. However, the mechanisms by which gels properties impact perception are not known. In order to obtain desired textures, the impact of gels properties on bolus formation must be investigated. The main relationships between model gels properties and texture perception are integrated together with data from literature in the second column of Table 7.3. Chew down texture attributes are ordered in function of appearance as stated in literature and as seen in TDS test in **Chapter 2** and **Chapter 5**.

7.4.2. Impact of gel design on bolus formation and link to texture perception

Fracture properties and other gels properties, such as melting, are expected to determine food breakdown in mouth. Knowing the impact of fracture properties on breakdown would fill the gap in the link between fracture properties and perception of texture attributes during chew down as shown in Figure 7.5. Food oral processing was described as the decrease in breakdown and the increase in lubrication over eating time by Hutchings and Lillford (1988). This sub-chapter discusses the decrease in structure, the increase in lubrication and changes in mechanical properties of the bolus that were observed in this Thesis and their link to dynamic texture perception.

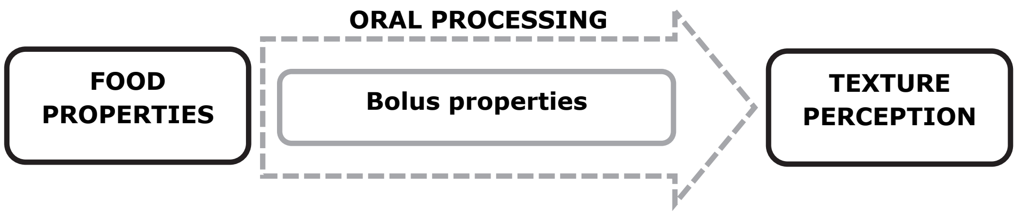


Figure 7.5 Linking food properties to bolus formation and subsequent texture perception

Decrease in degree of structure by fragmentation can be measured by quantifying particle size in the bolus which is a common characterisation of boli (Peyron et al. 2011; Guo et al. 2013; Hutchings et al. 2011; Mosca et al. 2012; Chen, 2013). Particle size in the boli was measured in **Chapters 3-6**. In all chapters, with increasing eating time, the number of fragments increased in the boli together with the total area of fragments and the size of fragments decreased. Roundness of the fragments, which is a descriptor of shape of the gel fragments in the boli, increased with oral processing time in **Chapters 5 & 6**. These results showed that for soft solid foods, which were gels and sausages, the formation of a safe-to-swallow bolus required breakdown of the food in small numerous and round fragments. Fracture properties are expected to impact greatly the breakdown of the boli in particles (Lillford, 2011). Fracture stress of gels did not have an impact on particle size and number in the boli in **Chapters 3 & 4** suggesting that subjects adapted their chewing force and frequency (Foster et al. 2006). Changes in chewing behaviour are discussed in the next sub-chapter. In **Chapter 5**, fracture stress influenced breakdown of gelatine gels but this might be related to melting properties of gelatine. In literature, food hardness was shown to have an impact on fragment size of the food bolus (Chen et al. 2013), but the range of hardness was wider than the one tested in this Thesis. Overall, fracture stress did not impact the particle formation during breakdown of the gels. Fracture strain impacted greatly the number and size of fragments. Gel with a low fracture strain broke down quickly in boli containing many small fragments in **Chapters 3-5**. As low fracture strain gels broke with a small deformation, they were broken down to a higher extent and faster than high fracture strain gels. In **Chapter 4**, agar/gelatine gels were shown to breakdown differently from other gels as they melted at mouth temperature. Boli from agar/gelatine gels contained smaller and rounder fragments than other gels, probably as the fragments melt in the mouth. This was confirmed in **Chapter 5**, where gelatine gels first broke down in an increasing number of particles which started to decrease after a certain eating duration. To conclude, the main factor influencing fragmentation of the gels were fracture strain and melting. It was found in **Chapter 3 & 4** that boli containing many small particles were perceived highly grainy or powdery. Such results explain the link between fracture strain and perception of graininess. As gels with low fracture strain were broken down in many particles, they were perceived as grainy towards the end of oral processing. This coincided with the separation of gels in two groups at the end of the sensory trajectories of **Chapter 2**, one group of high fracture strain gels that were perceived creamy and one group of low fracture strain gels that were perceived grainy.

In addition to fragmentation, decrease in structure of food occurs though dissolution, enzymatic breakdown or phase transition during oral processing. In this Thesis, the gels used could not be enzymatically degraded by amylases nor dissolved in saliva due to their composition. However, gelatine gels could melt at mouth temperature, which represents a decrease in structure by phase transition. In addition to reducing structure, melting of gelatine increases lubrication of food as it was shown to reduce friction in **Chapter 4**. Therefore, melting of gelatine contributes to both structure reduction and lubrication increase of the bolus. Partial melting of mixed agar/gelatine was hypothesized in **Chapters 2 & 3** but was not confirmed. In **Chapters 4 & 5**, gels containing only gelatine as gelling agent and that melted at mouth temperature were used. Melting resulted in small fragments in the boli and a high mixing in mouth. Mixing could be measured by texture image analysis in **Chapter 5** using the variable contrast. Contrast was shown to decrease with oral processing time in gelatine gels and to be lower in gels with lower concentration of gelatine as they melted faster. Mechanical contrast in the gel by combining an agar gel layer with a gelatine gel layer resulted in higher contrast of images of the bolus than a gelatine gel alone. This was due to the difference in melting between agar and gelatine, as agar did not melt; the solid bulk of the boli was mainly composed of small agar fragments. Such a difference in image contrast for agar and gelatine layers mixture did not impact perception. In gelatine gels, lowering contrast with oral processing time corresponded to creaminess being perceived dominant at the end of oral processing. In **Chapter 4**, melting gels were perceived creamier and more melting than other gels with similar fracture properties. It was already observed that gelatine gels broke down in large particles (Muñoz et al. 1986b) before finally melting in mouth (Inoue et al. 2009). Janssen et al. (2007) found that melting sensations were related to thinning of custard by enzymatic breakdown as well as low friction properties. In this Thesis, friction properties of agar/gelatine gels decreased with melting but remained higher than in other gel systems that did not melt. Therefore, mechanical breakdown by melting is expected to drive a high melting sensation, and friction to contribute to a lower extent. Melting was related to creaminess in this Thesis, which is in agreement with literature (Janssen et al. 2007). In conclusion, melting is a dynamic phenomenon contributing to bolus formation that increases creaminess perception towards the end of eating time.

Next to lubrication of the boli by phase transition, lubrication of the boli increases during oral processing by addition of saliva and release of fluids from the gel matrix. Saliva incorporation by gravimetrical analysis was measured in **Chapters 3, 4 & 6**. In all experiments, saliva content increased with increasing oral processing time, which is in agreement with literature (Tarrega et al. 2011). In **Chapters 3 & 4**, it was found that saliva incorporation was higher in gels with high dry matter and gels with low serum release. Such results suggest that a target value of moisture content is required to safely swallow soft solid foods. High saliva content in the bolus coincided with texture attributes, such as dry and sticky. These correlations are related to an adaptation of eating behaviour as a response to a sensory stimulus and are discussed in the next sub-chapter. Lubrication of the boli can be increased by release of fluids in the saliva, for instance gels with a high serum release required less saliva addition. Similarly, lubrication is expected to increase with oil release from the gel matrix which was measured in the boli in **Chapter 3**. Oil release was found to occur only in gels with unbound oil droplets to the gel matrix and to be influenced by fracture properties. Gels with low fracture strains released more oil than gels with high fracture strains and gels with low fracture stress released slightly more oil than gels with high fracture stress. Release of oil in unbound gels correlated to the total surface area of the gel fragments in the boli. However, release of oil in the saliva did not seem to impact perception of fat related attributes. A possibility is that most of the released droplets remained in the bulk of the bolus and that fracture properties overruled the small effect of oil droplets release.

