Chew on it

Consumer and food characteristics
steer oral processing behavior
and sensory perception

Monica G. Aguayo-Mendoza

Propositions

1. Elderly swallow a more broken-down food bolus than young consumers. (*this thesis*)
2. Adding particles to foods to steer oral processing behavior is only effective when texture contrast is perceivable. (this thesis)
3. Nutrition warning labels on food packages are effective to combat obesity in adults but not in children. (Basto-Abreu A. et al. (2020) Predicting obesity reduction after implementing warning labels in Mexico: A modeling study. PLoS Medicine 17(7): e1003221).
4. Sustainability performance should be a key element in all scientific grant proposals.
5. Parents making use of the “cry it out” sleep training method should reconsider parenthood as a whole.
6. Home office efficiency depends on social constructs.

Propositions belonging to the PhD thesis entitled

Chew on it:

Consumer and food characteristics steer oral processing behavior and sensory perception

Monica Gabriela Aguayo Mendoza
Wageningen, 23rd November 2020

Chew on it:

Consumer and food characteristics steer oral processing behavior and sensory perception

Monica Gabriela Aguayo Mendoza

Thesis committee

Promotors

Prof. Dr Markus Stieger

Personal chair, Sensory Science and Eating behaviour & Food Quality and Design
Wageningen University & Research

Prof. Dr Erik van der Linden

Professor of Physics and Physical Chemistry of Foods
Wageningen University & Research

Co-promotor

Dr Betina Piqueras-Fiszman

Associate professor, Marketing and Consumer Behavior
Wageningen University & Research

Other members

Prof. Dr Edith J.M. Feskens, Wageningen University & Research

Dr Andrew Rosenthal, University of Nottingham, United Kingdom

Dr Laura Laguna, Institute of Agrochemistry and Food Technology, Spain

Dr Nicoletta Pellegrini, University of Udine, Italy

This thesis was conducted under the auspices of the Graduate School VLAG (Advanced studies in Food Technology, Agrobiotechnology, Nutrition and Health Sciences).

Chew on it:

Consumer and food characteristics steer oral processing behavior and sensory perception

Monica Gabriela Aguayo Mendoza

Thesis

submitted in fulfilment of the requirements for the degree of doctor

at Wageningen University

by the authority of the Rector Magnificus,

Prof. Dr A.P.J. Mol,

in the presence of the

Thesis Committee appointed by the Academic Board

to be defended in public

on Monday 23 November 2020

at 1:30 p.m. in the Aula.

Monica Gabriela Aguayo Mendoza

Chew on it: Consumer and food characteristics steer oral processing behavior and sensory perception

240 pages.

PhD thesis, Wageningen University, Wageningen, The Netherlands (2020)

With references, with summary in English

ISBN: 978-94-6395-487-7

DOI: 10.18174/528478

*"Promise me you'll always remember that
you are braver than you believe,
stronger than you seem and
smarter than you think"
– Christopher Robin to Winnie the Pooh*

Carter Crocker

Contents

Chapter 1.	General Introduction	9
Chapter 2.	Capturing the impact of oral processing behavior on consumption time and dynamic sensory perception of ice creams differing in hardness	21
Chapter 3.	Oral processing behavior of drinkable, spoonable and chewable foods is primarily determined by rheological and mechanical food properties	47
Chapter 4.	Age, gender, ethnicity and eating capability influence oral processing behavior of liquid, semi-solid and solid foods differently	71
Chapter 5.	Adaptation in oral processing behavior of consumers differing in age, gender and ethnicity leads to differences in bolus properties but not in dynamic texture perception of sausages	95
Chapter 6.	How addition of peach gel particles to yogurt affects oral behavior, sensory perception and liking of consumers differing in age	119
Chapter 7.	Linking oral processing behavior to bolus properties and dynamic sensory perception of processed cheeses with bell pepper pieces	149
Chapter 8.	General discussion	177
	References	199
	Summary	223
	Acknowledgements	229
	About the author	235

1

General introduction

In recent years, food oral processing has arisen as a multidisciplinary research field that develops understanding of the multifactorial aspects of food enjoyment and consumption behavior ^{1,2}. Although food oral processing represents only a fraction of the time of the eating and digestion process, it is the phase that contributes considerably to the sensory experience of foods and the amount of food consumed. The main goal of oral processing is to convert foods into a bolus with sufficient structural breakdown that can be safely swallowed ³. However, knowledge of the way we manipulate food in our mouth and the fate of it can help to design food products that are goal-specific (e.g. control eating rate to control food intake) and population-specific (e.g. elderly consumers). Because of this, food scientists and nutritionists have recently shown an increased interest in oral processing research to bridge the knowledge between food structure, sensory perception and energy intake. This may facilitate the creation of food products that are nutritive and palatable for particular consumer groups ⁴.

1.1. The *triad* of food oral processing

Food oral processing refers to the oral manipulations of food upon ingestion (i.e. oral behavior) leading to the production of a bolus that is safe to swallow. During the structural transformation of foods into bolus, the properties of the bolus are continuously sensed and give rise to dynamics in sensory perception ⁵.

Though all ingested foods undergo a conversion into a safe to swallow bolus, the oral behavior required varies depending on the initial food state ⁶. Liquid foods do not require chewing, are drunk and accumulated in the oral cavity; after certain volume, the tongue rises immediately towards the palate and propels the liquid bolus in direction to the pharynx to be swallowed. This process typically takes less than 10s and is therefore shorter compared to semi-solid or solid foods. Semi-solid foods take more time to be orally processed. They are primarily squeezed between tongue and palate, mixed with saliva and then the food bolus is transported from the front of the mouth to the pharynx and swallowed. Finally, solid foods present a more complex and diverse oral behavior. Solid foods are ingested and transported to the occlusal surface of the molars to be comminuted, mixed with saliva while liquids are released from the food. After the food bolus is sufficiently broken down and lubricated, the bolus can be further squeezed between

tongue and palate before it is moved to the pharynx and swallowed ⁷. This process involves different jaw and tongue movements and takes typically between 10 and 45s.

In 1988, Hutchings and Lillford illustrated the breakdown pathway of various foods over consumption time ³. They emphasized the changes in food structure upon mechanical breakdown by oral processing and degree of lubrication produced by saliva and food moisture. At the endpoint of the pathways, the food bolus reached properties so that it can be swallowed safely. One of the most common ways to study bolus properties is through the collection of expectorated boli, followed by a series of physicochemical analyzes. The specific methods used to analyze bolus properties are mainly determined by the initial structure of the food. Bolus from solid foods are described in terms of physical structure, rheological and mechanical properties, bolus particle size distribution and moisture content. Bolus from semi-solid and liquid foods are primarily described in terms of physical structure, composition, tribological properties, interaction with saliva and/or oral surfaces ⁸. The bolus properties at the end of consumption time have been studied to characterize the properties that a bolus should display in order to stimulate the swallowing response. However, the physical characteristics of a bolus triggering a swallowing have not been fully identified yet. The swallow response has been suggested to depend on two thresholds, the particle size and moisture content. It has been suggested that the swallowing threshold is uniform across foods, so that regardless of the product characteristics boli with similar physicochemical properties are swallowed ⁹⁻¹¹. Nonetheless, these swallowing thresholds may vary considerably between consumers.

The evolution of bolus properties during oral processing from the first bite to the moment of swallowing (at specific time points representing early, middle and late stages of mastication) has been related to dynamic changes in bolus characteristics to dynamic sensory perception ¹²⁻¹⁴. As a result of the continuous changes of the food bolus structure throughout oral processing, sensory perception also changes dynamically. The dynamic nature of perception is reflected on the onset and offset of the attributes during the eating process. Therefore, studying sensory perception in relation to oral processing allows to better understand the underlying structural transitions that trigger specific (texture) sensations ¹⁵⁻¹⁷.

It is reasonable to assume that oral behavior impacts bolus formation and dynamic sensory perception. Oral processing induces food breakdown and bolus formation. Changes in bolus structure are sensed in the oral cavity. Signals are generated as a feedback mechanism to adjust oral behavior until a safe to swallow bolus is formed (Figure 1.1). Besides, oral processing behavior may impact sensory perception, for instance an increased number of chews can increase flavor release and perception. Vice versa, perception of specific sensory attributes can modify oral behavior, for instance bitter taste perception can decrease consumption time to reduce the time the food is sensed in the mouth ¹⁸.

Figure 1.1. The *triad* of food oral processing. Relationships and feedback mechanisms occurring between oral behavior, bolus properties and sensory perception.

As stated by Hutchings and Lillford, breakdown pathways are different for each food and each individual oral behavior ³. This was later corroborated by Rosenthal and Share when they demonstrated that products such as peanuts, peanut meal and peanut butter, which differ in starting structure, follow different breakdown pathways ¹⁹. Additionally, different strategies used by consumers to manipulate the food inside the mouth may consequently

lead to different bolus properties which may explain inter-individual differences in sensory perception ²⁰. Tracking the transformations of the bolus throughout oral processing until the swallowing point is therefore essential to understand the mechanisms that underlie texture perception ²¹. Further comprehensions into the relation between food structure, dynamic food oral breakdown and the dynamics of sensory perception can be advantageous for designing foods with tailored sensory profiles or targeted towards specific consumer groups ²². Despite major efforts being made in the last decades, it still remains unclear how specific consumer characteristics and food properties contribute to oral processing behavior and to what extent differences in oral behavior between consumers can explain inter-individual differences in sensory perception.

1.2. Variability in oral processing related to the consumer

The variability in oral processing can derive from specific consumer characteristics such as age, gender, and ethnicity ²³. Those differences in oral processing can be partly attributed to anatomical and physiological among consumers ^{1,5}. For instance, ageing decreases muscle mass, muscle activity, bite force, tongue pressure, oral volume and chewing efficiency ^{24–29}. These physiological changes lead elderly consumers to modify their oral behavior of solid foods by increasing consumption time and number of chews ^{27,30,31}. Despite the adaptation in oral processing with age, some studies reported that elderly consumers are less efficient in generating a safe to swallow bolus so that they swallow less comminuted boli than young consumers ³². However, contrasting results were found in another study which reported that elderly produce a more comminuted bolus than young consumers ³³.

Gender is another aspect that influences oral physiology. Males have higher maximum bite force, muscle activity, salivary flow, and lip-cheek strength than females ^{29,34–36}. These oral physiological differences may be advantageous for males so that they are more efficient to orally process foods and to produce boli ready to be swallow. Several studies demonstrated that males consume solid foods in a shorter period of time than females, and also consume foods with larger bite sizes and at higher eating rates than females ^{31,37,38}. On the other hand, other studies showed that females chew solid foods for shorter time than males, consequently producing harder and less homogeneous boli than males ³⁹. While clear

differences in oral physiology between males and females and differences in oral behavior between genders have been reported, most studies comparing oral processing between genders did not explore bolus properties. Consequently, it is not known how differences in oral behavior between males and females effect bolus properties and how potential differences in bolus properties between genders contribute to differences in sensory perception.

Another possible source of variability in oral processing might come from differences in ethnicity. It has been shown that facial dimensions like face length and width as well as lip dimensions differ between American-Caucasian, African-American, Hispanic and Asian ⁴⁰. Furthermore, ethnicity has been considered as one of the most relevant factors affecting oral structures such as vocal tract length and oral cavity volume among others ⁴¹. Overall, American-Caucasian have smaller oral volume than Chinese-Asian and African-American, and Chinese-Asian have larger vocal tract than American-Caucasian and African-American ⁴¹. The maximum chewing force exerted by Eskimos has been shown to be larger than the one applied by American-Caucasian ⁴². It is unknown how these (oral) physiological differences between different ethnicities impact food oral processing.

1.3. Variability in oral processing related to the food

In addition to consumer characteristics, food physical properties have a determining role in the way food is manipulated in the mouth. Oral processing behavior is very sensitive to structural differences between and within food categories ⁴³.

For homogeneous solid foods, several mechanical properties, such as food fracture stress, fracture strain and adhesiveness influence oral processing behavior ^{44–49}. From those properties, fracture stress is the most commonly explored. It has been shown that increasing fracture stress of model foods such as agar, carrageenan and gelatin gels, is associated with prolonged consumption time, increased number of chews, muscle activity and jaw opening amplitude ^{44,46,47,49}. Although model foods are convenient to isolate variables that may affect oral processing, they do not necessarily represent foods consumed daily. To overcome this issue, some studies characterized oral processing behavior of solid foods like cheese, nuts, meat and bread ^{50–53}. These studies demonstrated that real foods

exhibit a broad diversity in oral processing. However, they did not characterize the physical properties of the foods, thus no comprehensive knowledge between food properties and oral behavior is available. Apart from solid foods, only few studies examined the influence of rheological properties of liquids and semi-solid foods on oral processing behavior, showing that for a predetermined bite size, apparent shear viscosity is positively correlated with consumption time ⁵⁴. Nevertheless, under more realistic eating conditions, rheological properties of liquid and semi-solid foods may also affect bite size and consequently oral behavior may be influenced differently.

Foods consumed on daily basis differ in physical state and may be composed of several components. Foods that are composed of two or more components that differ in composition or physical state are termed heterogeneous foods. Examples of heterogeneous foods include yogurts with fruit pieces, soups with vegetables pieces, chocolates with whole nuts etc. While many foods that are consumed daily are heterogeneous foods, the majority of studies so far focused on investigating oral processing in relation to sensory perception of homogeneous foods. Our understanding of oral processing and sensory perception of heterogeneous foods is limited. With regards to heterogeneous solid foods, it has been shown that the properties of the food used as matrix influences oral behavior whereas the properties of the embedded particles do not ⁵⁵. However, how the properties of the matrix or particles influence oral behavior may dependent on whether texture contrast is perceived or not. Therefore, oral behavior observed among heterogeneous solids may differ from the behavior exhibited in other food categories.

Food physical properties also influence bolus properties. It has been shown that in homogeneous solids, the harder the food, the smaller the bolus particle size at the swallowing point is ^{9,56}. The amount of saliva incorporated in the bolus can be influenced by dry matter and fat content of the food consumed ^{10,57–59}. Furthermore, fracture stress has been associated with bolus hardness ¹². Initial food structure and the continuous transformation of bolus properties influences sensory perception ²³. Some examples of the relations between texture perception and bolus properties showed that bolus hardness is positively correlated with firmness perception and bolus particle size is associated with

graininess and powdery sensations^{12,60}. However, a deeper understanding of how bolus properties give rise to different sensory attributes is still lacking.

1.4. Rationale and outline of the thesis

A better understanding of differences in oral processing behavior among consumer segments can contribute to make steps towards a more tailored food production. Further research should clarify how ageing induces changes in bolus properties and how differences in bolus properties impact dynamic sensory perception. Additionally, research is needed to explain the effect of gender on oral behavior and its connection to bolus properties and dynamic texture perception. Similarly, up to date there is no information available how ethnicity influences oral behavior, bolus properties and dynamic texture perception.

In comparison to the knowledge on oral processing behavior of solid foods, little is known about the effect of consumer characteristics on oral processing of other food categories such as semi-solid and liquid foods. To steer oral behavior through modifications of food structure, a better understanding of how specific physicochemical and mechanical food properties influence oral processing behavior is needed. It is necessary to characterize the rheological and mechanical properties of commercially available foods covering a wide range of textures, including homogeneous and heterogeneous foods, and to characterize their oral behaviors.

The aim of the research described in this thesis was to determine the effect of food properties and consumer characteristics on oral processing behavior, bolus properties and sensory perception of foods. Figure 1.2 provides an overview of the conceptual framework of this thesis.

Chapter 2 compares introspective and observational methodologies (questionnaire and video recordings) to capture and categorize oral processing behavior(s) applied by young consumers during ice cream consumption. The impact of oral processing behavior on dynamic sensory perception of ice creams differing in hardness is quantified.

Chapter 3 presents the influence of rheological and mechanical food properties of liquid, semi-solid and solid foods on oral processing behavior. The effect of liking, familiarity and

frequency of consumption on oral behavior of these foods is discussed as well. **Chapter 4** describes the influence of consumer characteristics such as age, gender and ethnicity on oral processing behavior of the same liquid, semi-solid and solid foods described in **chapter 3**.

In **chapter 5** a predetermined bite size of one food (sausage) was used to investigate whether the observed differences on oral behavior shown in **chapter 4**, have an effect on bolus properties and dynamic sensory perception of different consumer groups.

The study described in **chapter 6** determined how the addition of peach gel particles differing in physicochemical properties to yogurt influences oral processing behavior, sensory perception and liking of consumers differing in age.

Chapter 7 extends the approach of **chapter 6** and includes different heterogeneous foods with systematic variations of matrix and particle properties. The objective of this study was to determine the influence of physicochemical properties of heterogeneous foods on oral processing, bolus properties and dynamic sensory perception.

Finally, **chapter 8** provides a general discussion of the findings of this thesis. Findings are discussed in relation to literature, possible applications are discussed and an outlook for future research is provided.

Figure 1.2. Conceptual framework of this thesis. Numbers in circles indicate chapter number.

2

Capturing the impact of oral processing behavior on consumption time and dynamic sensory perception of ice creams differing in hardness

This chapter has been published as:

Doyennette, M.* , Aguayo-Mendoza, M. G.* , Williamson, A.-M., Martins, S. I. F. S., Stieger, M. Capturing the impact of oral processing behaviour on consumption time and dynamic sensory perception of ice creams differing in hardness. *Food Quality and Preference* 103721 (2019). (*The authors contributed equally to this work)

Abstract

Little is known about the oral processing behavior of ice creams for which the quantification of oral manipulations remains challenging. The impact of oral processing behavior on dynamic sensory perception of ice creams has not been reported previously, although ice creams are anecdotally known to be consumed following different oral processing strategies. The aims of the study were (1) to compare different methodologies to characterize oral behaviors applied during consumption of ice cream, and (2) to understand how oral processing behavior influences dynamic sensory perception of ice creams. Oral processing behavior of ice creams was characterized by self-reporting and video recording of $n=103$ consumers. Most consumers applied either tongue movements or combined tongue and jaw oral behaviors. The video recording was clearly better than self-reporting in capturing the actually displayed eating behavior of ice creams. Consumption time was prolonged considerably when ice cream hardness increased or when oral behavior was changed during Temporal Dominance of Sensations (TDS) evaluations. When ice creams were consumed by letting them melt in mouth, dominance of sweetness and firmness were significantly prolonged. When ice creams were consumed by chewing, dominance of fruity aroma and coldness were significantly prolonged. We conclude that (1) eating behavior of ice creams is captured better by video recordings than self-reporting and that (2) oral processing behavior considerably changes dynamic texture and flavor perception of ice creams. This highlights the importance of controlling oral processing behavior when quantifying sensory properties of ice creams.

2.1. Introduction

Oral processing of foods and beverages consists of a complex set of operations occurring in-mouth, which include bolus lubrication, particle size reduction, transportation and temperature modification. These operations contribute to form a bolus suitable to swallow, which impacts sensory perception^{52,61}. Foods can be classified into three main categories: liquids, semi-solids and solids⁶², and each category requires different oral manipulations. Ice creams belong to the category of semi-solid foods that are mainly processed with compressive movements between tongue and palate with or without additional chewing activity before swallowing. Ice creams are anecdotally known to be consumed following different oral processing strategies such as licking, smooshing or biting. This popular food product is well known to be consumed through the entire age span, from infancy up to elderly people so that oral capacity⁶³ and therefore eating styles varies widely between consumers.

Characterizing food oral manipulation is possible via a wide range of methods such as instrumental, observational, or introspective methodologies^{64,65}. Most characterizations have been done for solid, chewable foods. Little is known about the oral processing behavior of semi-solid foods⁶⁶. This could be partly explained by the fact that capturing oral processing behavior of semi-solid foods remains a difficult task. Techniques such as electromyography cannot be properly used due to little muscle activity and limited mandibular movement during oral processing of semi-solid foods⁶⁷. Monitoring tongue movements could be of great value but remains quite invasive. Video recordings could be a good alternative and this technique is being more and more used to monitor food oral processing behavior^{68–70}. However, it is time and resource consuming. Self-reporting of preferred mouth behavior using questionnaires and visual supports has been suggested by Jeltema et al. as a simple and cost effective approach to quantify oral behavior^{71–73}.

Variations in natural oral processing behavior among consumers and its impact on sensory perception have been reported mainly for solid foods such as chocolates and sausages. For example, Carvalho-da-Silva found that subjects eating chocolates could be classified as ‘fast chewers’, ‘thorough chewers’ or ‘suckers’⁷⁴. The authors reported that eating behavior did not affect the discrimination of mouth-coating perception between chocolates. Devezeaux

investigated the impact of oral processing behavior on dynamic sensory perception of sausages⁷⁵. Two groups of subjects varying in their natural eating duration for a controlled portion size of sausages were studied. 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. This demonstrates that oral processing behavior can impact dynamic sensory perception of solid foods. Anecdotally, it is known that ice creams allow consumers to apply a variety of oral behaviors during consumption such as licking, chewing, melting, sucking, smooching and any combinations thereof. It is however unknown whether consumers naturally apply more than one eating behavior during the course of consumption to adapt to the dynamic properties of the ice cream and how oral processing behavior impacts sensory perception of ice creams. To summarize, little is known about the oral processing behavior of ice creams for which the quantification of oral manipulations remains challenging. The impact of oral processing behavior on dynamic sensory perception of ice creams has not been reported previously, although ice creams are known to be consumed following different oral processing strategies.

In addition to that, ice cream products can have a wide range of textural properties. Some products can be hard and require the application of force to scoop from a carton, whereas others are soft and easily extruded from an ice cream dispensing machine to form swirls on an ice cream cone. Ice cream products have the singularity of being eaten cold. Temperature has been reported to impact flavor release and sweetness perception^{76–82}, so it is of interest for the ice cream industry to understand the relative impact of eating behavior and ice cream characteristics on the sensory experience of the consumer. Based on a better understanding of the relationships between ice cream texture, eating behavior and sensory perception, methodological recommendations can be given for a more realistic assessment of ice cream products by the food industry. This knowledge could potentially help ice cream makers to develop products targeted towards specific consumer groups or targeted towards consumers displaying preferences for specific oral behaviors.

The aims of the study were (1) to compare different methodologies to characterize oral behaviors applied during consumption of ice cream, and (2) to understand how oral

processing behavior influences dynamic sensory perception of ice creams. This study was divided into two parts. In part 1, consumers were classified based on their natural oral processing behavior displayed during consumption of ice creams. Video recordings and self-reported questionnaires were compared to quantify oral processing behavior. Based on the outcomes of part 1, a sub-set of subjects were instructed to apply specific oral processing behaviors (natural, melting or chewing) during TDS evaluations of ice creams (part 2). The impact of oral processing behavior on consumption time and dynamic sensory perception were quantified for ice creams varying in hardness.

2.2. Materials and methods

2.2.1. Part 1: Oral behavior characterization

Participant selection

103 participants (75 female and 28 male) were recruited from Wageningen University and surroundings through advertising in social media. Participants age was between 18 and 30 years, were non-smokers, and had no tooth sensitivity and did not wear any dental braces. The vast majority of participants were students of Wageningen University. All participants were provided with information about the study and a written consent was obtained for the video recording procedure and the usage of personal information.

Sample preparation

Commercial vanilla ice cream (Hertog®, Unilever, The Netherlands) was purchased from a local retailer and stored at -18°C. All ice creams were purchased the same day from the same store. Each participant was provided with a sample of 35g of vanilla ice cream (Hertog®, Unilever, The Netherlands) placed in a Styrofoam cup and served at -18°C with a plastic tablespoon.

Video recording procedure

Videos were recorded in sensory booths isolated from external noise, odors, and any other distraction. The camera was positioned at approximately 50 cm distance from the face of the participant; close enough to take a complete picture of the face without being a distraction or discomfort to the participant while eating the ice cream. The participants

were instructed to maintain their head straight facing the camera, and not to block their mouth or face with their hand while eating the ice cream.

Participants were instructed to take one spoon of ice cream and to consume it as they would commonly do and to indicate the swallowing moment by raising a hand. This procedure was followed three times, so that participants consumed three consecutive spoons of ice cream from the same cup. The remaining ice cream was collected and weighed to determine the mass of ice cream consumed. Average bite size per spoon was determined by calculating the difference between initial and final weight of ice cream divided by three. Consumption time per participant and spoon was obtained from the video recordings. Consumption time was defined as the time period starting with the moment when participants put the spoon into the mouth and ending with the moment when participants indicated the swallowing point by raising their hand.

The videos were further analyzed. For the purpose of this study on ice cream, each participant was classified as follows into one of four oral behaviors categories. The classification in oral behavioral categories was inspired by the work of Jeltrema⁷¹:

- Chewers: when participants mainly moved the jaw in a vertical plane, up and down, during consumption.
- Tonguers: when participants mainly moved the jaw in a horizontal plane, making movements from left to right or front to back.
- Melters: when participants did not show any clear movement of the jaw during the consumption of the ice cream.
- Combined: when two or more of the above oral behaviors were used, participants were classified as combined.

The category “Suckers” used during the self-reporting procedure (see next section) was excluded during the analysis of video recordings as it was impossible to classify participants within this category by only observing the jaw movements. All video recordings were analyzed independently by two researchers, whenever agreement was not met, the video recordings were watched by both researchers and reclassified.

Self-reporting procedure

After the video recordings, participants were asked to self-report the oral processing behavior that they used to eat the ice cream. Participants were allowed to select one or multiple options. This assessment was done using a multiple-choice questionnaire that described different oral processing behaviors (Table 2.1).

Table 2.1. Questionnaire to self-assess oral behavior of ice cream consumption.

How did you consume the ice cream?	
☐	I used my teeth to bite into the ice cream and chewed on it.
☐	I used my tongue to push the ice cream against my palate and made various movements with my tongue when consuming the ice cream.
☐	I sucked on the ice cream.
☐	I let the ice cream melt on my tongue, moved my tongue very little or not at all and swallowed the ice cream.

2.2.2. Part 2: Sensory evaluation by temporal dominance of sensations

Participant selection

N=22 participants (14 females and 8 males) from part 1 of this study with an average age of 23 ± 2.5 years were invited to participate in the sensory evaluation (TDS). All participants were students of Wageningen University. Further selection criteria were that participants liked ice cream and consumed ice cream regularly, that is at least twice per month. All participants self-reported to have normal taste and smell capabilities. Written informed consent was obtained from all participants. Subjects were reimbursed for their participation.

Ice cream preparation

Two ice creams differing in hardness were produced in blocks of 200g by Unilever (Colworth Centre, UK). Differences in ice cream hardness were obtained by modifying the ice cream formulations. The hardness of ice creams was quantified using a texture analyzer (Stable Microsystems). A penetration test was performed with a 4mm diameter probe. The peak probe force required to reach a penetration depth of 20mm was measured at -18°C . The values obtained were 2.4 N for the low hardness ice cream and 19.6 N for the high hardness

ice cream. While ice cream hardness differed between samples by approximately 8x fold, the hardness of both ice creams was in the range of commercially available ice creams. The ice creams differing in hardness were similar in color, appearance and fruity flavor. For sensory assessment, samples of 5g were placed into Styrofoam cups labelled with a three-digit code, served at -18°C and provided monadically in randomized order.

TDS attribute selection

The study was conducted in English since participants were international. All instructions provided to the participants, the TDS attributes and their definitions were provided in English. Seven attributes describing taste, flavor and texture were chosen based on previous quantitative descriptive analyses of comparable ice creams^{83–87} and based on a discussion with experts for sensory evaluation of ice creams. The definitions of attributes are presented in Table 2.2.

TDS methodology

Training sessions

Two training sessions of 90 min were conducted. During the first session, the attribute list and definitions were presented to the participants. References for training were used for sweetness, smoothness, fruitiness and iciness. Milk with the same concentration of the aroma compounds as used in the ice creams was used as reference for fruitiness. A sucrose solution was provided as reference for sweetness. Crystals of sugar were given as reference to illustrate the texture of ice crystals. Spread cheese was used as reference to illustrate smoothness. The rest of the attributes were explained without providing reference samples. We acknowledge that not providing references for the three other sensory attributes might have introduced a bias in the attribute selection. However, the outcome of our study (see section 2.3.3) suggests that subjects were not biased as several attributes were selected with high level of agreement between participants for which no references were provided.

The next step during the first session was to familiarize the participants with the instructions for the three oral processing protocols selected:

- natural as eating the ice cream normally
- melting as letting the ice cream melt in the mouth without any tongue movements
- chewing as masticating the ice creams using the teeth.

Table 2.2. Attributes and definitions used in TDS evaluation of ice creams.

Attribute	Definition
Fruitiness	Aroma perception related to fruity notes perceived from a tailor-made flavor cocktail
Sweetness	Sweet perception evaluated in mouth during eating
Chewiness	Gummy sensation associated with a fairly cohesive substance that could almost be chewed
Iciness	Feeling of ice crystals in the mouth
Smoothness	Soft and uniform texture, no coarse or rough texture is detected
Coldness	Feeling of cold sensation in the mouth
Firmness	Amount of force required by the tongue to flatten the ice cream against the palate

Melting and chewing were selected from part 1 of the study as oral behaviors for part 2. While those oral behaviors do not necessarily represent the most commonly observed oral behavior when eating ice creams (see section 2.3.1), those oral behaviors reflect the largest differences in oral processing behavior of ice creams and were hence selected for part 2 of the study. Finally, the concept of temporality of sensations was introduced and the dominant sensation was explained as “the sensation that triggers the most attention at a point in time”⁸⁸.

The second session started with familiarization with the TDS methodology. The participants were provided with a sample of ice cream and instructed to perform a specific oral processing protocol while performing the TDS evaluation. This session allowed the participants to get familiar with the TDS methodology, the three oral processing protocols to be used during TDS evaluation (natural, melting and chewing) and to solve any remaining question.

Evaluation sessions

After the two training sessions, participants attended three sessions of 60 min. Each participant undertook TDS evaluations of both ice creams with all three types of oral

processing protocols. Per subject and session only one oral processing protocol was used. In every session, each participant assessed both ice creams in duplicate in a randomized order while applying one of the three oral processing protocols: natural, melting or chewing. Oral processing protocols were assigned to each participant in a randomized order over the three sessions.

TDS data were collected using EyeQuestion v3.11. Attributes were presented simultaneously in random order across the panel but remained in the same order for a given panelist during the whole study. Between ice cream samples, unsalted crackers and water were provided to clean the palate. Panelists were instructed to put the sample into their mouth and click the start button to begin the evaluation. Panelists were asked to select the sensation that they perceived as dominant at that moment while applying the oral processing protocol that was assigned. Panelists were informed that they did not have to select all attributes in the list, and that they could select the same attribute several times or never select an attribute. Finally, the stop button was pushed to indicate the swallowing point.

2.2.3. Data analysis

Statistical analyses were performed using SPSS Statistics v22.0. Data are presented as mean $\pm$ SE. A p-value <0.05 was considered statistically significant.

For part 1, independent samples t-tests were conducted to compare bite size and consumption time between female and male subjects. For part 2, total consumption time for each ice cream per instructed oral processing protocol was extracted from TDS data. A two-way repeated measures ANOVA was conducted to examine the effect of oral protocol (natural, melting or chewing) and ice cream hardness (low and high) and their interaction on consumption time. Post hoc pairwise comparisons were performed using Bonferroni's adjustment.

TDS curves and TDS difference curves were analyzed as described by Pineau et al.⁸⁸. To compare dynamic sensory perception between different oral processing protocols, TDS difference curves between different oral behaviors were calculated for the same ice creams. Principal Component Analysis (PCA) was performed on the standardized TDS time

data to obtain sensory trajectories of the two ice creams evaluated with the natural oral processing protocol. Ten time points were highlighted on the PCA plot, each point representing 10% of the consumption time as described by Lenfant ⁸⁹.

2.3. Results

2.3.1. Bite size, consumption time and oral processing behavior of ice cream

The average bite size per spoon of ice cream (Hertog[®]) was 4.2 ± 0.2 g for $n=103$ participants. The bite size was significantly different between males and females ($t(100)=-2.34$, $p=0.021$). Males had a significantly larger bite size (5.1 ± 0.2 g) than females (3.9 ± 0.4 g). The average consumption time per spoon of ice cream (Hertog[®]) was 11.5 ± 0.7 s and was not significantly different between males (11.4 ± 0.8 s) and females (11.6 ± 0.6 s) ($t(101)=0.139$, $p=0.062$).

Frequency of classification of self-reported oral processing behavior of ice cream (Hertog[®]) and frequency of classification of oral processing behavior based on analysis of video recordings are summarized in Table 2.3. It can be observed that for both self-reported and observed oral behavior, the two most frequent behaviors, accounting for 76.7% of all consumers were tonguers and combined behavior. Chewers only accounted for 13.6% (self-reported) and 21.4% of consumers (video recording analysis), respectively. However, we emphasize that 49.5% of the participants classified themselves using the multiple-choice questionnaire in a different category from the one observed in the video recordings.

For the second part of the study, we decided to focus on three oral behaviors: natural oral behavior, as well as two imposed oral behaviors (chewing and melting). Despite that the oral behaviors melting and chewing were not the most frequently observed oral behaviors when consuming ice creams, those oral behaviors were selected since they represent the two most extreme oral behaviors in terms of movement complexity.

2.3.1. Influence of oral processing behavior and ice cream hardness on consumption time during TDS evaluation

Table 2.4 summarizes ice cream consumption time during TDS evaluation following different oral processing protocols (chewing, natural and melting) for two ice creams differing in hardness. There was a significant effect of oral processing behavior on

consumption time [$F(1.2, 26.6)=33.64, p<.001$]. Chewing required the shortest consumption time, followed by the natural oral processing protocol, and lastly the melting protocol showed the longest consumption time. By changing oral behavior from chewing to melting, consumption time of ice creams doubled. There was also a significant effect of ice cream hardness on consumption time [$F(1, 21)=82.8, p<.001$]. With increasing ice cream hardness by 8x fold, consumption time increased by 1.5x fold.

Table 2.3. Frequency of consumers' (n=103) self-reported oral processing behavior by multiple choice questionnaire and by observation of oral processing behavior through video recording analysis.

Oral behavior classification	Self-reporting (%)	Video recording (%)
Combined behavior	27.2	39.8
Tonguers	49.5	36.9
Chewers	13.6	21.4
Melters	6.8	1.9
Suckers	2.9	0.0

Table 2.4. Consumption time during TDS evaluation (n=22, duplicate) of ice creams differing in hardness and when different oral processing behavior are applied. Different superscripts identify significant differences ($p<0.05$) between oral processing protocols (capital letters) and ice cream hardness levels (lowercase).