Increase of lubrication together with decrease in structure of the bolus impacted the mechanical properties of the bolus. Mechanical properties of the bolus were measured by Two Cycle Penetration Test in **Chapters 3, 5 & 6**. The parameters from TCPT identified as most relevant were first peak force, adhesiveness and flowability. Overall, first peak force decreased with increasing eating time in all experiments and flowability increased with eating time in **Chapters 3 & 5**. Such decrease in first peak force and increase in flowability were in line with a decrease in structure and an increase in lubrication of the boli during oral processing. Fracture strain seemed to have a small effect on first peak force in **Chapter 3**, but melting of gelatine gels, which had a high fracture strain, lowered first peak force in **Chapter 5**. Increasing fracture stress increased first peak force as gels fragments were harder. Flowability corresponds to the degree of the bolus returning back to its initial state and shape after one compression cycle by a combination of flowing and springing behaviour during the TCPT. Flowability was high in melting gelatine gels in **Chapter 5**. Flowability of boli was higher for high fracture strain gels and for low fracture stress gels. Flowability seemed to converge to a target value in **Chapter 3**, suggesting a target value of flowability might be required for swallowing. In **Chapter 3**, first peak force was correlated to in mouth firmness perception at 5 and 10 s of oral processing and flowability was negatively correlated to in mouth firmness during the all oral processing time. Moreover, flowability was positively correlated with melting and with creaminess perception at 5 and 10 s of oral processing. This suggests that mechanical properties of the boli, that depended both on reduction of structure and increase of lubrication of the boli, correlated best with complex texture attributes perceived at the end of oral processing, such as creaminess. Another TCPT output was adhesiveness. Adhesiveness increased over oral processing time as boli particles were wetted with saliva in **Chapter 6**. In **Chapter 3**, adhesiveness of the boli at 5 s of oral processing, before saliva contributes to adhesiveness of the boli, correlated with stickiness perception.

The main relationships between model gels boli properties and texture perception are integrated together with data from literature in the fourth column of Table 7.3.

7.4.1. Impact of chewing behaviour on texture perception

Eating behaviour is known to impact texture perception (Brown et al. 1994) and is known to constantly change due to a sensory feedback systems (van der Bilt, 1995). Therefore, understanding dynamic texture perception requires knowing dynamic oral processing physiology and behaviour, as illustrated in Figure 7.6.

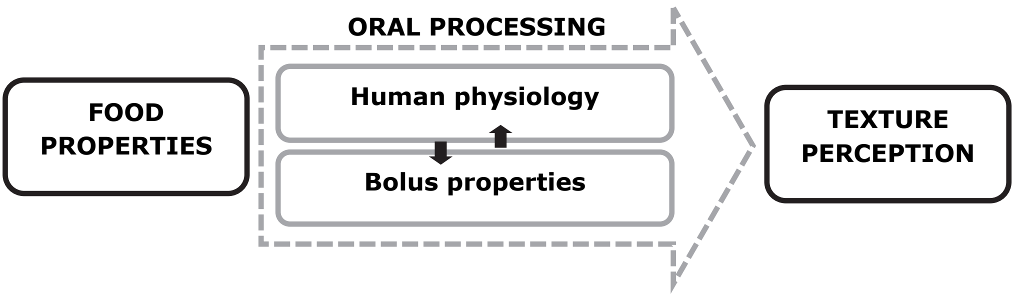


Figure 7.6 Linking human behaviour to texture perception

The eating behaviour that was measured in most chapters was eating duration, reported in **Chapters 2-6**. Eating duration was longer for gels or sausages with high fracture stress than for those with low fracture stress in all experiments. Fracture strain did not impact eating duration of agar/gelatine mixed gels in **Chapter 2**, carrageenan/LBG and gellan gels in **Chapter 4**, and agar and gelatine gels in **Chapter 5**. Such results on fracture stress and strain are in agreement with literature (Çakır et al. 2012). Melting of gelatine gels in **Chapter 4** resulted in a shorter eating time, but this was not observed in **Chapter 5**. Carrageenan/LBG gels were masticated slightly shorter than other gels. These gels showed serum release and are expected to be easily swallowed. Oil binding and the presence of mechanical contrast did not impact eating duration. In addition to eating duration, EMG was measured in **Chapters 5 & 6**. In Both chapters, it was found that muscle activity was higher at the beginning than at the end of oral processing. Such results were due to food breakdown. More muscle effort was required when the food was at its initial state than when it was processed in a bolus. Gels and sausages with a high fracture stress were masticated with a higher muscle activity. Compensation by masticating harder food with a higher muscle activity has been reported in literature (Peyron et al. 2002). These results explain that fracture stress of gels did not impact fragmentation of the bolus. Fracture strain and melting did not impact muscle activity in **Chapter 5**. Deformability of gels is expected to impact muscle activity (Koç et al. 2013b), however, changes in deformability were coupled with changes in melting behaviour in this chapter.

In **Chapter 6**, it was shown that bolus properties directly resulted from the eating duration of subjects. A longer eating duration resulted in a more comminuted bolus with more and smaller particles, more release of fat and addition of saliva, higher TCPT adhesiveness and lower TCPT first peak force. Moreover, muscle activity and number of chews were positively correlated with eating duration. Such relationship resulted in subjects of **Chapter 6**, when having a different natural eating duration, to swallow a different bolus and perceive different dominant attributes at the end of oral processing. These results show that eating duration has a consequent impact on perception. Not only eating duration is crucial for determining which attributes are perceived as dominant over time (beginning, middle, end of eating time), but also determining which attributes will be perceived depending on the subjects total eating duration. In addition, eating behaviour is expected to be adapted as the subjects perceive the food during eating. This is clear with the example of TCPT first peak force decreasing together with firmness perception and resulting in a decrease in muscle activity over eating time in **Chapter 5 & 6**. In **Chapters 3 & 4**, saliva content in the bolus positively correlated with perception of the attributes elastic, sticky, rough and powdery and negatively with the attributes slippery, moist and refreshing. This coincided with a shorter eating time being required in gels that were perceived moist and refreshing. Eating time is directly related to saliva addition in the

Table 7.3 Sensory attributes and related oral processing and rheology/fracture properties, completed from Koç et al. (2013). In Bold are relationships that were confirmed or added by this Thesis. (−) indicates negative correlations between sensory terms and other parameters.

EARLY CHEW DOWN TEXTURE ATTRIBUTES *(first chews)*			
Sensory attribute	**Rheology/fracture**	**Chewing behaviour**	**Bolus properties**
Hardness Firmness	**Fracture stress** Maximum compliance creep **Young's** and fracture modulus Work of fracture Stress intensity factor Fracture surface energy	Jaw−closing muscle activity Jaw movements Chewing velocity Number of chews **Chewing time** **Saliva incorporation**	**TCPT first peak force** **TCPT flowability (−)**
Fracturability Brittleness Crumbliness	**Fracture strain** Recoverable energy Fracture stress and modulus Held water	Number of chews Chewing time	
Deformability	Fracture strain	Occlusal duration	
MIDDLE CHEW DOWN TEXTURE ATTRIBUTES			
Sensory attribute	**Rheology/fracture**	**Chewing behaviour**	**Bolus properties**
Particle size Grainy Powdery	Fracture stress and strain	Muscle activities Number of chews Chewing time	**Size of fragments (−)**
Rate of breakdown	Fracture stress and strain (−)	Muscle activities Number of chews Chewing time	**Number of fragments (−)**
Adhesiveness Stickiness	Pressure sensitive adhesion Phase angle (tan δ) Fracture strain (−) **Fracture strain**	Jaw−opening muscle activity Anterior/posterior movements Chewing frequency (−)	**TCPT adhesiveness** **TCPT resilience** **Area of fragments (−)**
Moisture release	Held water (−)/**Syneresis** Recoverable energy (−)	Chewing frequency (−) **Chewing time (−)** **Saliva incorporation (−)**	**Size of fragments**
LATE CHEW DOWN TEXTURE ATTRIBUTES			
Sensory attribute	**Rheology/fracture**	**Chewing behaviour**	**Bolus properties**
Cohesiveness	Recoverable energy (−) Fracture strain (−)	Number of chews (−) Chewing time (−)	
Graininess Powderiness	**Fracture strain (−)**	Eating time	**Area and number of fragments**
Creaminess	**Fracture strain** **Fracture stress (−)** **Melt below 37 °C**		**TCPT flowability** **Number of fragments (−)**
Melting	**Melt below 37 °C**		**TCPT flowability**
RESIDUAL TEXTURE ATTRIBUTES			
Sensory attribute	**Rheology/fracture**	**Chewing behaviour**	**Bolus properties**
Particle mouth coating	Recoverable energy (−) **Fracture strain (−)**	Jaw and tongue movements frequency (−),**Chewing time**	**Number of fragments**
Moisture mouth coating	Held water (−), **syneresis** Recoverable energy (−)	Jaw and tongue movements frequency (−) **Saliva incorporation (−)**	

bolus (Tarrega et al. 2011) and a longer eating time results in higher saliva addition. Such results suggest that more saliva is added to sticky and dry gels to ensure a safe swallow.