Ice cream hardness level	Consumption time (s)	Oral behavior	Consumption time (s)
Low	20.6±1.0 ^a	Chewing	17.1±0.8 ^A
		Natural	22.6±1.4 ^B
High	29.1±1.3 ^b	Melting	34.9±2.4 ^C

2.3.2. Influence of oral processing behavior on dynamic sensory perception of ice creams differing in hardness

Typically, four sensations reached significance level during the evaluation of the two ice creams (Figure 2.1). Texture attributes such as smoothness and coldness were in general the dominant sensations during the first third of consumption time whereas in the last two thirds of consumption time, taste and aroma attributes such as sweetness and fruity were perceived as dominant sensations. This chronology of the occurrence of dominant

sensations was observed consistently for the two ice creams and all oral processing protocols (chewing, natural, and melting).

TDS difference curves comparing the dynamic sensory perception of ice creams differing in hardness when applying different oral processing behavior protocols are shown in Figure 2.2. For clarity reasons, only the two most different instructed oral processing behaviors are compared: melting and chewing.

In the low hardness ice cream, fruity aroma was significantly more dominant when chewing was applied, specifically in the middle of the consumption time. Additionally, sweetness was less dominant compared to when letting the ice cream melt in mouth (Figure 2.2.A).

In the high hardness ice cream, coldness was significantly more dominant when chewing was applied. Oppositely, firmness was significantly more dominant when the ice cream was left to melt in the mouth (Figure 2.2.B).

2.3.1. Sensory trajectories of ice creams differing in hardness

The sensory trajectories of the two ice creams for the natural oral processing behavior are shown in Figure 2.3.

The first two principal components account for 85.18% of the variance. Firmness and coldness are positively correlated in the first dimension. Sweetness and fruity aroma are also positively correlated in the first dimension but negatively correlated to firmness and coldness. In the second dimension, smoothness is negatively correlated to firmness. Differences were observed between the ice cream products. Generally, the sensory trajectories differed mainly along the second component, from firm to smooth, with high hardness ice cream being firm and low hardness ice cream being towards smooth.

The low hardness ice cream was positioned during the entire consumption time in the upper part of the PCA plot, which is mainly described by smoothness. It remained in the same position for the first half of consumption time and then moved towards sweet and fruity sensations during the second half of consumption time. The high hardness ice cream remained close to firmness and coldness for almost 85% of the consumption time, moving towards the sweet and fruity attributes before swallowing.

Figure 2.1. TDS curves for two ice creams differing in hardness (LH=Low hardness, HH=High hardness) assessed by n=22 subjects in duplicate while applying specific oral processing behaviors (chewing, natural and melting).

Figure 2.2. TDS difference curves comparing oral processing behavior protocols. Chewing oral behavior is always shown on top and melting oral behavior in the bottom; A) low hardness ice cream, B) high hardness ice cream.

Figure 2.3. Sensory trajectories of ice creams differing in hardness evaluated during the natural oral processing protocol. Low hardness ice cream is depicted in blue and high hardness ice cream in red.

2.4. Discussion

2.4.1. Video recordings and self-assessment of oral processing behavior of ice cream

In the present study, we used video recordings and self-assessment to capture and categorize the diversity of natural oral behaviors that can be applied during ice cream

consumption. Overall, the data from our study highlight that oral processing behavior can be clustered between subjects eating ice cream. Our data suggests that more than one third of consumers display a combination of different oral behaviors when consuming ice cream. Combined behavior was indeed the behavior observed most often during the video recording analysis (39.8%) while it was the second most self-reported behavior (27.2%). The properties of the ice cream change considerably during consumption. At the beginning, the ice cream is semi-solid and melts in mouth into a liquid during consumption, which may induce different oral behaviors. These findings highlight that simple classifications of consumers into chewers, melters etc. based on their oral processing behavior can be erroneous, since already within one food (ice cream) more than one third of consumers display combinations of different oral processing behaviors. We suggest that a classification of oral processing behavior of consumers based on eating rate (g/min) into slow and fast eaters is more objective and might be more useful to cluster consumers for their oral behavior.

The second most frequently observed oral processing behavior by video recordings was that consumers manipulated the ice cream only with their tongue (36.9%). This same behavior has been self-reported as being the most used one (49.5%). Manipulation with the tongue is the main oral behavior among semi-solid foods. This allows to distribute the food over a larger area of the oral mucosa to bring the sample to the temperature of the oral cavity and facilitates at the same time the sensory perception ⁶⁶.

Only a small fraction of consumers was classified as melters (1.9% during video recording and 9.8% with self-reporting) and suckers. The category of suckers was included in the self-report questionnaire following the categories suggested by Jeltrema ⁷¹. However, during the analysis of video recordings, it was impossible to classify participants within this category by only observing the jaw movements. Sucker is a classification that involves sucking movements with the tongue and palate, and it is mostly observed in solid foods such as caramel candies. Therefore, in a product like ice cream it was almost impossible to differentiate suckers from melters, and the suckers category was therefore eliminated from the video analysis. The little proportion of melters (and suckers) compared to the other oral behaviors applied to the ice cream can be explained by the necessity to apply a minimum

of movements to help quickly warm up the ice cream product by spreading the coldness across the mouth. In addition, de Wijk et al.⁶¹ found that the sensation of flavors and mouthfeel attributes requires at least some tongue movement. These manipulations mix food with saliva and thereby enhance mechanical and chemical breakdown, as well as help to position the food relative to the sense organs. Sucking and allowing the ice cream to melt does not induce lots of sensorial experience triggering, which might explain why they were not the most preferred way to process ice cream.

The fact that different types of oral behaviors were found in our study to process ice cream is in agreement with previous studies. Engelen classified people according to their oral processing behavior of custards and mayonnaise (semi-solid foods)⁶². Four different eating styles were described depending on how individuals used their tongue, palate and teeth to process food: simple (50%), tongue (13%), taster (20%) and manipulator (17%). Jeltrema⁷¹ suggested that individuals have a preferred way to manipulate foods in their mouths. Four mouth behavior groups have been suggested: chewers (43%), crunchers (33%), smooshers (16%) and suckers (8%). Crunchers and chewers like to use their teeth to break down foods, while suckers and smooshers prefer to manipulate food between the tongue and roof of the mouth. Recently, it was shown that for a variety of solid, chewable foods only small differences in chewing parameters quantified using video recordings were observed in consumers belonging to different mouth behavior groups⁹⁰. It was concluded that the membership to a mouth behavior group could not be predicted based on the observed chewing sequence and jaw movement parameters extracted from video recordings which captured the oral processing behavior of consumers actually eating the solid foods. In the present study, the difference that we observed compared to previous studies is that one of the most frequently observed categories of oral behaviors is a combination of multiple behaviors to orally process the ice cream. Therefore, a classification based on self-assessment of oral processing behavior of a variety of foods into one category of preferred mouth behavior might be an oversimplification. Most likely, consumers adopt an oral processing style which is optimized for them and balanced in terms of chewing efficiency and perception. For products like ice cream or chocolate that melt in the mouth, a more

complex eating behavior may be used (such as chewing at the start and letting melt at the end).

It should be noted that the vast majority of participants in this study were students. Therefore, the results of this study cannot be generalized to the overall market population of ice cream consumers. To be able to generalize the findings of the study to a general population, a broader population needs to be studied including children, adults and elderly, that is more representative of ice cream consumers. This was outside the scope of the current study.

To summarize, simple classifications of consumers into mouth behavior groups can be erroneous, since already within one food (ice cream) more than one third of consumers display combinations of different oral processing behaviors. We suggest that a classification of oral processing behavior of consumers based on eating rate (g/min) into slow and fast eaters is more objective and might be more useful to cluster consumers for their oral behavior.

We also observed that for almost half of the population, the oral behavior self-reported directly after consumption did not agree with the observed oral processing behavior. This could be explained by the fact that consumers are generally not aware of how they process foods in their mouths^{71,91}. Consumers process foods in rather unconscious and automatic ways and therefore they have little awareness of their real oral behavior. This suggests that oral behavior displayed during food consumption cannot be reliably predicted based on self-reported questionnaire assessments. The limitations of self-reporting have already been described in eating, feeding and mealtime research⁹². Among the biggest challenges of that methodology, social desirability bias and limited awareness of the behaviors asked by the participants can be mentioned⁹². Behavioral coding of videotaped eating behaviors seems to be a better alternative^{52,93}. A common methodology of coding schemes is necessary to help make progress in that field.

2.4.2. Chronology of dominant sensations

Textural attributes were perceived as dominant sensations at the beginning of consumption time whereas taste and aroma attributes were dominant sensations at the end of

consumption time. Such findings have been reported before for fish sticks and yoghurt^{94,95}. Both studies reported that textural attributes were perceived as dominant sensations during the first half of the consumption time and it was not until the second half of the consumption time that taste and aroma attributes became significantly dominant. Varela et al. investigated the influence of hydrocolloids on texture perception of ice creams⁸⁶. The results showed that attributes such as coldness and iciness, related to the presence of ice crystals, are perceived before more complex attributes like roughness, gumminess and mouth coating. de Wijk et al. have shown that temperature (coldness) requires little or no tongue movement and relatively short residence times in the mouth to be perceived^{61,66}. Contrary to that, other attributes require more oral manipulation and complex movements of the tongue to be perceived, like it is the case for taste and aroma. This is a consequence of the fact that certain deformations of the product should be done to release tastants and aroma molecules in the saliva/air from the food matrix while mechanoreceptors sense very quickly the textural attributes.

2.4.3. Impact of oral behavior on consumption time and dynamic sensory perception of ice creams

To the best of our knowledge, only two studies have used TDS methodology to quantify dynamic sensory perception of ice creams^{86,96}. Varela et al. investigated the influence of hydrocolloids on texture perception of ice creams and liking⁸⁶ while Kantono studied the impact of music on the sensory perception of ice cream⁹⁶. Varela et al. showed that ice cream composition substantially impacted dynamic sensory perception⁸⁶. None of the studies investigated the impact of ice cream properties on oral behavior. In the second part of our study, we asked participants to follow an imposed oral behavior (i.e. chewing and melting or to apply their natural eating behavior when performing a TDS assessment of ice cream differing in hardness. We did not video record subjects during the TDS evaluation to monitor oral processing behavior. However, the consumption time during the TDS evaluation differed significantly and considerably between the three oral processing protocols (Table 2.4): chewing (17s), natural (23s) and melting (35s) suggesting that subjects applied very different oral protocols during sensory evaluation of the ice creams. Based on the observed differences in consumption time during TDS and the familiarization sessions

given to the participants, we are confident that the oral protocols were followed by the subjects.

Also, we could speculate that asking panelists to adopt an oral processing style that may not be natural or familiar to them might have influenced the results of the study. However, the consumption time associated with each type of oral processing behaviors (Table 2.4) are in line with expectations and the results of part 1 of the study. Consumption time varied significantly up to 2x fold with type of oral processing behavior used to consume the ice creams. Regardless of ice cream hardness, when consumers let the ice cream melt in mouth without tongue and jaw movements (melting protocol), the consumption time was significantly longer than when consumers orally processed the ice cream as they normally do (natural protocol) which displayed a significantly longer consumption time than when consumer chewed the ice creams (chewing protocol). The destruction of ice cream structure during chewing is probably most efficient by compression movements between molars accompanied by a faster temperature increase of the ice cream due to more contact with tongue and cheeks. On the other hand, the melting protocol does not involve mouth movements but just heat transfer from mouth tissue to the ice cream. Therefore, the melting protocol may take longer time to produce an ice cream bolus that is safe to swallow in relation to its temperature and structure.

In a quantitative study with a wide variety of snack foods, Jeltema et al. found that crunchers were the fastest eaters followed by chewers, with suckers and smoothers being much slower eaters ⁷¹. Various oral processing strategies do not take the same time to process the same food product. Interestingly, consumption times observed with the natural eating protocol are intermediate between consumption times observed with the chewing and melting protocols. This is in agreement with findings of part 1 of our study, where we observed that consumers mostly used a combination of chewing and tongue movements to orally process the ice creams.

TDS curves (Figure 2.1) showed that overall fruity aroma was perceived as a dominant sensation earlier and for a longer time with the chewing protocol than with the melting protocol, especially in low hardness ice cream. This suggests that the chewing of ice creams might favor an increase in surface area generated during oral processing, which contributes

to an increased aroma release from the ice cream bolus^{97,98}. Also, the mixing and whirling between ice cream bolus and saliva during the chewing protocol might speed up the release of volatile compounds. Moreover, the opening and closing of the velum can be frequent, allowing volatile compounds to reach the aroma receptors continuously^{66,97,99}. Oppositely, during the melting protocol, the ice cream matrix changes its properties mainly due to temperature increase being the main factor contributing to aroma release¹⁰⁰. In this process, the food product remains static inside the mouth. Producing a proper food bolus takes longer time since there is no breakdown of the ice cream bolus by any action of teeth or tongue and the volatile compounds are transported by molecular diffusion. On top of that, the opening of the velum is very limited to prevent the liquid bolus flowing into the trachea, limiting the release of aroma compounds into the nasal cavity before swallowing.

As already mentioned, we acknowledge that the lack of references provided for chewiness, coldness and firmness might in principal have biased the selection behavior of the subjects. However, the effect is considered to be neglectable given that attributes firmness and coldness reached significance and a rather high levels of panel agreement for several samples suggesting that subjects selected those attributes despite the lack of reference samples provided. Dominance rates of firmness and smoothness were higher with the melting protocol. These findings might be explained by the fact that the evaluation of smoothness and firmness are mainly carried out between tongue and palate⁶⁶. During the chewing protocol, coldness was perceived as dominant for almost the whole consumption time for the high hardness ice cream whereas during the melting protocol, coldness was a dominant sensation only during the second half of consumption time. It may be possible that during melting, the contact of ice cream with the palate and tongue transfers the heat to the ice cream faster. Once the ice cream is melted, other sensory attributes start to become the dominant sensations and coldness sensation starts to disappear. It is also possible that the coldness attribute is more dominant during chewing due to the higher contact with teeth that can be sensitive to coldness.

These results demonstrate that when participants apply different oral behaviors to the same food product, dynamic sensory perception is considerably affected. This highlights the necessity to either control the oral processing behavior during analytical sensory

evaluations or have as realistic and natural as possible eating behaviors during sensory assessments rather than imposed protocols to ensure a proper capture of individual variations. This knowledge about the impact of oral processing behavior on dynamic sensory perception of ice creams is of value for ice cream makers since it can be used to customize products to consumers differing in eating behavior (for example ice cream suckers and chewers or children, adults and elderly).

2.4.4. Impact of ice cream hardness on consumption time and dynamic sensory perception

Consumers adapted their consumption time to the hardness of the ice cream. Increasing hardness of the ice cream by a factor of 8x increased consumption time by 1.5x fold. This can be explained by the fact that hard ice cream might require more oral manipulation to break down and melt to a bolus suitable for swallowing as compared to the softer ice cream. It should be noted that the hardness of both ice creams was within the range of the hardness of commercially available ice creams. This suggests that by manipulating the texture of ice creams within commercially acceptable boundaries, oral processing behavior can be influenced. Such result is in agreement with previous studies that have also shown an increment in time when product hardness increases ^{4,50,69,75}.

In addition to consumption time, hardness of ice creams influenced dynamic sensory perception. It was found that when ice cream hardness increased, the dominance of fruity aroma perception was delayed, and it was rated as dominant for a shorter time period. This is in line with previous studies using model gels varying in hardness. When gel hardness increased, the release of odors during consumption was slower ^{104–106}. This can be explained by the fact that taste and aroma compounds are only perceived by sensory receptors after being released from the food matrix ⁶. It is possible that the longer time to process the high hardness ice cream contributes to a slower release of aroma compounds from that ice cream into the oral cavity, delaying fruity aroma perception.

We also observed an increase in coldness perception and a delay in sweetness perception for the high hardness ice cream. As discussed previously this may result from additional oral manipulation and longer residence time in-mouth favoring more heat transfer between the

ice cream product and the oral cavity thereby impacting the temperature of the oral cavity and leading to an increase in coldness perception. Previous research that has shown that reducing the temperature of the tongue decreases sweetness perception which may explain the observed impact on sweet perception^{76–81}. Such mechanisms could come from a thermal modulation of the sensitivity of TRPM5, a cation channel that it is essential for transduction of sweet taste⁸⁰.

2.5. Conclusions

A wide range of oral behaviors were applied by consumers during ice cream consumption. Most consumers applied either tongue movements or combined oral behaviors such as chewing and allowing the ice cream to melt without oral movements. For almost half of the participants, the categorization of oral behavior based on self-reporting did not agree with the categorization of oral behavior based on the actual behavior displayed during consumption captured by video recordings. These results question the validity of self-reported questionnaires to capture oral processing behavior accurately. Video recordings are a more appropriate tool to quantify oral behavior.

During TDS assessment, consumption time increased by up to 2x fold when oral behavior was changed from chewing to natural oral processing behavior to letting the ice cream melt in mouth without jaw movements. With increasing ice cream hardness by 8x fold, consumption time increased by 1.5x fold for all oral behaviors. Similar chronology of dominant sensations was observed for the ice creams regardless of hardness and oral behavior. Texture attributes were perceived as dominant sensations at the beginning of consumption whereas taste and aroma attributes were dominant towards the end of consumption. Oral processing behavior and hardness influenced dynamic sensory perception. When ice creams were let to melt in mouth, dominance of sweetness and firmness was perceived for a longer period of time compared to when they were chewed. Oppositely, when ice creams were chewed, dominance of fruitiness and coldness was perceived for a longer period of time compared to when they were left to melt in mouth. The dynamic changes that happen throughout the consumption process, as well as the fact that consumers may apply different oral behaviors to the same food product should be considered during sensory evaluation. One methodological recommendation would be to

ensure that natural eating behavior is privileged over imposed protocol during sensory assessment of food products.

3

Oral processing behavior of drinkable, spoonable and chewable foods is primarily determined by rheological and mechanical food properties

This chapter has been published as:

Aguayo-Mendoza M.G.*, Ketel E.C.*, van der Linden E., Forde C.G., Piqueras-Fiszman B., Stieger M. Oral processing behavior of drinkable, spoonable and chewable foods is primarily determined by rheological and mechanical food properties. *Food Quality and Preference* 71, 87–95 (2019). (*The authors contributed equally to this work)

Abstract

Food oral processing plays a key role in sensory perception, consumer acceptance and food intake. However, little is known about the influence of physical food properties on oral processing of different type of food products. The primary objective of this study was to determine the influence of rheological and mechanical properties of foods on oral processing behavior of liquid (drinkable), semi-solid (spoonable) and solid foods (chewable). The secondary objective was to quantify the influence of product, liking, frequency of consumption and familiarity on oral processing behavior. Rheological and mechanical properties of 18 commercially available foods were quantified. Parameters describing oral processing behavior such as sip and bite size, consumption time, eating rate, number of swallows, number of chews, cycle duration, and chewing rate were extracted from video recordings of 61 consumers. Subjects evaluated products' liking, familiarity, and frequency of consumption using questionnaires. Consumers strongly adapted oral processing behavior with respect to bite size, consumption time, and eating rate to the rheological and mechanical properties of liquid, semi-solid and solid foods. This adaptation was observed within each food category. Chewing rate and chewing cycle duration of solid foods were not influenced by mechanical properties and remained relatively constant. Liking, familiarity, and consumption frequency showed to impact oral processing behavior, although to a lower degree than the rheological and mechanical properties of food. We conclude that the oral processing behaviors of liquid, semi-solid and solid foods are mainly determined by their rheological and mechanical properties.

3.1. Introduction

Oral processing is the manipulation and break down of food inside the mouth up to the moment of swallowing ^{1,6,107}. This process is dynamic and plays a central role in sensory perception and food intake. Therefore, oral processing is key for consumer acceptance of foods ^{1,3}.

Foods are processed differently in the mouth depending on their physical-chemical, rheological and mechanical properties ^{7,108–110}. Liquid foods are transported from the front of the mouth to the pharynx and then swallowed. Semi-solid foods are also transported from the front of the mouth to the pharynx but require additional tongue movements before swallowing. Solid foods are fragmented into particles by mastication during oral processing that are then further reduced in size, lubricated and mixed with saliva until particles agglomerate and a bolus is formed that is safe to swallow ^{111,112}. Oral processing behavior is usually characterized by parameters such as sip or bite size, number of chews per bite, oro-sensory exposure time, number of swallows, and eating rate ¹¹³.

The human diet consists of foods from across liquid, semi-solid and solid foods, though most of the previous studies to date have investigated oral processing behaviors associated with solid foods ^{47,51,52,113,114}. These studies showed that the number of chews and bite size vary depending on the food item consumed ¹¹³. Hardness of soft-solid model food gels was positively correlated with number of chews, muscle activity, and jaw opening amplitude ⁴⁷. Sensory attributes, such as firmness and chewiness were positively correlated with number of chews, chewing rate, chews per bite and oral exposure time and negatively correlated with eating rate ⁵¹. Eating rate represents the amount of food eaten per unit of time and has been associated with caloric intake ¹¹⁵. Forde et al. found that the way the food is prepared significantly influenced eating rate ⁵². The mashed version of a food was consumed with higher eating rates than when the same food was presented whole. However, it is not fully understood to what extent eating rate is determined by the mechanical properties of food.

In contrast to the many studies investigating oral processing behavior of solid foods, only few studies have examined the influence of rheological properties of liquid and semi-solid

foods on oral processing behavior^{54,116,117}. Chen & Lolivret found that apparent shear viscosity was positively correlated with perceived difficulty to swallow and longer residence time in mouth of liquid foods⁵⁴. de Wijk et al. compared bite size of liquid and semi-solid foods and demonstrated that bite size of semi-solid foods was smaller than bite/sip size of liquids¹¹⁶. Steele & Lieshout found that when comparing bite size within one food category, liquid foods, bite/sip size was not affected by product consistency¹¹⁷. This study focused on beverages with low viscosity such as water, milk, and apple juice. That said, the authors indicated that number of swallows decreased when consistency increased. These studies indicate that rheological properties of liquid and semi-solid foods may have an influence on oral processing behavior.

In addition to the effect of rheological and mechanical properties of foods on oral processing behavior, recent reviews have hypothesized that liking and familiarity could influence oral processing behavior^{118,119}. However, only a few studies account for food liking and/or familiarity when assessing oral processing behavior^{51,52,114,120}. The studies of Forde and Bellisle showed that for solids, liking was negatively correlated with chews per bite and chewing time^{52,120}. However, other studies showed no relationship between liking and oral processing behavior^{51,114}. Yet, the relationship between liking and familiarity for liquid and semi-solid foods and oral processing behavior remains unclear.

Therefore, the primary objective of this study was to determine the influence of rheological and mechanical properties of food on oral processing behavior of liquid (drinkable), semi-solid (spoonable) and solid (chewable) foods. The secondary objective was to quantify the influence of product, liking, frequency of consumption and familiarity on oral processing behavior.

3.2. Material and Methods

3.2.1. Test foods

Eighteen commercially available foods were used and classified into three categories: liquid/drinkable, semi-solid/spoonable, and solid/chewable foods (Table 3.1). These foods were chosen to represent a wide range of commercially available products that differ in rheological and mechanical properties. All foods were purchased in local supermarkets.

When cooking was needed for food preparation, the manufacturer's instructions provided on the label were followed.

3.2.2. Instrumental analyses

Viscosity measurements of liquid and semi-solid foods

Viscosity measurements were performed with a Modular Compact Rheometer 302 (MCR 302, Anton Paar, Graz, Austria) equipped with a concentric cylinder (CC17/TI-SN3960). Flow curves were recorded by measuring viscosity as a function of shear rate. Shear rate was increased from 0.1 s^{-1} to 1000 s^{-1} and then decreased from 1000 s^{-1} to 0.1 s^{-1} . All measurements were done in triplicate at the serving temperature of the foods (Table 3.1). Though the food temperature may vary during oral processing, it was assumed that the temperature of liquid and semi-solid foods changed only to a small extent during consumption. Thus, under this assumption the serving temperature was chosen as the relevant temperature for the rheological testing. The Ostwald-de Waele model ($\eta = K \dot{\gamma}^{n-1}$) was used to fit the flow curves to quantify consistency K and flow behavior index n . In the Ostwald-de Waele model η represents viscosity (Pas), $\dot{\gamma}$ (s^{-1}) shear rate, K consistency which corresponds to viscosity at a shear rate of 1 s^{-1} ($\eta_{1\text{s}^{-1}}$), and n the flow behavior index which indicates the magnitude of shear thinning behavior ($0 < n < 1$). Fitting of flow curves was done for viscosities ranging from 1 s^{-1} to 100 s^{-1} . All liquid, drinkable and semi-solid, spoonable foods were characterized following this procedure with the exception of water, tea, and sparkling water. Viscosity of water at 22°C and 55°C were obtained from the tables of the International association for the properties of water and steam ¹²¹, and used for water and tea. Viscosity of sparkling water was assumed to be the same as viscosity of still water.

Uniaxial compression tests of solid foods

A Texture Analyzer (TA.XT plus) equipped with a load cell of 50 kg and a compression plate of 75mm diameter was used to perform uniaxial compression tests on all chewable foods with the exception of noodles. Samples were cylinders with 15mm height and 18mm diameter.

Table 3.1. Overview of foods, brands, serving temperature, and presentation form.

Category	Product	Brand	Serving temperature	Presentation form
Liquid/Drinkable	Water	Tap water	22°C	100 g in a cup
	Sparkling water	Spa Intense	22°C	
	Green tea	Lipton vitality classic	55°C	
	Thin soup	Knorr Mix tomato soup	60°C	
	Thick soup	Unox Creamy tomato soup	60°C	
	Drinking yogurt	FrieslandCampina Strawberry Vifit	10°C	
Semi-solid/ Spoonable	Custard	FrieslandCampina Vanilla flavor	10°C	100 g in a bowl to be consumed with a spoon
	Skimmed yogurt	FrieslandCampina	10°C	
	Skyr	Arla Skyr natural flavor	10°C	
	Mashed potatoes	Supermarket private label	55°C	
Solid/Chewable	Old Gouda cheese	Supermarket private label	22°C	50 g on a plate to be consumed with fork and knife
	Young Gouda cheese	Supermarket private label	22°C	
	Beef(chuck)	Supermarket private label	70°C	
	Raw carrots	Supermarket private label	22°C	
	Chocolate	Lindt excellence 70% cacao	22°C	
	Noodles	Conimex wok noodles	22°C	
	Tofu (medium-firm)	Supermarket private label	22°C	
	Processed cheese	Bel Group Kiri	22°C	

Processed cheese (Kiri) was used in its original shape, a block of 37x37x14mm. To prevent friction between plate and samples during compression, the plate and the top of the sample surface were lubricated with paraffin oil. Ten replicates per sample were measured at 22°C at constant compression speed of 1mm/s up to a compression strain of 80%, except for chocolate that was compressed up to 30% strain. To be able to compare mechanical properties between solid, chewable foods differing largely in mechanical properties, Young's modulus and stress at 15% strain ($\sigma_{15\%}$) were calculated by averaging over the replicate measurements.

3.2.3. Subjects

61 Dutch-Caucasian subjects, 36 females and 25 males, with an average age of 44 ± 24 years, participated in this study. All participants underwent a dental screening to confirm they had complete dentition. Additionally, mastication efficiency was assessed as described previously^{122,123} and only subjects considered with good mastication efficiency, defined as subjects with a median particle size < 3.5 mm, were included. Eating Assessment Tool 10¹²⁴, a self-administered questionnaire originally developed for dysphagia evaluation, was used to discard subjects with any swallowing problem. Other inclusion criteria were BMI of 18.5–25 kg/m², normal taste and smell capabilities and no food allergies. Written informed consent was obtained from all participants and all subjects were reimbursed for their participation. The study was approved by the medical ethical committee of Wageningen University (NL58762.081.16).

3.2.4. Experimental procedure

During the test sessions participants consumed the test foods while being video recorded. Each subject was individually video recorded, in a well-lit room, isolated from external noise or any other distractions. Participants were asked not to eat for two hours before the sessions. Sessions were held between 13:00 – 17:00 hours and lasted 30 min. Participants consumed a total of 18 test foods divided over three sessions. In each session, participants consumed six test foods. Each session lasted for 30 min. Sessions were spread over 3 weeks, so that typically each subject participated in one session per week. Foods were presented one at a time in a completely randomized order.

Before starting video recording, the researcher placed four round stickers on the participant's face: two on the forehead spaced horizontally 5 cm, one on the tip of the nose, and one on the center of the chin. These stickers were used for video analysis. Participants were seated in a chair in front of a table with a video camera (Canon IXUS-500HS), approximately 50 cm from the participant's face. This distance was close enough to take a complete picture of the face without distracting or discomforting the participants. Participants were instructed to hold their head straight and not to block their mouth or face while eating.

Drinkable products were served in 100g portions in a plastic cup and subjects were instructed to drink the liquid products directly from the cup. Spoonable products were served in 100g portions in a bowl and subjects had to use a tablespoon to consume them. Finally, chewable foods were served in 50g portions and presented on a plate with fork and knife. Subjects were instructed to consume the solid foods as they would usually do, so subjects were free to use knife and fork or not in order to keep behavior as natural as possible. They were requested to consume three sips, three spoons or three bites of the food from the portion offered as they would normally do and to indicate the swallowing moment by raising their hand. Once the participants finished the three sips, spoons, or bites and indicated the last swallowing moment, the recording was stopped. All video recordings were done at 30 frames per second (fps). After the video recordings, samples were weighed to calculate the amount of food consumed. The portion size offered to the participants was considerably larger than the amount they consumed with the three sips, spoons, or bites.

3.2.5. Video analysis

A coding scheme was developed for the extraction of quantitative data using the software Kinovea (v0.8.15), a motion analysis software that tracks changes in the spatial position of specific markers in video recordings. Frequency of two key moments (bite and swallow) were recorded and the stickers placed on the nose and chin were labelled accordingly. The movement of those stickers relative to each other was extracted as X-Y coordinates over time. The stickers on the forehead were used as a reference to draw a line to calibrate the software with the number of pixels that represented 5 cm. Coding of the videos was divided between three researchers. To standardize the coding procedures, the researchers coded a set of 10 videos together. After analyses were done, approximately 10% of the videos were randomly selected and codification was validated.

Average bite size was determined by dividing the total weight of food consumed in three sips, spoons or bites by three. Consumption time of one sip, one spoon or one bite was defined as the time period when participants placed the sample in the mouth until the last swallow before the next bite or end of the video. Total consumption time was obtained by adding the consumption times of three sips, spoons, or bites. Total consumption time thus represents the time that foods were orally processed and excludes the time between sips,

spoons and bites. Number of swallows were recorded by counting the number of times the participant raised the hand. Eating rate was obtained by dividing the weight of food consumed by the total consumption time. To obtain the number of chews, the jaws vertical displacement was computed as the difference between the nose’s position and the chin marker at each time point. The number of chews was calculated by implementing a first derivative zero-crossing peak detection method of the jaw’s vertical displacement. Chewing cycle duration was obtained by dividing the total consumption time by the number of chews, and chewing rate represents the number of chews per second. These calculations were processed using a custom-made Excel macro. Table 3.2 shows the parameters describing oral processing behavior obtained for each product category.

Table 3.2. Parameters describing oral processing behavior of 18 foods belonging to three categories.

Variable	Drinkable	Spoonable	Chewable
Average bite/sip size (g)	●	●	●
Consumption time in (s)	●	●	●
Number of swallows	●	●	●
Eating rate (g/s)	●	●	●
Number of chews			●
Chewing cycle duration (s)			●
Chewing rate (chews/s)			●

3.2.6. Liking, familiarity and consumption frequency

Separately from the video coding session, frequency of consumption, familiarity, and liking of all foods were rated by all participants. Frequency of consumption and familiarity were assessed before the test sessions while liking was rated after the last sip, spoon or bite of product consumption. Frequency of consumption was rated using a 6-point scale where 1 indicated never consumed, 2 once a year, 3 once every six months, 4 once a month, 5 once a week, and 6 once a day. Familiarity was rated on a 5-point scale. 1 indicated not at all familiar, 2 slightly familiar, 3 moderately familiar, 4 very familiar, and 5 extremely familiar. Liking was assessed using a 9-point hedonic scale with 1 corresponding to dislike extremely, 2 dislike very much, 3 dislike moderately, 4 dislike slightly, 5 neither like nor dislike, 6 like slightly, 7 like moderately, 8 like very much, and 9 like extremely.

3.2.7. Statistical data analysis

All data analyses were done with SPSS (IBM SPSS statistics, version 24). Data is presented as mean $\pm$ SE. Normality of continuous variables was checked using Shapiro-Wilk tests. Non-normally distributed data was log-transformed. A p-value lower than 0.05 was considered statistically significant.

Analysis of covariance was conducted within each product category to determine the effect of food product on each oral processing variable considering product as independent factor. Liking, familiarity, frequency of consumption and participants age were used as covariates. Partial eta squared (η_p^2) was calculated to estimate effect sizes. Post hoc pairwise comparisons were performed using Bonferroni's adjustment. Additionally, an analysis of variance within each product category was conducted to compare products liking, familiarity and frequency of consumption.

Pearson correlation coefficients were computed to assess the relationships between oral behavior variables and rheological and mechanical properties.

3.3. Results

3.3.1. Rheological and mechanical properties of foods

Consistency K corresponding to viscosity at a shear rate of 1 s^{-1} and flow behavior index n indicating the magnitude of shear thinning behavior ($0 < n < 1$) of drinkable and spoonable foods are shown in Table 3.3. Water and warm tea display Newtonian flow behavior ($n=1$), and the difference in consistency K is caused by the temperature difference. All other drinkable and spoonable foods displayed shear thinning behavior to various degrees ($0.06 < n < 0.45$). Of all foods displaying shear thinning behavior, thin soup had the lowest and mashed potatoes the highest consistency K . Mashed potatoes displayed the lowest (strongest shear thinning behavior) and drinking yogurt the highest (weakest shear thinning behavior) flow behavior index n .

The Young's modulus and stress needed to compress to 15% strain ($\sigma_{15\%}$) for solid, chewable foods are shown in Table 3.4. Young's modulus ranged from 0.28 kPa for tofu to 50.31 kPa for carrot. $\sigma_{15\%}$ ranged from 4.42 kPa for tofu to 661.25 kPa for chocolate.

Table 3.3. Consistency K corresponding to viscosity at a shear rate of 1 s^{-1} and flow behavior index n indicating the magnitude of shear thinning behavior ($0 < n < 1$) of drinkable and spoonable foods

Category	Food	Consistency K (Pa·s)	Flow behavior index n
Liquid/Drinkable	Water	0.00095	1.00
	Sparkling water	0.00095	1.00
	Green tea	0.00050	1.00
	Thin soup	0.164	0.42
	Thick soup	3.530	0.25
	Drinking yogurt	1.312	0.45
Semi-solid/Spoonable	Custard	21.34	0.31
	Skimmed yogurt	20.59	0.38
	Skyr	55.20	0.28
	Mashed potatoes	207.61	0.06

Note: Flow curves were determined at serving temperature. Water and tea viscosities were obtained from Wagner & Kretzschmar, 2008.