The main relationships between chewing behaviour and texture perception are integrated together with data from literature in the third column of Table 7.3.

7.5. Recommendations and implications

The dynamic aspects of texture perception were put in evidence in this Thesis by using dynamic sensory methods and by monitoring changes in bolus properties and eating behaviour during oral processing. Moreover, several food properties were investigated in order to identify the drivers of temporal perception. Such information enables to design food texture more effectively, which could lead to an improved liking or the development of healthier products. Integrating the obtained results, the model shown in figure 7.6 was developed. This model summarizes the complex interactions between food properties and oral processing. Oral processing depends on oral physiology and behaviour, which is constantly updated during eating through a sensory regulation system. Oral physiology and behaviour control food breakdown and bolus properties, which are key to dynamic texture perception. As a result, texture perception depends both on food properties and individual variability between subjects. Moreover, texture perception is dynamic and is a multi-parameter attribute. Different parameters influence different texture attributes perceived at first bite, early chew down and late chew down. In the following sub-chapters, possible uses of this model are discussed.

7.5.1. Developing foods contributing to a healthier diet: Fat reduction

Emulsion-filled gels were used as a simple food model in this Thesis. However, many common food products have the structure of an emulsion-filled gel, such as sausages, cheese and some gelled desserts. Therefore, the learnings obtained from this Thesis can be used to design emulsion based foods with improved texture properties. Knowing the link between perception and food properties allows designing food for an improved sensorial experience as shown in Figure 7.6. One of the major texture attributes contributing to palatability of fat containing foods is creaminess (de Wijk et al. 2006b). Moreover, fat content is being reduced in processed foods to answer to consumers demand for foods that contribute to a healthier diet and palatability is often compromised due to such reformulations (Wilkinson et al. 2000). Several product properties were linked to an improved creaminess and fattiness perception in **Chapters 2-4**. Binding of oil droplets to the gel matrix did not impact fat related perception. This result suggests that various emulsifiers having different interactions with the food matrix can be used as replacement of one another without hindering fat perception, as long as fracture properties are kept constant. Increasing fracture strain was shown to improve creaminess and fattiness perception independently from other gel properties. This was explained by the resulting boli containing few large deformable particles as opposite to many small particles, which were perceived as grainy. Increasing fracture strain independently from fracture stress could enable to improve fat related perception in foods. Also reducing fracture stress resulted in a higher creaminess perception. Such input shows the challenge of fat reduction. In cheeses, fat reduction was shown to increase fracture stress (Guinee et al. 2000; Gwartney et al. 2002), but did not seem to change fracture strain (Gwartney; 2002). Such changes in fracture stress are an additional disadvantage of fat reduction for texture perception, as fracture stress could relate to firmness perception of cheeses. However, in cheeses, fracture mechanics do not relate well to perception of chew down attributes (Foegeding et al. 2003). Increasing fracture strain of low fat cheeses might improve slightly creaminess perception, but the impact of increasing fracture strain compared to the impact of reducing fat content is yet unknown. This could be due to the difference in composition between gels used in this Thesis and cheese, as gels contain little amount of ingredients and dry matter compared to cheese. In meat emulsions, fracture strain has been reported to correlate with acceptability (Tornberg et al. 2000), which indicates fracture strain might be a highly relevant parameter to control while lowering fat content of such products.

Another major property that increased the perception of fat related attributes was melting around mouth temperature. Melting increased the lubrication of the bolus and changed the mechanical properties of the bolus. Melting in mouth is known to create a desirable mouthfeel (Hayakawa et al. 2014) and introduce dynamic changes in texture that increase palatability (Hyde and Witherly, 1994). Therefore, stabilizing an emulsion-filled gel with hydrocolloids that melt in mouth should be preferred. In this Thesis, liquid fat was used, but melting of solid fat, similarly to melting of gelatine, could produce such a melting sensation. Replacing ingredients that provide a melt-in-mouth sensation by phase transition, such as gelatine or solid fat, is therefore challenging. The use of gelatine is common in meat based emulsions, desserts and several jellies. In addition, the melt-in-mouth properties of gelatine are often desired for flavour delivery (Koliandris et al. 2008). However, it might be discarded as its consumption is restricted by vegetarian and religious lifestyle choices. Many gelling proteins or polysaccharides are used to replace gelatine, but none of them can replace fully the mouthfeel of gelatine (Haug et al. 2004). Improvement of fish skin gelatine or thermo-reversible starched based gels might be promising, but replacing gelatine will be a challenge (Karim and Bhat, 2008).

7.5.2. Developing foods for target groups of consumers

Eating behaviour and physiology are contributing greatly to the food bolus formation and texture perception. Simple inter-individual differences, such as natural eating duration showed to impact dynamic texture perception of soft solid foods in **Chapter 6**. Therefore, differences in eating behaviour and physiology between groups of individuals should be taken into account when designing foods for target groups of consumers as shown in Figure 7.6. Two major options of food design involving a target group are trending: the growing of the elderly segment and the request for personalized foods.

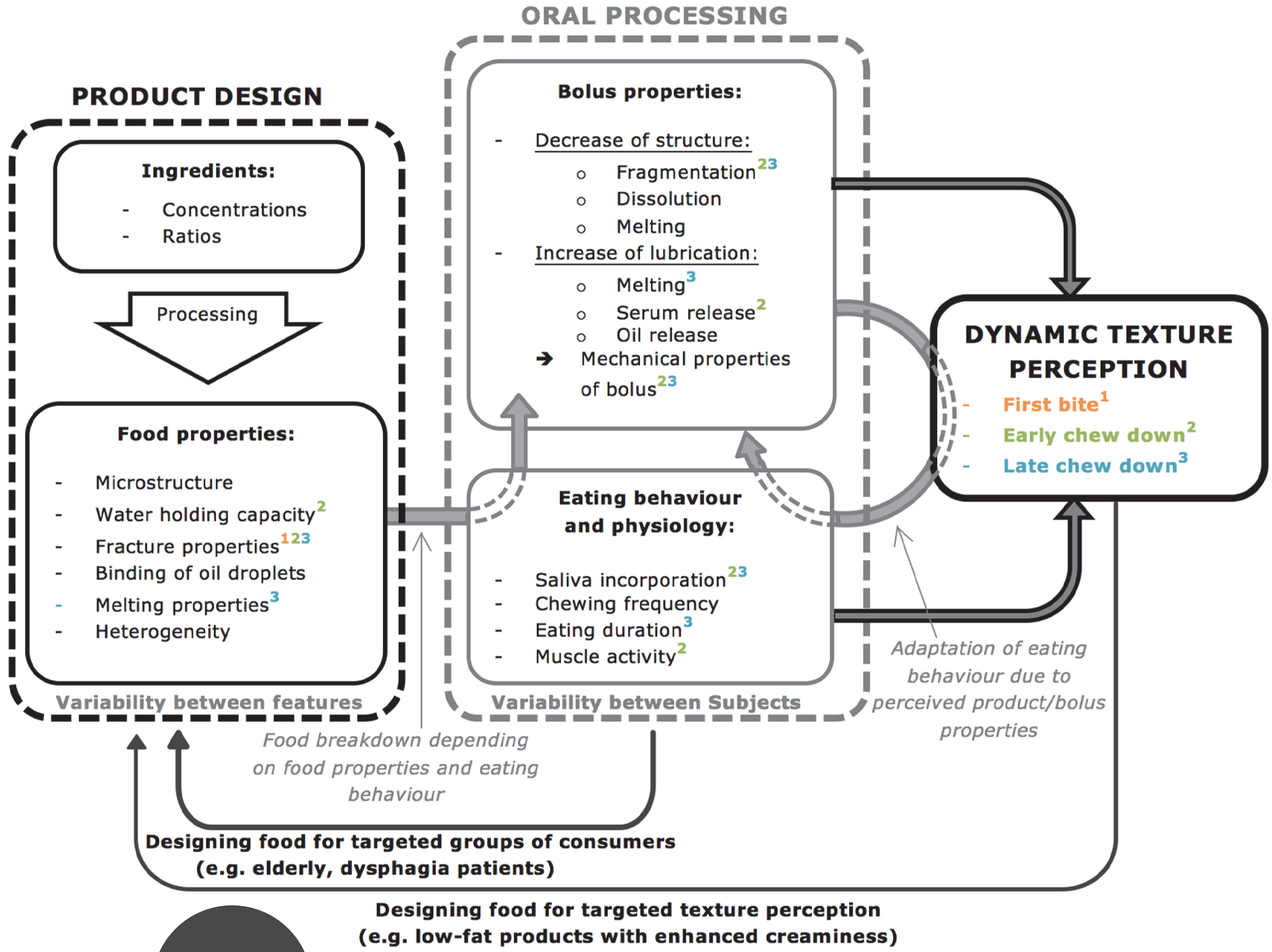
Elderly population is growing in Europe and represents a high portion of food consumers. Lower chewing muscle force was reported in elderly (Kohyama et al. 2002; Mioche, 2004) and different eating behaviours were shown for denture wearers (Mishellany et al. 2008). Chewing on solid and soft-solid food is a gratifying process and contributes to enjoyment of food. However, eating of hard, dry and tough food can be a problem for the elderly. Therefore, soft solid and solid foods should remain in elderly's diet, but may require modifications (Peleg, 1993). However, all elderly do not have the same physical condition and differences can be expected between segments of the elderly population. Therefore, when targeting a specific group of consumers it is important to consider the eating behaviour of this group on the investigated product. These observations are also valid for other consumer groups with specific needs, such as dysphasic patients.