Table 3.4. Mean and standard error of Young's modulus and stress at 15% strain ($\sigma_{15\%}$) of solid, chewable foods.

Category	Food	Young's modulus (kPa)	Stress at 15% strain $\sigma_{15\%}$ (kPa)
Solid/Chewable	Old Gouda cheese	14.59±0.82	169.3±8.45
	Young Gouda cheese	2.21±0.26	30.2±3.06
	Beef	1.77±0.31	22.9±3.41
	Raw carrots	50.31±3.18	607.0±33.41
	Chocolate	47.35±8.34	661.3±88.91
	Tofu	0.28±0.02	4.4±0.24
	Processed cheese	1.02±0.63	13.2±0.06

3.3.2. Product differences on oral processing behavior

Means of all parameters describing oral processing behavior of the $n=61$ subjects for all drinkable, spoonable, and chewable foods are presented in Table 3.5. Food products were significantly different on most parameters describing oral processing behavior.

Ingestion size significantly differed in drinkable [$F(5, 358)=10.21$, $p<.001$, $\eta_p^2=.13$], spoonable [$F(3, 238)=4.44$, $p=.005$, $\eta_p^2=.05$], and chewable [$F(7, 478)=11.94$, $p<.001$, $\eta_p^2=.15$] foods. Drinkable foods were eaten with an average sip size of 15.0 g, spoonable

foods had an average bite size of 10.6g whereas chewable foods had an average bite size 4.8 g.

Consumption time significantly differed in drinkable, spoonable, and chewable foods [$F(5, 359)=19.35$, $p<.001$, $\eta_p^2=.21$; $F(3, 239)=32.30$, $p<.001$, $\eta_p^2=.29$; $F(7, 478)=30.01$, $p<.001$, $\eta_p^2=.31$ respectively]. Consumption time for drinkable foods was on average 3.7 s, for spoonable foods 5.4 s, and for chewable foods 21.3 s.

Number of swallows significantly differed in drinkable [$F(5, 360)=8.55$, $p<.001$, $\eta_p^2=.11$] and spoonable foods [$F(3, 240)=6.24$, $p<.001$, $\eta_p^2=.07$]. However, chewable products did not differ on number of swallows. The number of swallows taken for drinkable foods was on average 1.2, for spoonable foods 1.4, and for chewable foods 1.8.

Eating rate significantly differed in drinkable, spoonable, and chewable foods [$F(5, 359)=24.59$, $p<.001$, $\eta_p^2=.26$; $F(3, 238)=29.09$, $p<.001$, $\eta_p^2=.27$; $F(7, 478)=36.76$, $p<.001$, $\eta_p^2=.35$ respectively]. The average eating rate was 4.4 g/s for drinkable products, 2.2 g/s for spoonable, and 0.2 g/s for chewable foods.

Number of chews significantly differed between products [$F(7, 444)=42.58$, $p<.001$, $\eta_p^2=.39$] for chewable foods, and ranged from 16.7 chews for processed cheese to 47.2 chews for meat. Moreover, significant effects on chewing rate and cycle duration were observed [$F(7, 479)=9.44$, $p<.001$, $\eta_p^2=.12$].

These results show an interrelationship between oral processing parameters. Chewable foods that were eaten at the slowest rate also had the smallest bite size, greatest chews per bite and longest consumption time (i.e. Gouda, carrots, beef). By contrast drinkable and spoonable foods that were eaten the fastest, had the largest bite size, required no chewing and had the shortest consumption time (i.e. water, skimmed yogurt).

3.3.3. Effect of liking, familiarity and frequency of consumption on oral processing behavior

There were significant differences in liking, familiarity, and frequency of consumption within product categories, as shown in Table 3.5. The univariate analyses of covariance

showed significant effects of liking, frequency of consumption, and familiarity on some of the parameters describing oral processing behavior.

Liking was significantly related to bite size of drinkable [$F(1,358)=9.24$, $p=.003$, $\eta_p^2=.02$], spoonable [$F(1,238)=36.42$, $p<.001$, $\eta_p^2=.13$] and chewable foods [$F(1,478)=23.80$, $p<.001$, $\eta_p^2=.05$]. Bite size increased as the liking rating increased. Regarding the eating rate, liking was significant in spoonable [$F(1,238)=15.02$, $p<.001$, $\eta_p^2=.06$] and chewable foods [$F(1,478)=20.69$, $p<.001$, $\eta_p^2=.04$]. Participants consumed larger amounts per second as liking increased.

Familiarity was also significant for consumption time [$F(1,478)=5.51$, $p=.019$, $\eta_p^2=.01$] and number of chews [$F(1,477)=10.94$, $p<.001$, $\eta_p^2=.02$] of solid foods. Consumption time and number of chews increased as familiarity rating increased.

Finally, frequency of consumption was significant for bite size of spoonable foods [$F(1,238)=8.35$, $p=.004$, $\eta_p^2=.03$] and number of chews of solids products [$F(1,477)=5.06$, $p=.025$, $\eta_p^2=.01$], bite size and number chews decreased with products that were consumed less frequently.

Summarizing, for those variables that showed significant effects of liking, results were as expected, liking leads to larger bite sizes and faster eating rates. Regarding familiarity and frequency of consumption, there were no clear expectations, but the results suggests that people tend to chew more for products that are less well known and less frequently consumed. However, the effect sizes of familiarity and frequency of consumption are much smaller compared to the effect size of liking.

Table 3.5. Means of parameters describing oral processing behavior, liking, familiarity and frequency of consumption for all drinkable, spoonable, and chewable foods. Values are reported as mean±SE. Superscripts indicate significant differences between means within each column within a product category ($p<0.05$).

	Bite size (g)	Consumption time (s)	Number of swallows	Eating rate (g/s)	Number of chews	Chewing rate (chews/s)	Cycle duration (s)	Liking	Familiarity	Frequency of consumption
<i>Drinkable</i>										
Water	18.0±1.1 ^c	2.8±1.1 ^a	1.1±1.0 ^a	6.3±1.1 ^c	-	-	-	5.9±0.2 ^b	4.9±0.1 ^b	6.0±0.1 ^b
Sparkling water	16.8±1.1 ^c	3.1±1.1 ^{ab}	1.2±1.0 ^{ab}	5.3±1.1 ^{bc}	-	-	-	5.4±0.2 ^{ab}	4.1±0.1 ^a	3.8±0.1 ^a
Green tea	15.5±1.1 ^{bc}	2.9±1.1 ^a	1.1±1.0 ^a	5.0±1.1 ^{bc}	-	-	-	5.0±0.2 ^a	4.7±0.1 ^b	5.7±0.1 ^b
Thin soup	12.7±1.1 ^{ab}	3.3±1.1 ^{ab}	1.2±1.0 ^{ab}	4.0±1.1 ^b	-	-	-	7.0±0.2 ^c	4.2±0.1 ^a	3.9±0.1 ^a
Thick soup	11.2±1.1 ^a	6.0±1.1 ^c	1.5±1.0 ^c	2.0±1.1 ^a	-	-	-	7.2±0.2 ^c	4.2±0.1 ^a	3.9±0.1 ^a
Drinking yogurt	15.6±1.1 ^{bc}	3.9±1.1 ^b	1.3±1.0 ^{bc}	4.1±1.1 ^b	-	-	-	7.1±0.2 ^c	3.9±0.1 ^a	3.6±0.1 ^a
Mean within category	15.0	3.7	1.2	4.4				6.3	4.3	4.5
<i>Spoonable</i>										
Custard	11.0±1.1 ^{ab}	3.6±1.1 ^a	1.3±1.0 ^a	3.0±1.1 ^b	-	-	-	7.1±0.2 ^b	3.8±0.1 ^b	3.8±0.1 ^b
Skimmed yogurt	12.6±1.1 ^b	3.8±1.1 ^a	1.3±1.0 ^{ab}	3.0±1.1 ^b	-	-	-	6.4±0.2 ^a	4.6±0.1 ^c	5.5±0.1 ^c
Skyr	8.9±1.1 ^a	6.8±1.1 ^b	1.6±1.0 ^c	1.5±1.1 ^a	-	-	-	5.9±0.2 ^a	2.2±0.1 ^a	2.1±0.1 ^a
Mashed potatoes	9.7±1.1 ^a	7.2±1.1 ^b	1.6±1.0 ^{bc}	1.4±1.1 ^a	-	-	-	5.7±0.2 ^a	4.0±0.1 ^b	3.7±0.1 ^b
Mean within category	10.6	5.4	1.4	2.2				6.3	3.6	3.8

Chewable										
Old Gouda cheese	4.0±1.1 ^b	23.2±1.0 ^{cd}	1.9±1.1	0.2±1.1 ^a	30.0±1.0 ^{cd}	1.3±1.0 ^{ab}	0.8±1.0 ^{cd}	7.2±0.2 ^d	4.1±0.1 ^{bc}	4.5±0.1 ^c
Young Gouda cheese	5.0±1.1 ^{bc}	18.8±1.0 ^{bc}	1.7±1.1	0.3±1.1 ^b	25.9±1.0 ^{bc}	1.3±1.0 ^{bc}	0.7±1.0 ^{bc}	6.8±0.2 ^{cd}	4.3±0.1 ^{bc}	4.9±0.1 ^{cd}
Beef	5.4±1.1 ^c	33.2±1.0 ^e	2.0±1.1	0.2±1.1 ^a	47.2±1.0 ^e	1.4±1.0 ^{cd}	0.7±1.0 ^{ab}	5.8±0.2 ^b	4.3±0.1 ^{bc}	4.7±0.1 ^{cd}
Raw carrots	4.0±1.1 ^b	24.4±1.0 ^d	1.8±1.1	0.2±1.1 ^a	36.6±1.0 ^d	1.5±1.0 ^d	0.7±1.0 ^a	6.9±0.2 ^{cd}	4.5±0.1 ^c	4.7±0.1 ^{cd}
Chocolate	2.9±1.1 ^a	22.0±1.0 ^{cd}	1.8±1.1	0.1±1.1 ^a	29.7±1.0 ^c	1.3±1.0 ^{abc}	0.8±1.0 ^{bcd}	7.5±0.2 ^d	4.6±0.1 ^c	5.1±0.1 ^d
Noodles	6.0±1.1 ^c	17.3±1.0 ^b	1.7±1.1	0.3±1.1 ^{bc}	23.8±1.0 ^b	1.4±1.0 ^{bcd}	0.7±1.0 ^{abc}	5.6±0.2 ^b	3.9±0.1 ^b	3.9±0.1 ^b
Tofu	5.3±1.1 ^{bc}	17.6±1.1 ^{bc}	1.6±1.1	0.3±1.1 ^{bc}	23.4±1.1 ^b	1.4±1.0 ^{bcd}	0.7±1.0 ^{abc}	3.3±0.2 ^a	2.9±0.1 ^a	2.6±0.1 ^a
Processed cheese	5.4±1.1 ^c	13.9±1.0 ^a	1.7±1.1	0.4±1.1 ^c	16.7±1.0 ^a	1.2±1.0 ^a	0.8±1.0 ^d	6.3±0.2 ^{bc}	3.8±0.1 ^b	3.6±0.1 ^b
Mean within category	4.8	21.3	1.8	0.2	29.1	1.4	0.7	6.2	4.0	4.3

3.3.4. Relationships between oral processing behavior and rheological and mechanical properties of foods

Pearson correlation coefficients were calculated to assess the relationships between parameters describing oral processing behavior and rheological and mechanical properties of drinkable, spoonable, and chewable foods (Table 3.6). Bite size of liquid and semi-solid foods was negatively correlated with product consistency K ($r=-.880$, $n=10$, $p<.001$) (Figure 3.1.A and Table 3.6) and positively correlated with flow behavior index n ($r=.891$, $n=10$, $p<.001$). Bite size of chewable foods was negatively correlated with stress ($\sigma_{15\%}$) ($r=-.912$, $n=7$, $p=.004$) and Young's modulus ($r=-.899$, $n=7$, $p=.006$) (Figure 3.2.A and Table 3.6).

Table 3.6. Pearson correlation coefficient of rheological and mechanical properties of foods and parameters describing oral processing behavior.

	Bite size	Consumption time	Number of swallows	Eating rate	Number of Chews	Chewing rate	Cycle duration
<i>Liquid and semi-solid foods</i>							
Consistency K^a	-.880**	.750*	.853**	-.915**	-	-	-
Flow behavior index n	.891**	-.762*	-.848**	.921**	-	-	-
<i>Solid foods</i>							
Stress ($\sigma_{15\%}$) ^a	-.912**	.307	.420	-.774*	.334	.234	-.224
Modulus ^a	-.899**	.315	.440	-.771*	.341	.226	-.215

*Correlation is significant at $p<0.05$ level and **correlation is significant at $p<0.01$ level. ^a Variables were transformed into logarithmic scale.

Consumption time was positively correlated with consistency ($r=.750$, $n=10$, $p=.012$) and negatively with flow behavior index ($r=-.762$, $n=10$, $p=.010$) (Figure 3.1.B and Table 3.6). Figure 3.2.B shows that for chewable foods, with increasing $\sigma_{15\%}$ or Young's modulus consumption time tended to increase. However, this correlation was not significant since beef deviates from the trend line. When beef is removed from the data analysis, the correlation between consumption time and Young's modulus becomes significant ($r=.846$, $n=6$, $p=.034$) (Figure 3.2.D). Likewise, a trend was observed with regards to number of chews and $\sigma_{15\%}$. With increasing $\sigma_{15\%}$ or Young's modulus, the number of chews increased.

However, this trend was not significant unless beef is removed from data, then the correlation is $r=.815$, $n=6$, $p=.048$.

Figure 3.1. Correlations between consistency K and (A) bite size, (B) consumption time, (C) eating rate and (D) number of swallows of liquid and semi-solid foods.

Eating rate was negatively correlated with product consistency for liquid and semi-solid foods and $\sigma_{15\%}$ for solid foods ($r=-.915$, $n=10$, $p<.001$; $r=-.774$, $n=7$, $p=.041$ respectively). It can be observed that when consistency or stress increased eating rate decreased (Figure 3.1.C, Figure 3.2.C and Table 3.6). The number of swallows positively correlated with consistency ($r=.853$, $n=10$, $p=.002$), therefore products that had a higher consistency K needed more swallows than foods with lower consistency K. Other oral processing parameters such as number of chews, chewing rate, and cycle duration did not significantly correlate with the rheological and mechanical properties of solid, chewable foods.

Figure 3.2. Correlations between Young's modulus and (A) bite size, (B) consumption time of all products, (C) Eating rate and (D) consumption time excluding beef meat.

3.4. Discussion

The primary objective of this study was to determine the influence of rheological and mechanical properties of food on oral processing behavior of liquid (drinkable), semi-solid (spoonable), and solid (chewable) foods. The secondary objective was to quantify the influence of product, liking, frequency of consumption, and familiarity on oral processing. The results demonstrate that there are differences in oral processing behavior within food product categories. Furthermore, the effect sizes measured indicate that the parameters describing oral processing are mainly influenced by the food product consumed and to a lesser degree by liking, familiarity, and frequency of consumption. Thus, consumers primarily adapt their bite size, consumption time and eating rate to the rheological and mechanical properties of the foods being eaten.

The present study showed that bite size has an inverse relationship with consistency K for drinkable and spoonable foods and with stress needed to compress to 15% strain ($\sigma_{15\%}$) for chewable foods. In line with our results are the results of de Wijk who investigated the effect of viscosity on bite size of one liquid (milk) and one semi-solid food (custard) ¹¹⁶. He showed that the more viscous semi-solid food was eaten with a significantly smaller bite size than the less viscous liquid food. Both liquid and semi-solid foods were sipped through a straw while in the present study liquid foods were drunk from a cup and semi-solid foods were consumed with a spoon. The effect of viscosity on bite size seems to be the same independent of the ingestion procedure, as foods with a greater consistency were consumed with a smaller sip/bite size. In addition, we observed that temperature appears to influence the flow properties and bite size of drinkable foods, where warm foods were consumed with smaller sips compared to cold foods. This effect may be a self-protection reflex of the consumers to avoid damage to the soft tissues of the oral cavity caused by warm foods or could reflect temperature related changes in product consistency. For instance, we observed that warm thick soup was consumed with significantly smaller sips than cold drinking yogurt. Likewise, warm tea tended to be consumed with smaller sips than cold water, although this difference was not significant.

It is generally accepted that oral processing of liquids is mainly transportation of the bolus from the front of the mouth to the pharynx. Therefore, it is not surprising that drinkable foods have a shorter residence time in the oral cavity compared to spoonable and chewable foods. However, differences in rheological and mechanical properties can also extend in mouth residence time within a food category. We observed that within the category of drinkable foods, consumption time increases with increasing consistency although sip size decreases. In the category of spoonable foods we observed the same; consumption time increases with increasing consistency although bite size decreases. In the category of chewable foods, consumption time increases with increasing Young's modulus or stress needed to compress to 15% strain ($\sigma_{15\%}$) although bite size decreases. Engelen et al. investigated oral processing behavior of solid foods ⁵⁰. In contrast to our study, Engelen et al. gave the subjects a predetermined and constant bite size. Their results showed that tough solid foods needed longer consumption times and a higher number of chews than

softer solid food. To summarize, the rheological and mechanical properties of liquid, semi-solid and solid foods influence consumption time and sip/bite size in opposing manners. With increasing consistency of liquid and semi-solid foods or Young's modulus and $\sigma_{15\%}$ of solid foods consumption time increases although bite size decreases. This suggests that consumption time of liquid, semi-solid and solid foods seems to be determined by rheological and mechanical food properties.