The increasing demand for mass produced personalized food represents an opportunity, yet a challenge, for developing new tailored textures. In the case of texture, different segments of consumers with different preferred textures have been identified by marketers (Jeltema et al. 2014). Based on questionnaires, individuals were separated in 4 categories based on their preferred textures. Eating behaviour of these consumer categories (i.e. by EMG) and their texture perception (i.e. by TDS) of a specific product could be measured. Such an input when completed by the known preferences of each groups could enable the design of a tailored texturized product for each consumer group.

7.5.3. Mimicking oral processes

Development of imitative tests with mechanical mouth might be needed to fully measure instrumentally the complex mechanisms leading to texture perception. Such mechanical mouth and chewing robots have been developed in several ways (Xu et al. 2008; Salles et al. 2007). Results on bolus formation, as obtained in this Thesis, are an important input for the design of such machines. In addition, knowing the link between bolus formation and dynamic texture perception is essential to interpret the output of such machines in relation to sensorial perception.

Figure 7.7 Integration of product properties and oral processing in relation to dynamic texture perception and implications in food design. Superscript numbers indicate that parameters impact perception during (1) the early, (2) middle and (3) late chew down texture perception.



7

7.6. General conclusions

- Texture perception is highly dynamic as it depends on constant manipulation and transformation of food in the oral cavity, therefore the use of sensorial methods that consider these dynamics is essential.
- Product properties govern food breakdown and perception. Fracture properties are highly relevant in the perception of first bite texture attributes as well as chew down texture attributes. In addition, other food properties, such as melting and serum release, have a high impact on texture perception. All these food properties have to be monitored and could be controlled for designing desired texture properties of food.
- Properties of the bolus unravel the link between food properties and texture perception. Fragmentation and changes in mechanical properties of the bolus explain the perception of many attributes, including complex multimodal attributes such as creaminess. These results are valuable input to understand the mechanisms linking food design to texture perception. Moreover, they could be used for the elaboration of sophisticated testing methods such as mechanical mouths.
- Eating behaviour is highly relevant for bolus formation and texture perception, and should be taken into account when designing food products for target consumer groups. With the trending topics of ageing population and personalized food products, effective food texture design will be required.

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SUMMARY

Food texture is a major factor contributing to perceived quality and enjoyment of food. Texture of food is complex as it depends on several senses, such as touch and hearing, and is perceived in the mouth while food is broken down by mastication. Recent sensory methods, adding a time dimension to texture assessments, have been developed. These methods improved the understanding of dynamic texture perception. Often, food structure and rheology are measured or controlled to investigate texture perception. Fracture properties of food are known to be important in dynamic texture perception as fragmentation of solid food is required before swallowing. Next to fragmentation, other changes of food structure occur during oral processing, such as saliva incorporation in the bolus. These changes enable the formation a food bolus comminuted and lubricated enough to be swallowed. Understanding food texture perception requires a multifaceted approach including food structure design, dynamic texture assessment and measurements of food oral processing. Such approaches have been followed in recent scientific work using cheeses, breads and biscuits. Studying model foods allows to extend our understanding of dynamic texture perception. Indeed, the structure of gels is easily controlled compared to more complex commercial foods. The objective of this thesis was to better understand the relationship between food structure and texture perception by investigating dynamic changes in bolus properties during oral processing.

In a first study (described in Chapter 2 & 3), emulsion filled gels made of agar and gelatine were used. Changing the composition of the gels resulted in different fracture stress (low/high), fracture strain (low/high) and oil release (oil droplets bound/unbound to the gel matrix). These gels were designed to investigate dynamic texture perception. As several sensory techniques enable to measure texture perception over time, the aim of **Chapter 2** was to compare quantitative descriptive analysis (QDA), temporal dominance of sensation (TDS) and progressive profiling in the assessment of dynamic texture of gels. It was found that QDA gave a comprehensive description of gels texture with attributes perceived at first bite, during chew-down or after swallow. This indicated that fracture properties of gels controlled the perception of first bite attributes (i.e. fracture stress correlated with firmness and fracture strain with brittleness perception), but also impacted the perception of chew down texture attributes. Progressive profiling showed the evolution of a few attributes intensity overtime. For instance, creaminess increased and firmness decreased with oral processing time for all gels. TDS discriminated similarly between gels compared to QDA and progressive profiling. In addition, TDS showed the succession of attributes dominance over oral processing time. For instance, specific texture attributes were perceived as dominant sensations in the beginning (firm), middle (moist, refreshing, elastic, and sticky) and end of oral processing (grainy, melting, and creamy). The TDS sensory trajectories demonstrated that the succession of attributes was similar between samples but samples with a high or low fracture strain were perceived differently at the end of oral processing. It was shown that all three sensory methods could assess dynamic texture perception of semi-solid gels effectively, and they conveyed complementary information. Mechanical properties of the gels were found to influence the perception of texture attributes at first bite and at later stages of mastication.

As texture perception of emulsion-filled gels was confirmed to be a dynamic process, oral processing of the gels might unravel the complex relationships between fracture properties of gels and the perception of chew down texture attributes. In **Chapter 3**, the gels described in Chapter 2 were used to characterize properties of the bolus formed during oral processing. These properties enabled to explain perception of chew down texture attributes at the early, middle and end stages of oral processing. In the beginning of oral processing firmness perception, which was dominant in TDS, correlated with mechanical properties of the boli, such as first penetration peak force and flowability. In the middle of oral processing, several attributes were perceived dominant and correlations between boli properties and texture perception became more complex. The perception of elastic and sticky sensory attributes was related to the mechanical bolus properties resilience and adhesiveness, whereas the perception of moist and refreshing sensory attributes was related to the mechanical bolus property flowability. In the end of oral processing, the attributes creamy or grainy where dominantly perceived in the gels depending on the fracture strain of the gels. Creaminess was related to high bolus flowability, while graininess was related to boli with a high number of broken down particles. Such differences in boli properties were partly explained by fracture properties of the gels. Binding of oil droplets to the gel matrix resulted in different amount of oil being released in the bolus, but this did not impact creaminess perception. Results from Chapter 3 confirmed that bolus formation and changes in the properties of the bolus underlay the changes in texture perception during oral processing.

Fracture properties where shown to impact the perception of first bite texture attributes and chew down texture attributes in Chapters 2 & 3. However, changing fracture properties of model gels was found to be coupled with changes in composition, which might impact texture perception. For instance, Chapters 2 & 3 used mixtures of agar and gelatine which, next to having different fracture properties, might have different melting behaviours at mouth temperature. In **Chapter 4**, gels with similar fracture properties were prepared from different ingredients, which can cause changes in gel properties, such as syneresis and melting behaviour, and, thereby, could impact perception. Twelve emulsion filled mixed gels were prepared following a 2x2x3 factorial design: gels varying in fracture stress (high/low) and fracture strain (high/low) were prepared using three different mixed gelling agents (agar/gelatine; carrageenan/locust bean gum (LBG); high/low acyl gellan). The fracture properties were controlled in the three gelling agent systems yielding gels varying in composition, but exhibiting similar fracture properties. Gels made from different gelling agents differed in serum release and melting properties. Carrageenan/LBG and gellan gels exhibited serum release and did not melt at mouth temperature, whereas agar/gelatine gels did not show serum release and melted below mouth temperature. Both serum release and melting of gels were found to decrease friction. The oral processing of gels was impacted by fracture properties of gels. Agar/gelatine gels broke down differently than carrageenan/LBG and gellan gels due to in mouth melting. Sensory perception of the gels showed that agar/gelatine gels were perceived differently from the other gel systems. Fracture properties had a high impact on perception of texture attributes at first bite and also during chew down. For instance, increasing fracture strain decreased perceived brittleness and increased perception of elastic, slippery, melting and creamy attributes. The main conclusions from Chapter 4 were that fracture properties of gels, independently from composition, contributed to 47 % of variation in the perception of chew down texture attributes for all gel systems studied. In addition, composition of the gels impacted properties, such as melting or syneresis of the gels, which contributed to 48% of variation in the perception of gels. For instance, melting of gelatine increased creaminess perception and overruled the effect of fracture properties. Therefore, fracture properties, along with other properties of food, can be controlled to obtain a more desirable texture profile.

The gels used in Chapter 2-4 were homogeneous at macroscopic length scale. However, many foods that are highly palatable are composed of multiple components, which can have considerably different mechanical properties leading to contrasting texture sensations. The combination of macroscopic components with contrasting mechanical properties in composite foods results in complex food breakdown behaviour in mouth and texture perception. In **Chapter 5,** the impact of contrasting mechanical properties in foods on oral processing behaviour and dynamic texture perception of semi-solid model gels was investigated. As reference stimuli, four layered emulsion filled gels displaying no mechanical contrast were prepared using 1 and 2 wt% agar or 2.5 and 5.5 wt% gelatine. Two layers of emulsion filled gels varying in mechanical properties were combined to yield six layered emulsion filled gels with contrasting mechanical properties. Firstly, the homogeneous emulsion filed gels without mechanical contrast were characterized. Those gels differed considerably in fracture stress and strain leading to characteristic differences in oral processing behaviour, bolus properties and dynamic texture perception. Secondly, the bolus properties, oral processing behaviour and dynamic sensory perception of the 6 emulsion filled gels with contrasting mechanical properties were compared to the 4 emulsion filled gels without mechanical contrast using Principal Component Analysis (PCA). Emulsion filled gels with mechanical contrast containing agar gel layers had similar bolus properties and in mouth breakdown behaviour as agar gels without mechanical contrast. The resulting mechanical contrast between the layers remained during oral processing as observed by image analysis of the in mouth mixing behaviour of the boli. Emulsion filled gels with mechanical contrast were perceived as a combination of the individual layers which they were composed of. The temporal sensory profiles and sensory trajectories of the emulsion filled gels with mechanical contrast fell between the temporal sensory profiles and sensory trajectories of the two gel layers which they were composed of. Layers with high concentrations of gelling agents tended to dominate the dynamic sensory profile of emulsion filled gels with mechanical contrast when combined with layers with low concentrations of the opposite gelling agent. It was concluded that separate components in emulsion filled gels with mechanical contrast are perceived separately in mouth over oral processing time.

Chapters 2-5 focused on oral processing through the aspect of bolus formation. However, oral physiology and behaviour are an important aspect of oral processing. In addition to food properties and bolus properties, it was found in Chapters 2-5 that eating behaviour was tightly linked to texture perception. Bolus properties depended on eating duration and coincided with the total muscle activity. Differences in oral processing behaviour have been found to impact texture perception of food in literature. Therefore, differences in naturally preferred eating duration of a food are expected to impact bolus formation and texture perception of this specific food. In **Chapter 6**, the influence of naturally preferred eating duration on eating behaviour, bolus formation and dynamic texture perception of sausages was investigated. Sausages being real foods with a structure close to emulsion-filled gels. A group of “long duration eaters” (n=11) and a group of “short duration eaters” (n=12) were selected based on their natural eating duration when consuming a controlled portion of sausage. When eating two different sausages, the long duration eaters ate on average twice as long as the short duration eaters for both sausages. The two groups of eaters chewed the sausage with the same muscle effort rate and the same chewing frequency. As long duration eaters ate twice as long as short duration eaters, their total muscle effort and total number of chews were significantly higher than for the short duration eaters. Therefore, they did not compensate for a different eating duration by a different chewing behaviour. As a result of different eating duration, short duration eaters swallowed a bolus that was firmer and less adhesive, that contained fewer and larger particles, and that contained less released fat and added saliva than short duration eaters. Thus, they were comfortable swallowing a less broken down bolus. These differences in bolus properties at swallow coincided with different texture perception between long and short duration eaters at the end of oral processing, as showed by TDS. Therefore, differences in eating duration between subjects can lead to differences in bolus properties of sausages causing differences in dynamic texture perception of the same sausage. These results highlighted the interest to measured oral processing behaviour to fully understand dynamic texture perception.

In **Chapter 7**, the results from the thesis and their implications were discussed. Fracture properties, melting and serum release of gels were identified as the main gel properties influencing dynamic texture perception. Fracture strain and melting of gels were the main properties influencing bolus formation together with eating duration of subjects. Bolus formation was recurrently explaining chew down texture attributes in all Chapters. The bolus properties that explained most changes in texture perception were fragmentation, such as particle size and number, and mechanical properties, such as flowability and adhesiveness. Oral processing behaviour, mainly eating duration and the resulting saliva addition, also were related with perception of chew down texture attributes. This was typically due to a sensory feedback process, the perception of some attributes resulting in a different chewing duration. Overall, the implication of the results of this thesis were discussed towards the design of foods fit for a healthy diet and foods for target consumer groups, which are the two main areas of food development requiring a better understanding of food texture design.

The research conducted in this thesis confirmed the importance of food properties, such as fracture properties, in oral breakdown of food and perception of dynamic texture of food. Different sensory science methods were used successfully in the assessment of dynamic texture perception of food gels. It was shown that perception of food at first bites and early chew down depends mainly of food properties. Whereas perception of food texture during chew down, in addition to food properties, depends on the properties of the formed bolus. The impact of different food properties were compared and quantified providing input for designing soft solid foods with a desired dynamic texture profile. Moreover, the properties of boli that control chew down texture attributes were identified providing better understanding of the mechanism underlying the perception of chew down texture attributes. Knowing these mechanisms, it was found that differences in oral processing behaviour between consumer groups could impact texture perception of the same food. Quantifying food oral breakdown to improve the understanding of dynamic texture perception is a promising approach. Combining food structure, oral processing and sensory science was key in this thesis to identify successfully which parameters can control dynamic texture perception of food.

SAMENVATTING

Textuur levert een belangrijke bijdrage aan de kwaliteit en het genot van voedsel. De textuur van voedsel is een complex begrip, omdat het afhankelijk is van verschillende zintuigen, zoals gevoel en gehoor. Daarnaast wordt textuur waargenomen in de mond tijdens het kauwen en de afbraak van het product. In het Engels wordt hiervoor de term Oral Processing gebruikt. Oral processing omvat het hele proces van mechanische bewerking van voedsel vanaf het moment dat het in de mond genomen wordt totdat het doorgeslikt wordt. In deze samenvatting wordt de term kauwen gebruikt om dit hele proces aan te geven. Recentelijk zijn sensorische methoden ontwikkeld, die deze tijdsdimensie aan de textuurbeoordeling toegevoegd hebben. Deze nieuwe methoden verbeteren het inzicht in de dynamiek van textuurperceptie. Om textuurperceptie te bestuderen worden vaak de structuur en reologische eigenschappen van voedsel gemeten. Breukeigenschappen zijn belangrijke parameters voor de dynamiek van textuurperceptie van vaste producten, omdat deze producten eerst verkleind moeten worden voordat ze doorgeslikt kunnen worden. Tijdens het kauwen van voedsel verandert niet alleen de deeltjesgrootte, maar er vinden ook andere veranderingen plaats, zoals de opname van speeksel. Al deze veranderingen leveren een bolus op die voldoende verkleind is en voldoende bevochtigd is om veilig te kunnen doorslikken. Begrip van de textuurperceptie van voedsel vraagt om een multidisciplinaire aanpak, inclusief het ontwerpen van de structuur, analyse van de dynamica van de textuur en metingen om het kauwproces te kwantificeren. Een dergelijke aanpak is in de literatuur beschreven voor kaas, brood en biscuit. Om fundamenteel begrip te verzamelen is het gebruik van modelproducten, zoals gelen, aan te bevelen. De structuur van gelen is inderdaad makkelijker te controleren en te sturen dan die van complexe voedingsmiddelen. In dit proefschrift zijn zogenaamde emulsie-gevulde gelen gebruikt. Dit zijn modelproducten waarin emulsiedruppels zijn ingebed in een gegeleerde matrix. Deze emulsie-gevulde gelen wordt gebruikt als modelproduct voor bijvoorbeeld kaas, toetjes en worst. Voor de leesbaarheid van deze samenvatting wordt in het vervolg gesproken over gelen, maar dat zijn in alle gevallen emulsie-gevulde gelen. De doelstelling van dit proefschrift was het opvullen van het gat in kennis tussen de structuur van voedingsmiddelen en de textuurperceptie door het onderzoeken van de dynamiek van de veranderingen van de bolus tijdens het kauwen van deze producten.