The number of chews per bite were significantly different between solid foods. The correlation between number of chews and mechanical properties of solid foods was not significant. We observed that beef is a product that differed from the other foods tested, probably due to its fibrous, anisotropic structure which strongly influences mechanical properties. In our study, this effect has been neglected during the characterization of the mechanical properties of beef. In order to form a bolus suitable to swallow, the beef meat needs to be well mashed by teeth, and even in the swallowing point some intact fibers can be observed in the bolus ⁵⁸. Nevertheless, it is interesting to notice that the number of chews observed in this study for beef are similar to the values found by Mioche ³⁹. Another possible factor by which beef might have contribute to the lack of a relation between the number of chews and mechanical properties is the difference between the serving temperature (70°C) and the temperature for the rheological measurements (22°C). With the exception of beef, we observe that for the other solid foods the number of chews tends to increase with increasing $\sigma_{15\%}$. A similar trend has been shown before for model gels indicating that people unconsciously adapt the number of chews to the mechanical properties of food ⁴⁷.

Eating rate was also highly correlated with the rheological and mechanical properties of food. In liquid and semi-solid foods when consistency increases eating rate decreases. Furthermore, in solid foods, Young's modulus and $\sigma_{15\%}$ negatively correlated with eating rate. These results show that more viscous liquid and semi-solid foods and stiffer solid foods were consumed with lower eating rates. Four other studies assessed the eating rate of commonly consumed foods and suggested that eating rate decreases as foods become more solid and harder, though those studies did not characterize the rheological and mechanical properties of the foods ^{51–53,115}. Therefore, modifying food texture may be a way

to nudge food ingestion, since it has been shown that decreasing eating rate using food textures, can lead to lower food intake ^{125,126}. Therefore, these findings could be used to objectively screen foods' mechanical properties and identify those foods that are likely to slow down eating rate and consequently support energy intake reduction.

It should be noted that the Young's modulus represents a mechanical property determined under small deformation, typically at strains below 5%. The 15% strain, which was used in this study, represents also for many foods a deformation that can be considered relatively small compared to the deformations occurring during oral processing of solid foods. While the observed negative correlations between Young's modulus or $\sigma_{15\%}$ and eating rate are significant, during mastication chewable foods are fractured repetitively, hence neither Young's modulus nor $\sigma_{15\%}$ are mechanical properties which are determined under conditions mimicking oral processing behavior. It is therefore surprising that these measures yielded such strong correlations with oral processing behaviors, given they do not accurately reflect the kind of mechanical stress and deformation food structure undergoes during mastication. Since mastication of solid foods involves large deformations it would be interesting to quantify the relationships between parameters describing oral processing behavior and mechanical properties of solid foods determined under large deformation or under repetitive compression such as Texture Profile Analysis (TPA).

Cycle duration and chewing rate remained considerably stable across chewable foods, with an average of 0.7s and 1.4 chews/s, respectively. These values are in line with previously reported results ^{127,128}. Those studies reported a mean chewing rate of 1.3 and 1.5 chews/s. The stability of chewing rate and cycle duration may be explained by the fact that mastication is a rhythmic motor action originated in the central pattern generator in the brainstem that keeps chewing movements constant and fairly independent of the mechanical properties of the solid foods ¹²⁹. However, probably as consequence of the sensory feedback provided by the food bolus ¹³⁰, some minor but significant differences were observed between products.

Number of swallows per bite ranged from 1.1 to 2.0 across food categories. Drinkable products required fewer swallows than spoonable foods, and the later required fewer swallows than chewable foods. These results show that during oral processing of a single

bite, multiple swallows can take place and that a complete feeding sequence normally involves one or two swallows as has been indicated in previous researches ^{7,131}. In drinkable and spoonable foods, products that had a higher consistency needed more swallows to finish the food bolus than products with a lower consistency probably because at higher consistencies perceived difficulty to swallow increases ⁵⁴. In the case of chewable foods, multiple swallows occurred since some parts of the bolus may be ready to swallow earlier than others ⁷.

Liking, familiarity, and frequency of consumption were significantly related to parameters describing oral processing behavior such as bite size, consumption time, number of chews, and eating rate. However, their effect on oral processing is smaller in comparison to the product effect. In agreement with these results are those of Ferriday, who showed that liking of solid foods had a small effect on bite size and eating rate ¹¹⁴. Both studies show that variations in liking do not impact oral processing as much as the variations in a product, similar deductions can be extended to familiarity and frequency of consumption. Nevertheless, it should be noted that liking was measured after the product was tasted and not before or between bites. Therefore, from the results of this study we cannot assume that the effect of liking on the oral processing parameters is strictly causal.

3.5. Conclusions

Mechanical and rheological properties of food within a product category (liquid/drinkable, semi-solid/spoonable, solid/chewable) influence oral processing behavior. The effect of rheological and mechanical properties on parameters describing oral processing behavior of liquid, semi-solid, and solid foods is considerably larger than the effects of liking, familiarity, and frequency of consumption on those parameters. We suggest that oral processing of drinkable, spoonable, and chewable foods is a process mainly driven by the rheological and mechanical food properties. We conclude that consumers adapt their oral processing behavior (i.e. bite size, consumption time, eating rate, and number of chews in solid foods) to the rheological and mechanical properties of foods even when they belong to the same food category. Furthermore, oral processing descriptors like chewing rate and cycle duration remain constant and independent of the mechanical properties of solid foods.

4

Age, gender, ethnicity and eating capability influence oral processing behavior of liquid, semi-solid and solid foods differently

This chapter has been published as:

Ketel E.C. *, Aguayo-Mendoza M.G. *, de Wijk R.A., de Graaf C., Piqueras-Fiszman B., Stieger M. Age, gender, ethnicity and eating capability influence oral processing behaviour of liquid, semi-solid and solid foods differently. *Food Research International* 119, 143–151 (2019).(*The authors contributed equally to this work)

Abstract

Food oral processing depends on food properties and consumer characteristics. The aim of this study was to determine the effect of age, gender, ethnicity and eating capability on oral processing behavior of liquid, semisolid and solid foods. Oral processing behavior of 18 commercially available foods was compared between Dutch-Caucasian adults (18-30 yrs), Chinese-Asian adults (18-30 yrs), Dutch-Caucasian elderly (60-80 yrs), and consumers with mild swallowing problems and/or low mastication efficiency (18-80 yrs). Elderly consumed all foods with lower eating rates (g/s) than young adults by increasing consumption time (s). Females consumed solid foods with lower eating rates (g/s) than males by reducing bite size (g). Chinese-Asian consumers consumed liquid and solid foods with lower eating rates (g/s) than Dutch-Caucasian consumers by reducing bites size (g). Chinese-Asian consumers consumed semi-solid foods with lower eating rates (g/s) than Dutch-Caucasian consumers by reducing bite size (g) and increasing consumption time (s). Consumers with decreased mastication efficiency or mild swallowing problems showed similar oral processing behavior than healthy consumers, probably because reduction in eating capability was limited in the group. This shows that different consumer groups adapt eating rate (g/s) in different ways by modifying bite size (g), consumption time (s) or both. To conclude, age, gender and ethnicity influence oral processing behavior of liquid, semi-solid and solid foods differently. Understanding differences in oral processing behavior of specific consumer groups can assist in steering sensory perception, food choice and energy intake of specific consumer groups such as the elderly.

4.1. Introduction

Oral processing behavior is the first stage of food digestion, which is affected by food properties and consumer characteristics ¹. Physical-chemical, rheological and mechanical properties of foods strongly determine oral processing behavior ^{7,110}. Forde et al. found large variations in number of bites, chews per bite and eating rate (g/s) for different solid, savory meal components of European and Asian foods ^{51,52,132}. Faster eating rates (g/s) have been related to higher ad-libitum energy intakes and higher body mass index ¹³³. Eating rates (g/s) and food intake have been demonstrated to depend on food texture ^{51,125,126,132,134}. The ability to orally process foods can affect food intake and food choices among vulnerable populations, including elderly and consumers with decreased eating capability ^{135,136}. Changes in oral processing behavior, and especially eating rate (g/s), have been established to impact food intake and body mass index (BMI), and consequently impact public health ^{137–140}. In comparison to solid foods, less is known about the oral processing behavior of liquid and semi-solid foods. Liquids require different oral processing behavior than solids, which consists mainly of transportation of the fluid from the front to the back of the mouth. Aguayo-Mendoza et al. recently studied oral processing behavior of liquid, semi-solid and solid foods ⁶⁹. Rheological and mechanical properties of liquid, semi-solid and solid foods were the main determinants for oral processing behavior. Instrumental texture properties of a broad range of solid foods strongly correlated with eating rate (g/s) and oral processing behavior ¹⁴¹. These studies highlight that rheological, mechanical and texture properties of foods are important determinants of oral processing behavior, especially eating rate (g/s), which strongly influence ad libitum food intake.

In addition to the influence of food properties on oral processing behavior and eating rate (g/s), characteristics of the consumer such as age, gender and ethnicity, also alter oral behavior. Most consumers follow individual chewing strategies when masticating ¹⁴². The term ‘individual chewing strategies’ has been introduced by Yven et al. to describe different adaptation strategies of consumers in oral processing behavior for different foods. Yven et al. discovered 3 different adaptation strategies used by subjects to process foods. Subjects changed a combination of the number of chewing cycles, consumption time (s) and amplitude of muscle contraction in response to food product characteristics. Mastication

behavior can influence sensory perception of foods. Chewing sausages for a shorter or longer time gave rise to differences in bolus properties which led to differences in texture perception ⁷⁵. These studies show that variation in oral processing behavior can explain differences in sensory perception between individuals or consumer groups.

Ageing induces changes in oral physiology and anatomy causing changes in oral processing behavior ³². Essential oral functionalities, such as dental status, jaw muscle activity, bite force, tongue pressure and oral volume, decrease with age and affect oral processing ^{24,143–147}. Changes in oral physiology and anatomy during ageing lead to adaptation of food oral processing behavior. Elderly chew solid foods longer, with higher number of chews and with lower mastication efficiency compared to young adults ¹⁴⁸. To compensate for declined mastication efficiency, elderly increase the number of chews until swallowing. Similar results were found for a variety of solid foods demonstrating that chewing duration and number of chews increased with age while muscle activity per chew declined ^{27,31}. Elderly tend to have fewer teeth, influencing both the ease and comfort of chewing and the oral health-related quality of life ^{136,149}. Few studies investigated oral processing behavior of liquid foods either in young adults or elderly ^{150,151}. In contrast to numerous studies investigating the influence of age on oral processing of solid foods, to the best of our knowledge the influence of age on oral processing behavior of liquid and semi-solid foods has not yet been compared. Understanding age related changes in oral processing behavior of foods may provide new solutions to increase energy intake in elderly, vulnerable populations, and hence might contribute to fighting risks of nutrition related non-communicable diseases in elderly with poorer mastication ability.

In addition to age, gender affects oral processing behavior. Oral physiology was suggested to partially explain differences in food oral processing behavior between females and males. Males displayed higher maximum bite force, salivary flow and higher lip and cheek strength compared to females, which can facilitate oral processing behavior ^{29,34,35,145}. Males displayed higher muscle activities and masticatory frequency when chewing solid foods than females ^{38,119,152}. Males showed shorter chewing cycle durations, shorter meal durations, lower number of chews, larger bite sizes (g) and higher eating rates (g/s) than females for a variety of solid foods ^{37,38,152,153}. While numerous studies investigated the

effect of gender on oral processing behavior of solid foods, the influence of gender on oral processing behavior of liquid and semi-solid foods has not been studied yet.

Ethnicity was found to affect the oral volume ⁴¹. Chinese-Asian consumers were found to have larger volumes of the oral cavity compared to Caucasian Americans and African Americans. Differences in oral physiology and anatomy between consumers belonging to different ethnicities might cause differences in food oral processing behavior. Very little is known about the effect of ethnicity on oral processing behavior of liquid, semi-solid and solid foods.

Physiological and anatomical differences may result in differences in eating capability. According to Laguna & Chen, eating capability is an individual's capability to process foods during consumption ⁶⁵. Eating capability is a combination of one's physical, physiological and mental-coordination capabilities in handling and consuming food. The physical capabilities is often quantified with a mastication efficiency test, whereby a food or model food is consumed for a number of chewing cycles, spit out and number and size of particles quantified ^{65,143,154}. Another measure of eating capability is the ability to swallow foods safely and painless. Belafsky et al. developed the Eating Assessment Tool (EAT-10), a 10-item questionnaire assessing swallowing problems ¹²⁴. Both mastication efficiency and swallowing problems contribute to eating capability, which might influence food oral processing behavior. Strong reductions of eating and swallowing capabilities are known as dysphagia ¹⁵⁵. Dysphagia patients are considered to display unhealthy swallowing behavior ¹⁵⁵, and are outside the scope of our study. However, little is known about oral processing behavior of healthy consumers with reduced mastication efficiencies.

To summarize, consumer characteristics such as age, gender, ethnicity and eating capability and rheological, mechanical and texture properties of foods contribute to oral processing behavior. The aim of this study was to determine the effect of age, gender, ethnicity and eating capability on oral processing behavior of liquid, semi-solid and solid foods. Oral processing behavior of 18 commercially available foods, ranging from liquids, semi-solids to solids, was compared between Dutch-Caucasian adults; Chinese-Asian adults; Dutch-Caucasian elderly and consumers with mild, self-reported swallowing problems and/or low

mastication efficiency. The effect of rheological and mechanical properties of these foods on oral processing behavior has been reported previously ⁶⁹.

4.2. Materials & method

4.2.1. Participants

Four groups of consumers participated in this study, including n=32 healthy adults with Dutch nationality and Caucasian ethnicity (9 males and 23 females, range 18–30 yrs., mean 21.3 ± 1.5 yrs.), n=29 healthy elderly with Dutch nationality and Caucasian ethnicity (13 males and 16 females, range 60–80 yrs., mean 70.0 ± 3.8 yrs), n=35 healthy adults with Chinese nationality and Asian ethnicity (11 males and 24 females, range 18–30 yrs., mean 23.9 ± 2.0 yrs) and n=39 participants with decreased eating capability (15 males and 24 females, range 18–80 yrs., mean 37.1 ± 22.2 yrs). The fourth consumer group included both Caucasian (n=32) and Asian (n=7) ethnicities. Dental status of all participants (n=135) was checked visually by the researchers before the study. Elderly participants were included only when 2 or less teeth were missing. Young participants were included only when no teeth were missing. All participants did not have removable crowns, implants or dentures. Other inclusion criteria were BMI between 18.5 and 25 kg/m², normal taste and smell capabilities and no beard (otherwise stickers for tracking oral behavior did not adhere). Screening of participants was done during an information meeting to ensure participants fulfil the selection criteria for the specific consumer groups. This was done through a questionnaire and an assessment of the eating capability.

Eating capability was assessed by classifying all 135 participants as either 'healthy consumers' (first three groups) or 'consumers with mild mastication and/or swallowing problems' (fourth group). Mastication efficiency was determined by a mastication test using an artificial test food (Optosil) as described previously ¹⁵⁶. Participants chewed 14 cubes of Optosil (5×5×5mm; total weight approximately 3.5 g) for 20 chews. Participants spat out the test food. Fragments were filtered and dried in an oven at 80°C for 25 min. Once dried, particles were separated in a petri-dish, scanned (Canon 9000F Mark II) and number of particles and particle size were determined using the imaging software ImageJ. Participants were classified as 'healthy consumers' when >50% of particles had an average size

of <3.5mm. Swallowing problems were self-assessed by the EAT-10, a questionnaire with 10 statements on swallowing problems ¹²⁴. A score 0–2 was defined as having no swallowing problems and participants were classified as “healthy consumers”. Thirty-nine participants were included in the fourth group with decreased eating capability. This group consisted of 30 participants with low mastication efficiency; 7 participants with minor swallowing problems; and 2 participants with both low mastication efficiency and minor swallowing problems.

Participants gave written informed consent to join the study and received financial reimbursement for their participation. The study was approved by the medical ethical committee of Wageningen University (NL58762.081.16).

4.2.2. Foods

Participants consumed 18 commercially available foods covering a wide range of physical properties, classified as liquid (drinkable), semisolid (spoonable) or solid (chewable) (Table 4.1). The 18 foods were selected to include foods differing in consistency and texture within the categories of liquid, semi-solid and solid foods. Only foods that are commonly consumed were included in the study. Hundred grams of drinkable foods were presented in a cup. 50g of the spoonable and chewable foods were presented in a bowl or on a plate. The three cheeses, tofu and chocolate were cut into rectangular or square shapes to ensure easy consumption. Meat was cut into a piece of 50g and cutlery was given to the participants to cut the meat in their preferred bite size (g). Three small carrots were provided for the carrot sample. 50g of noodles were placed on a plate. Portion size of the foods were chosen to provide enough foods for 3 sips/bites, taking into account the variation in sip/bite size (g) of the three food categories. Standard serving materials were used for the serving of the foods, including regular plastic cups (180 mL) and heat resistant cups (180 mL) for the liquids; a small ceramic bowl (300 mL) and table spoon (15 mL) for the semi-solids; and dinner plate (24 cm diameter), fork and knife for the solids. Cutlery was provided for the consumption of the spoonable and chewable foods. Participants consumed only the beef, noodles and spoonable foods with cutlery. All other chewable foods, (chocolate, carrots, tofu and all cheeses) were consumed by most participants using the fingers.