In de eerste studie (beschreven in de hoofdstukken 2 en 3) zijn gelen op basis van gelatine en agar gebruikt. Door de compositie van deze modelproducten te variëren werd een proefopzet in een full factorial design ontworpen. De gelen varieerden in de breukspanning (laag/hoog), vervorming bij breuk (laag/hoog) en in de mate van olie-uittreding (oliedruppels die gebonden/ongebonden waren in de gelmatrix). Deze proefopzet was specifiek ontworpen om de dynamiek van de textuurperceptie te kunnen bestuderen. Omdat deze dynamiek van textuurperceptie met verschillende sensorische technieken gemeten kan worden, was de doelstelling van **Hoofdstuk 2** om een vergelijk te maken tussen een kwantitatieve sensorische beoordeling (quantitative descriptive analysis; QDA), tijdelijke dominantie van sensorische attributen (temporal dominance of sensation; TDS) en het volgen van de intensiteit van een sensorisch attribuut in de tijd (progressive profiling). In het vervolg van deze samenvatting zullen de Engelse termen en afkortingen gebruikt worden. De resultaten toonden aan dat QDA een volledige en brede beschrijving van de textuur van de modelproducten geeft, met sensorische attributen die waargenomen worden bij de eerste hap, tijdens het kauwen en na het doorslikken. Dit liet zien dat de breukeigenschappen van de gelen bepalend zijn voor de perceptie van sensorische attributen bij de eerste hap (zo is de breukspanning gerelateerd aan de waargenomen stevigheid en de vervorming bij breuk aan de waargenomen brosheid), maar ook invloed hebben op de waarneming van attributen tijdens het kauwen. Progressive profiling geeft de ontwikkeling van één attribuut in de tijd weer. Bijvoorbeeld, romigheid neemt toe gedurende het kauwen, terwijl stevigheid afneemt. De tijd die nodig is om het product te kauwen wordt hierna benoemd als kauwtijd. TDS onderscheidde de modelproducten op een vergelijkbare manier als QDA en progressive profiling. Daarnaast geeft TDS ook de dominantie van de verschillende attributen gedurende de kauwtijd. Specifieke dominante textuurattributen werden gekoppeld aan specifieke momenten tijdens het kauwen. In het begin van de kauwtijd was dit stevigheid, in het midden waren dit vochtig, verfrissend, elastisch en plakkerig, en aan het eind van de kauwtijd waren dit korrelig, smeltend en romig. De op TDS gebaseerde sensorische trajecten lieten zien, dat de volgorde van de attributen vergelijkbaar was voor alle producten, maar dat producten met een lage of een hoge vervorming bij breuk verschillend worden waargenomen aan het eind van de kauwtijd. De resultaten toonden aan dat elk van de drie methoden gebruikt kan worden om de dynamiek van textuurperceptie op een effectieve manier te bepalen. Deze drie methoden leverden vergelijkbare informatie op. De mechanische eigenschappen (breukeigenschappen) beïnvloedden de waarneming van textuurattributen zowel bij de eerste hap als tijdens het verdere kauwen van het product.

Nadat aangetoond was dat textuurperceptie een dynamisch proces is, was de vraag of het gedrag van de gelen tijdens het kauwen belangrijk is om de complexe relatie tussen breukeigenschappen en textuurperceptie tijdens het kauwen op te kunnen lossen. In **Hoofdstuk 3** zijn dezelfde gelen als in hoofdstuk 2 gebruikt om de eigenschappen van het product tijdens het kauwen te bepalen. Een gekauwd voedingsmiddel wordt bolus (enkelvoud) of boli (meervoud) genoemd. De eigenschappen van deze boli maken het mogelijk om de waarneming van textuurperceptie tijdens de kauwtijd (begin, middel en eind) te verklaren. De mechanische eigenschappen van de boli werden bepaald met een 2-cycli-penetratiemeeting. In het begin van de kauwtijd is het attribuut stevig, dat dominant was in de TDS meting, gecorreleerd met de mechanische eigenschappen van de boli, zoals de maximale kracht bij de eerste penetratie en het vloeigedrag. In het midden van de kauwtijd werden verschillende attributen als dominant waargenomen en werden de relaties tussen attributen en eigenschappen van de boli complex. De perceptie van de sensorische attributen elastisch en plakkerig waren gerelateerd aan de bolus-eigenschappen vervormbaarheid en adhesief. De waarneming van de sensorische attributen vochtig en verfrissend waren gerelateerd aan de bolus-eigenschap vloeigedrag. Aan het eind van de kauwtijd waren de attributen korrelig en romig dominant afhankelijk van de vervorming bij breuk van de gelen. Romigheid relateerde aan een hoog vloeigedrag van de boli, terwijl korreligheid relateerde aan een groot aantal stukjes in de boli. Deze verschillen in de eigenschappen van de boli konden gedeeltelijk uit de breukeigenschappen van de modelproducten bepaald worden. De binding van de emulsiedruppels aan de gelmatrix (gebonden vs. ongebonden druppels) resulteerde in verschillende hoeveelheden olie die uit de boli vrijkwamen, maar relateerde niet aan de sensorische waarneming van romigheid. De resultaten van hoofdstuk 3 bevestigden dat de vorming van de bolus en de veranderingen in de eigenschappen van de bolus verantwoordelijk zijn voor de veranderingen in de textuurperceptie tijdens kauwen.

In hoofdstukken 2 & 3 is aangetoond dat breukeigenschappen de perceptie van de textuurattributen bij de eerste hap en bij het kauwen beïnvloeden. Echter, bij de gebruikte modelproducten gingen de veranderingen in breukeigenschappen gepaard met veranderingen in de samenstelling, wat een invloed op de perceptie zou kunnen hebben. Zo hebben de gelen op basis van gelatine en agar (gebruikt in de hoofdstukken 2 & 3) niet alleen verschillende breukeigenschappen, maar ook een verschillende smeltgedrag in de mond. Voor **Hoofdstuk 4** zijn gelen gemaakt met gelijke breukeigenschappen, maar met verschillende ingrediënten. Dit verschil in ingrediënten resulteerde in verschillende eigenschappen, zoals synerese en smeltgedrag, en zouden daarmee een verschil in perceptie kunnen geven. Twaalf gelen werden volgens een 2x2x3 factorial design ontworpen. Gelen met verschil in breukspanning (laag/hoog) en vervorming bij breuk (laag/hoog) werden gemaakt met drie verschillende combinaties van verdikkingsmiddelen (agar/gelatine; carrageen/johannesbroodpitmeel; gellaan gum met een hoog en laag aantal acyl-groepen). In elk van de drie combinaties van verdikkingsmiddelen werden de concentraties gevarieerd om gelijke breukeigenschappen te kunnen creëren. Gelen gemaakt met verschillende verdikkingsmiddelen verschilden in mate van vochtuittreding en smeltgedrag. Carrageen/johannesbroodpitmeel en gellaan gelen vertoonden vochtuittreding, maar smolten niet bij lichaamstemperatuur, terwijl agar/gelatine gelen geen vochtuittreding vertoonden en wel beneden lichaamstemperatuur smolten. Zowel vochtuittreding als smelten resulteerde in een verlaagde frictie. Het kauwen van deze gelen werd beïnvloed door de breukeigenschappen en de ingrediënten. Agar/gelatine gelen vielen op een andere manier uit elkaar tijdens het kauwen dan de carrageen/johannesbroodpitmeel en gellaan gelen als gevolg van het verschil in smeltgedrag. Sensorische analyse van de gelen toonde aan dat agar/gelatine gelen sensorisch anders werden waargenomen dan de overige gelen. De breukeigenschappen waren van grote invloed op de perceptie van textuurattributen bij de eerste hap en ook tijdens het kauwen. Bij voorbeeld, een verhoging van de vervorming bij breuk resulteerde in een verminderde perceptie van het attribuut kruimeligheid en een verhoogde perceptie van de attributen elastisch, slipperig, smeltend en romig. De belangrijkste conclusies van hoofdstuk 4 zijn dat breukeigenschappen van de gelen (onafhankelijk van de samenstelling) 47% van de variatie in de sensorische textuurperceptie van deze gelen kunnen verklaren. Daarnaast verklaarde de samenstelling van de gelen 48% van de variatie in de sensorische textuurperceptie. Zo zorgde het smelten van gelatine voor een toename in de perceptie van romig en reduceerde hiermee de invloed van de breukeigenschappen van gelatinegelen. Samenvattend, de breukeigenschappen en de samenstelling van voedingsmiddelen kunnen gebruikt worden om de textuur daarvan te sturen.