Table 4.1. Overview of all 18 food products belonging to 3 food categories.

Category	Product	Brand	Serving temperature	Presentation form
Liquid/Drinkable	Water	Tap water	22°C	100g in a cup
	Sparkling water	Spa Intense	22°C	
	Green tea	Lipton vitality classic	55°C	
	Thin tomato soup	Knorr Mix tomato	60°C	
	Thick tomato soup	Unox Creamy tomato	60°C	
	Strawberry drinking yogurt	FrieslandCampina Vifit	10°C	
Semi-solid/Spoonable	Vanilla custard	FrieslandCampina Vanille vla	10°C	100g in a bowl to be consumed with a spoon
	Strawberry yogurt	FrieslandCampina Magere yoghurt	10°C	
	Skyr natural flavor*	Arla Skyr naturel	10°C	
	Mashed potatoes	Supermarket private label	55°C	
Solid/Chewable	Old Gouda cheese	Supermarket private label	22°C	50g on a plate to be consumed with fork and knife
	Young Gouda cheese	Supermarket private label	22°C	
	Beef	Supermarket private label	70°C	
	Raw carrots	Supermarket private label	22°C	
	Dark chocolate	Lindt excellence 70% cacao	22°C	
	Noodles	Conimex wok noodles	22°C	
	Tofu	Supermarket private label	22°C	
	Processed cheese	Bel Group Kiri	22°C	

* Icelandic dairy product having the consistency of strained yogurt.

All foods were commercially available and purchased in local supermarkets. The beef and noodles were prepared following a standard cooking procedure to minimize variation between samples. Beef was cooked in a pan for at least 15 min until a core temperature of 70°C was reached. Noodles were cooked for 5 min in boiling water. Preparation of the other foods was done by following the instructions on the package. Rheological and mechanical properties of all foods and the influence of those properties on oral processing behavior have been reported previously ⁶⁹.

4.2.3. Experimental procedure

Oral processing behavior was monitored by video recordings using a camera (Canon IXUS-500HS) placed on a tripod. Video recordings were conducted individually in a test room

without any distraction. Before the test session, participants were asked to not eat two hours preceding the session. All 18 food products were consumed once in a randomized order over 3 sessions of 30 min. Participants were instructed to take 3 bites or sips of each food product but were free with respect to bite size (g), consumption time (s), number of chews, number of swallows, etc. To indicate a swallow, participants raised their hand. Liking of all foods was assessed on a 9-point hedonic scale after consumption.

4.2.4. Video analysis

Video recordings were analyzed to extract parameters describing oral processing behavior of all participants for each food product. The oral processing movements were tracked by two stickers on the face of the participants similar to previous studies ^{69,157}. Participants were asked to not block the stickers with their hands while eating and to minimize head movements during consumption. The sticker on the nose represents a reference point, and the sticker on the chin a mobile point. The distance between mobile point and reference point was used to extract 6 oral processing parameters: consumption time (s) defined as average of consumption time (s) of three bites or sips until swallowing; number of swallows obtained by counting number of times participant raised arm; chews per bite defined as the number of chews per bite calculated from vertical jaw displacement; average bite size (g) calculated by weighing food before and after consumption and dividing weight by three; eating rate (g/s) by dividing total amount of food consumed by total consumption time (s); chewing rate (chews/s) calculated by dividing total number of chews by total consumption time (s). Chews per bite and chewing rate were only assessed for solid, chewable foods.

For quantification of chews per bite the vertical jaw displacement was determined using Kinovea (v0.8.15) as the difference between the position of the stickers on nose and chin over time. When plotting the jaw displacement over time, each peak indicates a single chewing cycle. A first derivative zero crossing peak detection on the jaw's vertical displacement was used to extract the chews per bite from the data. It was assumed that, despite the instructions, small movements of the head of the subject during consumption occurred, the distance between the sticker on the nose and the sticker on the chin was not strongly affected. When the mouth is closed or fully opened, the distance between both stickers was not affected by head movements. Consequently, no data transformation to

correct for head movement was applied. Several of the oral processing parameters were highly correlated, since several parameters are derived from other oral processing parameters. Thirteen of the fifteen Pearson correlations were found to be significant (Table 4.2), including consumption time and chews per bite with a Pearson correlation of 0.943 ($p < .001$). Interrelationships between oral processing parameters were previously described

93.

4.2.5. Statistical data analysis

Statistical data analysis was conducted with SPSS (IBM SPSS Statistics 23). Normality of variables was checked, and non-normal distributed data was log-transformed. Each food category, liquid, semisolid and solid foods, was analyzed separately. Mean and SE are presented for the three food categories. All values are averaged over foods within a category and compared between consumer groups. Repeated measures analyses of variance (ANOVA) were performed with all six oral processing parameters (consumption time (s), average bite size (g), chews per bite, number of swallows, eating rate (g/s), chewing rate) as dependent variables. ANOVA's included age, gender, ethnicity, Optosil score, EAT-10 score and product as between-subject factors and liking as covariate. Age, gender, ethnicity, Optosil score and EAT-10 score were included as categorical variables. Categorical variable age included a young (<30 yrs., $n=93$) and elderly group (>60 yrs., $n=31$). The young group included young Dutch-Caucasian and young Chinese-Asian participants. A group of consumers with good mastication efficiency (>50% of masticated particles had an average size of <3.5mm, $n=103$) and a group with low mastication efficiency ($\leq 50\%$ of masticated particles had an average size of <3.5mm, $n=32$) were compared. The EAT-10 score variable included a group with no swallowing problems (score 3 or more, $n=126$) and a group with mild-swallowing problems (score 0–2, $n=9$). Additional analyses of covariance (ANCOVA) were conducted to predict the effect of consumer characteristics and average bite size (g) of 18 food products on other oral processing parameters. Consumption time (s) for all three food categories and chews per bite (only for solid foods) were included as dependent variables; age, gender, ethnicity as between-subject factors; and average bite size (g) and liking as covariates. Effect sizes were calculated with Cohen's d values. Pearson correlations

of all 6 oral processing parameters were conducted to explore inter-relationships for all oral processing parameters.

4.3. Results

4.3.1. Effect of age on oral processing behavior of liquid, semi-solid and solid foods

Figure 4.1. Eating rate (g/s) for the drinkable, spoonable and chewable food for the various consumer groups, (A) Comparison between young ($n = 93$, 18-30 yrs) vs. elderly consumers ($n = 31$, > 60 yrs), (B) female ($n = 86$) vs. male ($n = 49$) consumers and (C) Dutch-Caucasian ($n = 93$) vs. Chinese-Asian ($n = 42$) consumers.

Table 4.3 summarizes the results of the effect of age on parameters describing oral processing behavior. A significant effect of age on consumption time (s) was found for all three food categories, drinkable [$F(1,113)=18.844$, $p<.001$], spoonable [$F(1,115)=16.778$, $p<.001$] and chewable foods [$F(1,110)=11.276$, $p=.001$]. Consumption time (s) was significantly longer for elderly (>60 yrs) than young consumers (<30 yrs). Elderly took on average 7.0s longer for consumption of chewable foods (Cohen's $d=3.4$), 1.3s longer for consumption of drinkable foods (Cohen's $d=2.4$) and 0.8s longer for consumption of spoonable foods (Cohen's $d=0.8$). A significant effect of age on average bite size (g) was only found for drinkable foods [$F(1,113)=4.398$, $p=.038$].

Elderly took on average 3.8g larger sips (Cohen's $d=8.9$) than young consumers. No significant effect of age on average bite size (g) of spoonable and chewable foods was found. A significant effect of age on eating rate (g/s) was found (Figure 4.1.A and Table

4.3) for drinkable [$F(1,113)=6.704$, $p=.011$], spoonable [$F(1,115)=9.142$, $p=.003$] and chewable foods [$F(1,110)=12.568$, $p=.001$]. Elderly consumed drinkable foods with a 0.8 g/s (Cohen's $d=2.6$) lower eating rate (g/s), spoonable foods with 0.1 g/s (Cohen's $d=0.3$) lower eating rate (g/s) and chewable foods with 4.0 g/s (Cohen's $d=4.0$) lower eating rate (g/s). For solid foods, the effect of age on chews per bite was significant [$F(1,110)=10.385$, $p=.002$] with elderly needing on average 10 more chews before swallowing solid foods compared to young consumers. Chewing rate and number of swallows were not significantly affected by age.

4.3.2. Effect of gender on oral processing behavior of liquid, semi-solid and solid foods

The results of the effect of gender on oral processing behavior are shown in Table 4.4. No significant effect of gender on consumption time (s) was found for all three food categories. A significant effect of gender on average bite size (g) was found for all three food categories, drinkable [$F(1,113)=6.434$, $p=.013$], spoonable [$F(1,115)=5.925$, $p=.016$] and chewable foods [$F(1,110)=7.896$, $p=.006$]. Males had an average 3.8g larger sip size for drinkable foods (Cohen's $d=9.5$), 3.3g larger average bite size (g) for spoonable foods (Cohen's $d=8.9$) and 1.3g larger average bite size (g) for chewable foods (Cohen's $d=8.5$). Gender significantly affected eating rate (g/s) only for chewable foods [$F(1,110)=6.859$, $p=.010$], with females consuming chewable foods with a 0.1 g/s lower eating rate (g/s) than males (Figure 4.1.B and Table 4.4). Eating rate (g/s) did not differ significantly between females and males for drinkable and spoonable foods. Chews per bite, chewing rate and number of swallows were not significantly different between males and females in all three food categories.

4.3.3. Effect of ethnicity on oral processing behavior of liquid, semi-solid and solid foods

Table 4.5 summarizes the results of the effect of ethnicity on oral processing parameters. No significant effect of ethnicity on consumption time (s) was observed for all three food categories. Ethnicity significantly affected average bite size (g) for all three food categories, drinkable [$F(1,113)=12.322$, $p=.001$], spoonable [$F(1,115)=23.782$, $p<.001$] and chewable

foods [$F(1,110)=10.150$, $p=.002$]. Sip size of drinkable foods was 4.8g smaller for Chinese-Asian compared to Dutch-Caucasian consumers (Cohen's $d=11.2$). Average bite size (g) of spoonable foods was 3.8g smaller for Chinese-Asian compared to Dutch-Caucasian consumers (Cohen's $d=9.7$) and average bite size (g) of chewable foods was 1.8g smaller for Chinese-Asian compared to Dutch-Caucasian consumers (Cohen's $d=10.7$). Ethnicity significantly affected eating rate (g/s) (Figure 4.1.C and Table 4.5) for drinkable [$F(1,113)=12.529$, $p=.001$], spoonable [$F(1,115)=15.349$, $p<.001$] and chewable foods [$F(1,110)=7.590$, $p=.007$]. Chinese-Asian consumers had a 1.4 g/s lower eating rate (g/s) compared to Dutch-Caucasian consumers, for drinkable foods (Cohen's $d=5.1$), 1.5 g/s lower eating rate (g/s) for spoonable foods (Cohen's $d=6.7$) and 0.1 g/s lower eating rate (g/s) for chewable foods (Cohen's $d=7.0$). No significant effect of ethnicity on chews per bite, chewing rate and number of swallows was observed.

4.3.4. Effect of mastication efficiency and mild swallowing problems on oral processing behavior of liquid, semi-solid and solid foods

Table 4.6 and Table 4.7 summarize the results of the effect of mastication efficiency and mild swallowing problems on oral processing parameters. No significant effect of mastication efficiency and mild swallowing problems were found for any of the oral processing parameters for any of the three food categories. The consumer groups with high (>50% of masticated particles had an average size of <3.5mm, $n=103$) and low mastication efficiency ($\leq 50\%$ of masticated particles had an average size of <3.5mm, $n=32$) and the consumer groups without (EAT-10 score 0–2, $n=126$) and with mild swallowing problems (EAT-10 score 3 or more, $n=9$) showed no significant differences in drinking and chewing behavior.

4.3.5. Effect of average bite size (g) and consumer characteristics on parameters describing oral processing behavior

Additional ANCOVA's were conducted to investigate the effect of average bite size (g) and consumer characteristics (age, gender and ethnicity) on consumption time (s) and chews per bite. For chewable foods, a significant effect of average bite size (g) [$F(1,1062)=76.556$, $p<.001$], age [$F(1,1062)=73.412$, $p<.001$] and gender [$F(1,1062)=4.655$, $p=.031$] on

consumption time (s) was found. Consumer with a larger average bite size (g), older age and male consumers chewed solid foods with longer consumption time (s). No significant effect of average bite size (g) on consumption time (s) and chews per bite was found for drinkable and spoonable foods. A second ANCOVA model found a significant effect of average bite size (g) [$F(1,1054)=71.570$, $p<.001$], age [$F(1,1054)=56.304$, $p<.001$] and ethnicity [$F(1,1054)=8.936$, $p<.001$] on chews per bite for solid foods. Consumers with a larger average bite size (g), older age and Caucasian consumers chewed solid foods with more chews per bite.

Table 4.2. Pearson correlations of all 6 oral processing parameters.

	Consumption time	Bite size	Number of swallows	Eating rate	Chews per bite	Chewing rate
Consumption time	-	-0.418**	0.557**	-0.539**	0.943**	-0.089*
Bite size	-0.418**	-	-0.103**	0.691**	0.262**	-0.001
Number of swallows	0.557**	-0.103**	-	-0.372**	0.450**	-0.226**
Eating rate	-0.539**	0.691**	-0.372**	-	-0.377**	0.021
Chews per bite	0.943**	0.262**	0.450**	-0.377**	-	0.204**
Chewing rate	-0.089*	-0.001	-0.226**	0.021	0.204**	-

* Correlation is significant with p<.01, ** Correlation is significant with p<.001

Table 4.3. Mean values and SE for parameters describing oral processing behavior of Young (<30 yrs, n=93) and Elderly (>60 yrs, n=31) consumers for all drinkable, spoonable and chewable foods.

	Drinkable		Spoonable		Chewable	
	Young	Elderly	Young	Elderly	Young	Elderly
Consumption time (s)	2.9±0.5	4.4±0.8	5.5±0.9	6.3±1.3	18.5±1.6	25.5±2.5
Bite size (g)	12.7±0.3	16.5±0.5	8.9±0.3	11.3±0.5	4.5±0.1	5.1±0.2
Number of swallows (-)	1.3±0.1	1.3±0.2	1.5±0.2	1.5±0.3	1.8±0.1	1.8±0.2
Eating rate (g/s)	5.8±0.2	5.0±0.3	2.52±0.2	2.45±0.3	0.3±0.01	0.2±0.01
Chews per bite (-)	-	-	-	-	25.9±2.1	35.8±3.3
Chewing rate (chews/s)	-	-	-	-	1.4±0.01	1.4±0.01

* Age effect is significant at p<.05, ** at p<.01 and *** at p<.001.

Table 4.4. Mean values and SE for parameters describing oral processing behavior of Female (n=86) and Male (n=49) consumers for all drinkable, spoonable and chewable foods.

	Drinkable		Spoonable		Chewable	
	Female	Male	F(Cohen's d)	Female	Male	F(Cohen's d)
Consumption time (s)	3.3±0.5	3.6±0.7	0.6 (0.5)	5.4±0.9	6.23±1.15	1.3 (0.9)
Bite size (g)	12.2±0.4	16.0±0.5	6.4 (9.5)***	8.2±0.3	11.46±0.41	5.9 (8.9)**
Number of swallows (-)	1.3±0.1	1.3±0.2	0.0 (0.4)	1.5±0.2	1.5±0.22	0.0 (0.0)
Eating rate (g/s)	5.1±0.2	6.0±0.3	0.7 (3.2)	2.2±0.2	2.84±0.23	0.4 (3.2)
Chews per bite (-)	-	-	-	-	-	-
Chewing rate (chews/s)	-	-	-	-	-	-

* Gender effect is significant at p<.05, ** at p<.01 and *** at p<.001.

Table 4.5. Mean values and SE for parameters describing oral processing behavior of Dutch-Caucasian (n=93) and Chinese-Asian (n=42) consumers for all drinkable, spoonable and chewable foods.

	Drinkable		Spoonable		Chewable	
	Caucasian	Asian	F(Cohen's d)	Caucasian	Asian	F(Cohen's d)
Consumption time (s)	3.6±0.5	3.0±0.8	2.4 (0.9)	5.6±0.9	6.1±1.3	1.0 (0.4)**
Bite size (g)	15.5±0.3	10.7±0.5	12.3 (11.2)***	11.0±0.3	7.2±0.5	23.8 (9.7)***
Number of swallows (-)	1.3±0.1	1.3±0.2	0.2 (0.4)	1.5±0.2	1.5±0.3	0.6 (0.1)
Eating rate (g/s)	6.0±0.2	4.6±0.3	12.5 (5.1)***	3.0±0.2	1.5±0.3	15.3 (6.7)***
Chews per bite (-)	-	-	-	-	-	-
Chewing rate (chews/s)	-	-	-	-	-	-

* Ethnicity effect is significant at p<.05, ** at p<.01 and *** at p<.001

Table 4.6. Mean values and SE for parameters describing oral processing behavior of consumers with low (≤50% of masticated particles had an average size of <3.5mm, n=32) and high (>50% of masticated particles had an average size of <3.5mm, n=103) mastication efficiency for all drinkable, spoonable and chewable foods.