De gelen zoals die in de hoofdstukken 2-4 gebruikt zijn, waren homogeen op een macroscopische schaal (met het oog waarneembaar). Echter, veel voedingsmiddelen zijn opgebouwd uit verschillende componenten, die verschillende mechanische eigenschappen kunnen hebben, wat leidt tot textuurcontrast. De combinatie van macroscopische componenten in een samengesteld voedingsmiddel resulteert in een complexe manier van uiteenvallen tijdens het kauwen en tot een complexe textuurperceptie. In **Hoofdstuk 5** is de invloed van contrasterende mechanische eigenschappen op kauwgedrag en de dynamiek van textuurperceptie in gegeleerde modelproducten onderzocht. Er werden agargelen met 1 en 2 % agar of gelatinegelen met 2,5 en 5,5% gelatine gebruikt. Als referentieproducten (geen contrast) werden twee lagen van identieke gelen gebruikt. Zes producten met contrast in de mechanische eigenschappen werden gemaakt met combinaties van de vier referentieproducten (twee lagen van verschillende gelen). Eerst werden de referentiegelen gekarakteriseerd. Deze gelen vertoonden een duidelijk verschil in breukspanning en vervorming bij breuk, die resulteerden in karakteristieke verschillen in kauwgedrag, boluseigenschappen en dynamische textuurperceptie. Als tweede werden boluseigenschappen, kauwgedrag en de dynamische textuurperceptie van de 6 gelen met textuurcontrast vergeleken met die van de 4 referentiegelen. Voor deze vergelijking werd gebruik gemaakt van Principal Component Analysis (PCA). De samengestelde gelen met één agarlaag hadden gelijke bolus- en breukeigenschappen als de homogene agargelen. Het contrast in mechanische eigenschappen tussen de lagen bleef bestaan tijdens het kauwen. Dit werd aangetoond door beeldanalyse van de boli die na verschillende tijden kauwen werden uitgespuugd. De gelen met contrast in mechanische eigenschappen werden waargenomen als een combinatie van de twee individuele lagen waaruit ze waren opgebouwd. De sensorische profielen, die de dominantie van sensorische attributen tijdens het kauwen weergeven, lieten zien dat de trajecten voor gelen met contrast tussen die van de corresponderende homogene gelen gepositioneerd waren. De lagen met een hoge concentratie geleermiddel neigen de dynamische, sensorische profilen van de gelen met contrast te domineren als ze gecombineerd werden met een laag van de lage concentratie van het andere geleermiddel. Dus een hoge concentratie agar domineert over een lage concentratie gelatine. Concluderend, de individuele lagen in de samengestelde gelen werden afzonderlijk waargenomen gedurende de kauwtijd.

De hoofdstukken 2-5 richtten zich op het ontwikkelen van begrip over het kauwgedrag door analyses van de vorming van bolus. Maar de fysiologie van de mond en de kauwbewegingen zijn een even belangrijk aspect van kauwgedrag. In hoofdstukken 2-5 werd gevonden dat naast de eigenschappen van de voedingsmiddelen en de bolus ook het eetgedrag een belangrijke invloed op de textuurperceptie heeft. De eigenschappen van de bolus hingen af van de kauwtijd en vielen samen met de totale spieractiviteit. In de literatuur is ook beschreven dat verschillen in kauwbewegingen van invloed zijn op textuurperceptie. Op basis hiervan is het te verwachten dat de natuurlijke kauwtijd van invloed zal zijn op de vorming van de bolus en de textuurperceptie van specifieke producten. Met natuurlijke kauwtijd wordt de tijd bedoeld die een persoon zelf prettig vindt om op een product te kauwen. In **Hoofdstuk 6** is de invloed van de natuurlijke kauwtijd op de kauwbewegingen, vorming van de bolus en de dynamische textuurperceptie van worsten onderzocht. Als product met een structuur die vergelijkbaar is met die van de eerder bestudeerde gelen werden worsten gekozen. Een groep “eters met een lange kauwtijd” (n=11) en een groep “eters met een korte kauwtijd” (n=12) werden geselecteerd op basis van de natuurlijke voorkeurs kauwtijd bij het eten van een vaste hoeveelheid worst. Er werden twee soorten worst gebruikt. De eters met een lange kauwtijd deden gemiddelde tweemaal zo lang over het eten als de eters met een korte kauwtijd. Beide groepen kauwden de worst met dezelfde frequentie en dezelfde spieractiviteit. Omdat de eters met een lange kauwtijd tweemaal zo lang kauwden als de eters met een korte kauwtijd was hun totale spieractiviteit en het totaal aantal kauwbewegingen ook veel groter. De verschillende groepen compenseerde hun verschil in kauwtijd niet door een ander kauwgedrag. Als een gevolg van het verschil in kauwtijd, slikten de eters met een korte kauwtijd een bolus in die steviger en minder plakkerig was, die minder maar grotere stukjes bevatte en die minder vrijgekomen vet en opgenomen speeksel bevatte dan de bolus van de eters met een lange kauwtijd. Dus de eters met een korte kauwtijd kunnen bolus inslikken die minder ver verkleind is. Deze verschillen in de eigenschappen van de bolus op het moment van slikken vallen samen met verschillen in de dynamische textuurperceptie tussen de twee groepen, zoals werd aangetoond met TDS. Dus verschillen in eet- en kauwgedrag tussen personen kan resulteren in verschillen in boluseigenschappen wat weer resulteert in verschillen in de dynamiek van de textuurperceptie van identieke producten. De twee groepen consumenten beleven hetzelfde product dus anders. Deze resultaten tonen aan dat meten van kauwgedrag en –bewegingen helpt bij het beter begrijpen van de dynamiek van textuurperceptie.

In **Hoofdstuk 7** worden de resultaten van dit proefschrift en de consequenties daarvan bediscussieerd. Breukeigenschappen, smeltgedrag en vochtuittreding werden geïdentificeerd als de belangrijke eigenschappen van gegeleerde producten die bepalend zijn voor de dynamiek van textuurperceptie. De vervorming bij breuk en het smeltgedrag waren, samen met de kauwtijd, de belangrijkste bepalende eigenschappen voor de vorming van de bolus tijdens het kauwen. De vorming van de bolus werd herhaaldelijk in alle hoofdstukken aangetoond als verklaring voor de textuurattributen die waargenomen worden tijdens het kauwen van voedsel. De boluseigenschappen die de meeste veranderingen in de textuurperceptie verklaarden waren de deeltjeseigenschappen, zoals deeltjesgrootte en –aantal, en de mechanische eigenschappen van de bolus, zoals vervormbaarheid en plakkerigheid. Kauwgedrag, met name de kauwtijd en als gevolg daarvan de toevoeging van speeksel, relateerden ook aan de waarneming van textuurattributen tijdens het kauwen. Via een sensorisch feedback mechanisme zorgt de perceptie van sommige textuurattributen voor een verandering in de kauwtijd. De consequenties van dit proefschrift werden besproken in het licht van het ontwerp van voedingsmiddelen die passen binnen een gezond dieet of toegespitst zijn of specifieke doelgroepen, zoals ouderen. Dit zijn de twee gebieden van productontwikkeling die gebaat zijn bij een beter begrip van het ontwerp van de textuur van voedingsmiddel.

Het onderzoek zoals in dit proefschrift beschreven is, toont het belang aan van de eigenschappen van voedingsmiddelen, zoals breukeigenschappen, voor het kauwen van de producten en de waarneming van de dynamiek van de textuurperceptie. Verschillende sensorische technieken werden gebruikt om deze dynamiek van de textuurperceptie van gegeleerde voedingsmiddelen te kwantificeren. Aangetoond werd dat de producteigenschappen met name belangrijk zijn voor de perceptie van attributen tijdens de eerste hap en het begin van het kauwproces. De waarneming van de textuur tijdens het verdere kauwen is naast de producteigenschappen ook afhankelijk van de eigenschappen van de bolus. De invloed van verschillende producteigenschappen werd bestudeerd en gekwantificeerd om zodoende input te leveren voor het ontwerp van gegeleerde voedingsmiddelen met een gewenst dynamisch textuurprofiel. Verder werden de eigenschappen van de bolus die bepalend zijn voor de sensorische attributen tijdens het kauwen, geïdentificeerd. Dit heeft geleid tot een beter begrip van de mechanismen die een rol spelen bij het tot stand komen van textuurattributen tijdens het kauwen. Met de kennis van deze mechanismen werd aangetoond dat verschillen in kauwgedrag tussen groepen consumenten kunnen leiden tot een verschil in textuurperceptie van eenzelfde product. Het kwantificeren van verandering in het voedingsmiddel tijdens het kauwen (de vorming van de bolus) is een veelbelovende aanpak om begrip te krijgen van de dynamiek van textuurperceptie. Het combineren van de structuur van voedingsmiddelen, kauwgedrag en sensorische technieken was de sleutel in dit proefschrift om te kunnen identificeren welke parameters bepalend zijn voor de dynamiek van textuurperceptie.

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A PhD is definitely not a solitary experience,
Marine

ABOUT THE AUTHOR

LIST OF PUBLICATIONS

Publications in peer-reviewed journals:

Devezeaux de Lavergne, M., van Delft, M., van de Velde, F., van Boekel, M.A.J.S. and Stieger, M. (2015). Dynamic texture perception and oral processing of semi-solid food gels: Part 1: A comparison between QDA, progressive profiling and TDS. Food Hydrocolloids 43 : 207-217.

Devezeaux de Lavergne, M., van de Velde, F., van Boekel, M.A.J.S. and Stieger, M. (2015). Dynamic texture perception and oral processing of semi-solid food gels: Part 2: Impact of breakdown behaviour on bolus properties and dynamic texture perception. Food Hydrocolloids 49 : 61-72.

Devezeaux de Lavergne, M., Derks, J.A.M, Ketel, E.C., de Wijk R.A. and Stieger, M. (2015). Eating behaviour explains differences between individuals in dynamic texture perception of sausages. Food Quality and Preference 41 : 189-200.

Devezeaux de Lavergne, M., Tournier, C., Bertrand, D., Salles, C., van de Velde, F. and Stieger, M. (2016). Dynamic texture perception, oral processing behaviour and bolus properties of emulsion-filled gels with and without contrasting mechanical properties. Food Hydrocolloids 52: 648-660.

Submitted for publication:

Devezeaux de Lavergne, M., Strijbosch, V.M.G., van den Broek, A.W.M., van de Velde, F. and Stieger, M. Uncoupling the impact of fracture properties and composition on sensory perception of emulsion-filled gels.

Manuscript in preparation:

Devezeaux de Lavergne, M., van de Velde, F. and Stieger, M. Bolus matters. The implication of food oral breakdown in dynamic texture perception: A review of recent developments in the field.

Oral presentations at conferences:

6th International Symposium on Delivery of Functionality in Complex Food Systems, Paris (2015): “Interplay between fracture properties and composition in emulsion filled gels in relation to dynamic texture perception.”

11th International Congress on Engineering and Food, Quebec (2015): “Impact of food gel fracture properties on in mouth breakdown and dynamic texture perception”

3rd International Conference on Food Oral Processing, Wageningen (2014): “Influence of eating speed on bolus formation, chewing behaviour and dynamic texture perception of sausages”

1st Asian Sensory and Consumer Research Symposium (SenseAsia), Singapore (2014): **Workshop:** Challenging Frontiers TDS "Dynamic texture perception and food oral processing"

1st Food Structure and Functionality Forum Symposium; Amsterdam (2014): "Impact of food gel fracture properties on in mouth breakdown and dynamic texture perception"

10th Pangborn Sensory Science Symposium; Rio de Janeiro (2013): "Linking dynamic texture perception to oral processing and bolus properties of food gels"

Poster presentations at conferences:
3rd International Conference on Food Oral Processing, Wageningen (2015): "Influence of gel fracture properties on in-mouth breakdown behaviour and dynamic texture perception."

1st Asian Sensory and Consumer Research Symposium (SenseAsia), Singapore (2015): "Can eating behaviour explain differences in texture perception between consumers?"

10th Pangborn Sensory Science Symposium, Rio de Janeiro (2013): "Dynamic texture perception of gels: A comparison between QDA, sequential profiling and TDS."

BIOGRAPHY

Marine Devezeaux de Lavergne was born on the 11th of March 1988 in Clamart, France. She grew up in Ile de France where she studied for her high school, in Antony, and preparatory classes, in Paris. In September 2007, she started her cursus of "Ingénieur en Agro-alimentaire" in AgroParisTech in Massy, France. From September to December 2008, she carried an internship in Danone Research Center Daniel Carasso in Palaiseau (France) where she worked on a method to dose Cystein in fermented dairy products. She had the opportunity in August 2009 to enter the European Masters in Food Studies offered by Wageningen University as part of her training in AgroParisTech. Part of the European Masters classes took place in Wageningen University, University College of Cork, AgroParisTech and Lund University. During her Masters, Marine did an 8 months internship in the R&D centre of Mondeléz in Munich, Germany. She worked on improving the sensory profile of cream cheese by using additives and several fermentation conditions. She obtained both her degree of Masters in Food Technology from Wageningen University and her degree of Engineer in Food Sciences from AgroParisTech in August 2011. In September 2011, Marine was appointed as a PhD fellow at TI Food and Nutrition and at the Food Quality and Design (FQD) group of Wageningen University. Her PhD project focused on linking bolus formation to dynamic texture perception in soft solid foods, as part of the "Texture and Taste" TIFN project. She participated as well in teaching practical's, supervising six master students and organising, together with six PhD fellows, the PhD study tour of FQD to Singapore and Thailand in 2014.

OVERVIEW OF COMPLETED TRAINING AND ACTIVITIES

Discipline specific activities

Courses

Statistics for Sensory Sciences, 2012, Campden, UK
Rheology and structure of food, 2012, Wageningen, NL
Food energy intake, 2012, Wageningen, NL
Industrial proteins, 2013, Wageningen, NL
Advanced food analysis, 2013, Wageningen, NL
Nutriscience, 2013, Wageningen, NL

Conferences

7th NIZO Dairy Conference, 2011, Papendal, NL
2nd International Conference on Food oral processing, 2011, Beaune, FR
10th Pangborn sensory science symposium, 2013, Rio de Janeiro, BR
1st Food Structure and Functionality Forum Symposium, 2014, Amsterdam, NL
3rd International Conference on Food oral processing, 2014, Wageningen, NL
1st Asian Sensory and Consumer Research Symposium (SenseAsia), 2014, Singapore, SG
11th International Congress on Engineering and Food, 2015, Quebec, CA
6th International Symposium on Delivery of Functionality in Complex Food Systems, 2015, Paris, FR

General courses

VLAG PhD week, 2012, Baarlo, NL
Longitudinal data analysis, 2013, Wageningen, NL
Communication with the Media and the General Public, 2013, Wageningen, NL
Scientific writing, 2013, Wageningen, NL
Teaching and supervising master students, 2012, Wageningen, NL
Mobilising your scientific network, 2014, Wageningen, NL
Techniques of writing and presenting a scientific paper, 2014, Wageningen, NL
Career Perspective, 2014, Wageningen, NL
European Nutrition Leadership Platform essentials edition, 2015, Luxembourg, LU

Optional courses and activities

Preparation of research proposal, 2011
Participated in the PhD study tour to the UK, 2012
Participated and organised the PhD study tour to Singapore and Thailand, 2014

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Colophon

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