	Drinkable		Spoonable		Chewable	
	Low	High	F(Cohen's d)	Low	High	F(Cohen's d)
Consumption time (s)	3.1±0.7	3.6±0.5	1.1 (0.7)	5.2±1.2	6.1±0.9	2.0 (0.9)
Bite size (g)	13.7±0.5	14.1±0.4	2.2 (1.0)	9.5±0.4	9.9±0.3	3.4 (1.1)
Number of swallows	1.4±0.2	1.3±0.1	0.0 (0.9)	1.5±0.2	1.5±0.2	0.7 (0.3)
Eating rate (g/s)	5.8±0.3	5.3±0.2	0.0 (1.8)	2.8±0.2	2.3±0.2	0.0 (2.2)
Chews per bite (-)	-	-	-	-	-	-
Chewing rate (chews/s)	-	-	-	-	-	-

Table 4.7. Mean values and SE for parameters describing oral processing behavior of consumers with mild (score 0-2, n=126) and without (score 3 or more, n=9) swallowing problems for all drinkable, spoonable and chewable foods.

	Drinkable		Spoonable		Chewable	
	No problems	Mild problems	F(Cohen's d)	No problems	Mild problems	F(Cohen's d)
Consumption time (s)	3.8±0.4	2.3±1.2	2.6 (2.0)	6.0±0.6	5.3±2.1	0.0 (0.5)
Bite size (g)	14.4±0.3	12.6±0.8	0.1 (3.5)	10.3±0.2	8.2±0.7	0.0 (4.3)
Number of swallows	1.4±0.1	1.2±0.3	0.3 (0.8)	1.5±0.1	1.4±0.4	0.5 (0.6)
Eating rate (g/s)	5.3±0.2	6.1±0.5	1.6 (2.3)	2.6±0.1	2.1±0.4	0.0 (2.0)
Chews per bite (-)	-	-	-	-	-	-
Chewing rate (chews/s)	-	-	-	-	-	-

4.4. Discussion

The aim of this study was to determine the effect of age, gender, ethnicity and eating capability on oral processing behavior of liquid, semi-solid and solid foods. This study found an effect of age, gender and ethnicity on multiple oral processing parameters for foods ranging from liquids to solids.

Elderly consumers had longer consumption times (s) and lower eating rates (g/s) than young consumers for liquid, semi-solid and solid foods. Elderly consumers displayed larger average bite sizes (g) than young consumers only for liquid foods and masticated solid foods with more chews per bite compared to young consumers. The increase in consumption time (s) and chews per bite for elderly for solid foods is in line with multiple other studies ^{27,31,32}. The increase in consumption time (s) and reduction in eating rate (g/s) for liquid and semi-solid foods in the elderly has not been reported yet but shows similar and consistent trends as observed for the chewing behavior of solid foods. The elderly participating in the current study had two or less missing teeth, no removable crowns, dentures or implants, thus the dental status of the elderly can be considered good. Therefore, the effect of declining dental status in the elderly on oral processing behavior is negligible in our study. We speculate that the decline in muscle mass with ageing caused the observed changes in oral processing behavior. During ageing physiological changes occur, including declining muscle strength and increasing difficulty with complex motor activities ³². Elderly in this study might have compensated for loss of muscle strength by increasing consumption time (s) and chews per bite, which has been found in previous studies ^{27,31}. Due to longer consumption time (s), eating rate (g/s) of elderly was significantly lower compared to eating rate (g/s) of young consumers. Surprisingly, average bite size (g) of drinkable foods was larger for elderly compared to young consumers whereas average bite size (g) of spoonable and chewable foods did not differ between elderly and young consumers. We currently do not have a thorough explanation for this observation. It would be interesting whether these findings can be validated in a different population with similar selection criteria in a different study. Oral volume has been reported to decrease during ageing ²⁴. Thus, if bite size (g) was strongly related to oral volume, bite size (g) would have been expected to decrease for all three food categories. We speculate that the effect of age on bite size (g) is not necessarily

related to oral volume but might be associated with other physiological and anatomical parameters. We conclude that drinking behavior of liquid foods and oral processing behavior of spoonable foods are affected by age in a similar manner as chewing behavior of solid foods.

With respect to the influence of gender on oral processing behavior of liquid, semi-solid and solid foods, males had larger average bite size (g) for liquid, semi-solid and solid foods and higher eating rate (g/s) for solid foods than females. Consumption time (s) did not differ between males and females for any of the food categories. Significant larger average bite sizes (g) for males compared to females for solid foods are in agreement with previous studies on oral processing behavior of solid foods ^{37,38}. Park and Shin found larger bite size (g) and higher eating rate (g/s) for males than females ³⁸. No previous studies have reported yet the influence of gender on oral processing behavior of liquids and semi-solids, however the current study shows similar behavior for liquids and semi-solids as for solid foods. The largest differences in average bite size (g) between males and females were observed in drinkable foods. Liquids were consumed in a cup, resulting in larger average bite size (g) compared to semi-solid and solid foods which were consumed with a fork or spoon ⁶⁹. Males had a larger average bite size (g) than females for the three food categories, whereas consumption time (s) did not differ. This suggest that compared to females, males increase eating rate (g/s) by increasing bite size (g), while masticating for the same time. Park and Shin found higher eating rates (g/s), larger bite size (g) and shorter meal duration for males ³⁸, indicating both bite size (g) and meal duration contribute to higher eating rate (g/s) of males compared to females. However, in the current study we do not find a difference in consumption time (s) between genders. Oral physiological and anatomical parameters could also influence oral processing behavior. Muscle strength and salivary flow rate are known to be larger in males compared to females ^{29,145}. Muscle strength and salivary flow rate can facilitate oral processing behavior and might reduce consumption time (s) and increase eating rate (g/s). Maximum bite force has been shown to be larger in males than females and exceeds for both genders the forces needed to chew even hard, solid foods ^{25,158}. In the current study we observe a different mechanism where eating rate (g/s) was increased in males by increasing average bite size (g). It is questionable whether the

maximum muscle strength is necessary for oral processing of the foods in the current study. It is therefore interesting to study the importance of muscle strength and other physiological parameters, including salivary flow rate, on the oral processing behavior of males and females. Secondly, males have a higher energy need compared to females, which can explain the higher eating rate (g/s) for males¹⁵⁹. Henry et al. found a positive association between eating rate (g/s) and basal metabolic rate (BMR)¹⁵⁹, indicating different energy requirements of both genders impact eating behavior. We conclude that gender affects oral processing behavior of liquid and semi-solid foods in a similar manner as solid foods.

Oral processing behavior of liquid, semi-solid and solid foods by consumers belonging to different ethnicities has not been compared yet. Average bite size (g) and eating rate (g/s) were lower for Chinese-Asian than Dutch-Caucasian consumers for liquid, semi-solid and solid foods. Consumption time (s) was higher for Chinese-Asian than Dutch-Caucasian consumers for semi-solid foods and did not differ for liquid and solid foods. Similar to the effect of gender on eating rate (g/s), the difference in eating rate (g/s) between the two ethnicities is realized mainly by changing bite size (g) rather than consumption time (s). Since the oral processing behavior of consumers with different ethnicity has not been studied before, it is not clear whether the physical ability to adapt bite size (g) and/or consumption time (s) drives oral processing behavior. Difference in eating behavior between Chinese-Asian and Dutch-Caucasian consumers might be explained by differences in oral physiology and anatomy, such as differences in volume of oral cavity. Xue and Hao found that Chinese-Asian consumer have a larger oral cavity compared to Caucasian-American consumers⁴¹. This could suggest an inverse relationship between volume of oral cavity and bite size (g), with a smaller bite size (g) for consumers with a larger oral cavity. However, the link between volume of oral cavity with oral processing behavior has not been studied yet and different ethnicities which is recommended as future studies. In addition, differences in culture and eating habits may contribute to differences in oral processing behavior between Chinese-Asian and Dutch-Caucasian consumers. The consumers in the current study were selected by a combination of ethnicity, either Asian or Caucasian, and nationality, either Chinese or Dutch. Ethnicity might be linked to physiology and anatomy, whereas nationality might be linked more to culture, eating habits and consumption

context. Consumers might adapt their eating behavior to the culture, while the physiology might not adapt. Consumption in company of other people for instance, is known to increase food intake compared to consumption alone due to a longer consumption time ¹⁶⁰. As Asian cultures are known to be more group-focused compared to the individual-focused Western cultures ¹⁶¹, this might affect their oral processing behavior for instance by a longer consumption time and lower eating rate (g/s). The use of different utensils could also affect the oral processing behavior. Consumption with chopsticks is known to result in lower eating rates (g/s) compared to consumption with a spoon ¹⁶². In the current study, spoonable foods were consumed using spoons and chewable foods were consumed by most participants using their hands (chocolate, carrots, tofu and all cheeses) or using fork and knife (beef, noodles). Drinking from a cup and eating with a spoon is as common for Chinese-Asian as for Dutch-Caucasian. This suggests that the lower eating rate (g/s) observed in this study is unlikely to be explained by differences in the skill of using cutlery. In general, cultural differences in cutlery familiarity might influence oral processing behavior of foods, but this would need further research. We conclude that for liquid, semi-solid and solid foods Chinese-Asian consumer orally process foods with smaller average bite sizes (g) and lower eating rate (g/s) than Dutch-Caucasian consumers.

Mastication efficiency and mild swallowing problems did not significantly affect oral processing parameters in this study. This group of consumers consisted of healthy consumers with no major mastication or swallowing issues, only subjects with mild self-reported mastication and swallowing issues participated in the study, and all subjects had good dental status. This might explain the lack of difference in oral processing behavior between the groups with low and high mastication efficiency and between the groups without and with mild, self-reported swallowing problems. Mastication efficiency of all groups was assessed during one session but might have varied day-to-day. Nevertheless, we did not observe significant differences in eating behavior between the groups with low and high mastication efficiency. Other studies that included a decreased eating capability group, selected either consumers with more severe mastication or swallowing problems (i.e. dental patients) or limited the selection criteria to dental status (i.e. denture wearers and natural dentition). Both were excluded for this study. The selection of relatively healthy

participants in this study was done on purpose to compare only healthy participants. The participants with decreased eating capability in this study also include a large variation in age and ethnicity, resulting in a heterogeneous group with decreased eating capability. This could explain the lack of differences observed between the group with decreased eating capabilities and the 'healthy' consumers in oral processing behavior in our study. Future studies on the effect of eating capability should keep this in mind when defining inclusion criteria.

It is important to acknowledge the limitations of the study. First, the sample size of the four consumer groups is relatively small. In total, $n=135$ subjects participated in the study. Those subjects were divided into four groups, so that each group consisted of <40 subjects. Groups also differed in number of subjects. Therefore, the comparisons of the different consumer groups are not necessarily balanced. It would be interesting to validate the findings of this study in future studies with larger and balanced consumer groups. Secondly, only $n=35$ adults with Chinese nationality and Asian ethnicity participated in this study. We emphasize that this group is by no means representative for Asians. Findings of this study cannot be extrapolated to a generalized, Asian population since sample size of this study is too small and excluded Asians of different nationality, e.g. Indian Asians and Indonesian Asians. Future studies should include larger groups of Asian consumers, with a variety of nationalities. Thirdly, the number of foods in this study was limited to 18 drinkable, spoonable and chewable foods. While foods varying in consistency were included in the study, the foods do not cover the full range of complete food structures that are commonly consumed foods and its structures and textures. Future studies should include more foods to cover all commonly consumed products. Since this is a first explorative study on oral processing behavior of spoonable, drinkable and chewable foods in different consumers groups, only a selection of foods were studied in $n=135$ subjects. The current study showed that age, gender and ethnicity effect oral processing behavior of liquid, semi-solid and solid foods. These consumers groups might have generated different food bolus during oral processing. This might possibly lead to differences in sensory and texture perception between the consumer groups. Future studies should explore further how differences in oral processing behavior between consumer groups can be used to explain differences in

sensory perception between groups. Eating rate (g/s) is well known to impact food intake, energy intake and subsequently body weight, therefore impacting public health. Understanding differences in oral processing behavior between consumer groups may provide new solutions to regulate food intake in vulnerable populations, for example contribute to increased food intake in the elderly or decreased food intake in the overweight.

4.5. Conclusions

Age, gender and ethnicity affected oral processing behavior of various liquid (drinkable), semi-solid (spoonable) and solid (chewable) foods differently. Elderly consumed all foods with longer consumption time (s), liquid foods with larger average bite size (g) and all foods with lower eating rates (g/s) than young consumers. Males consumed all foods with the same consumption time (s), all foods with larger average bite sizes (g) and solid foods with higher eating rate (g/s) than females. Chinese-Asian consumers consumed semi-solid foods with longer consumption time (s), all foods with smaller bites sizes and all foods with lower eating rates (g/s) than Dutch-Caucasian consumers. Eating rate (g/s) was generally modified by changing consumption time (s) or average bite size (g) or both. Eating rate (g/s) of elderly compared to young adults seems to be reduced mainly by increasing consumption time (s) while average bite size (g) remains constant, with the exception of semi-solid foods. Females in comparison to males seem to reduce eating rate (g/s) of solid foods mainly by taking smaller bites while keeping consumption time (s) constant. Chinese-Asian in comparison to Dutch-Caucasian consumers seem to realize lower eating rates (g/s) mainly by decreasing bite size (g) while keeping consumption time (s) constant with the exception of semi-solid foods. These differences in oral processing behavior might be explained by differences in oral physiology, anatomy and nutritional needs between consumer groups. To further understand oral processing behavior of different consumers, it is important to further compare oral physiology and anatomy between consumer groups and link this with the oral processing behavior. It should also be explored in future studies how differences in oral processing behavior between larger consumers groups influence sensory perception, acceptance and food intake of a broader range of foods.

5

Adaptation in oral processing behavior of consumers differing in age, gender and ethnicity leads to differences in bolus properties but not in dynamic texture perception of sausages

This chapter has been submitted as:

Aguayo-Mendoza, M. G., Martinez-Almaguer, E. F., Piqueras-Fiszman, B. & Stieger, M.

Differences in oral processing behavior of consumers varying in age, gender and ethnicity lead to changes in bolus properties but only to small differences in dynamic texture perception of sausages.

Abstract

Consumer characteristics such as age, gender and ethnicity influence food oral processing behavior. The aim of this study was to determine the effect of age, gender and ethnicity on consumption time, bolus properties and dynamic sensory perception of sausages. Consumption time, bolus properties (saliva incorporation, particle size distribution and rheological properties) and dynamic texture perception (Temporal Dominance of Sensations, TDS) were compared between young Dutch-Caucasian ($n=21$; 22 ± 2.8 yrs), young Chinese-Asian ($n=21$; 23 ± 1.6 yrs), and older Dutch-Caucasian ($n=22$; 70 ± 4.3 yrs) adults. Older adults ($25.6s$) masticated the sausage sample 22% longer than young adults ($21.0s$). Older adults produced sausage boli that were softer, more adhesive, less cohesive and consisting of more particles than young adults. Older females produced more adhesive and less cohesive sausage bolus than older males. Chinese females had 75.6% longer consumption time ($29.5s$) than Dutch females ($16.8s$). Chinese males masticated the sausages in less time ($18.8s$) than Chinese females ($29.5s$). Chinese adults produced softer and less cohesive bolus with slightly smaller and more particles than Dutch adults. Saliva incorporation and bolus particle size were not affected by age, gender and ethnicity. The effect of consumer characteristics on bolus properties was mediated by consumption time. At the beginning and end of consumption time, dynamic texture perception of sausages was similar for all consumer groups and strongly correlated with bolus properties. Differences in dynamic texture perception between consumer groups were observed only during the middle stages of mastication. We conclude that consumers differing in age, gender and ethnicity adapt oral processing time to safely swallow bolus with textural properties optimized for their needs. Thus, consumption time is the underlying mechanism that explains the differences in bolus properties between the consumer groups. While adaptation in consumption time of sausages leads to differences in bolus properties, it does not lead to considerable differences in dynamic texture perception.

5.1. Introduction

In order to form a swallowable bolus, oral processing behavior is adapted to the rheological and mechanical properties of foods by modifying bite size, consumption time, number of chews^{69,113} and/or muscle activity¹⁴². Food oral processing behavior also depends on consumer characteristics such as age, gender and ethnicity. Several studies demonstrated that older adults masticate foods with more chewing cycles, longer chewing times and lower eating rates than young adults^{27,31,68,163}. Females chew foods longer than males and take smaller bites leading to lower eating rates than males^{31,37,38,68}. While the influence of age and gender on food oral processing behavior has been studied extensively, little is known about the effect of ethnicity on food oral processing behavior. Recent studies indicated that bite size and eating rate are lower in Asians than Caucasians⁶⁸. Differences in oral processing behavior may impact the structural transitions of the bolus during mastication and in turn might impact sensory perception¹⁶⁴.

The goal of oral processing is to achieve a ready and safe to swallow bolus^{165,166}. Solid foods are broken down into many small particles during oral processing and lubricated with saliva and serum released from the food³. The swallowing threshold depends mainly on the level of structure breakdown and the lubrication properties of the bolus. Bolus formation and properties may be impacted by oral processing behavior, so that differences in oral processing behavior contribute to differences in bolus properties. How bolus properties evolve during mastication and when the bolus is sensed as safe to swallow may depend on individual characteristics of the consumer and may vary between groups of consumers.

During bolus formation in the oral cavity the sensory properties of the food are constantly evaluated. Dynamic perception of texture attributes may be linked to dynamic structural transformations of the bolus. Differences in sensory perception upon changes in oral behavior have been reported previously for various foods^{75,167}. Currently, there is a lack of understanding how differences in oral processing behavior between consumer groups lead to differences in bolus properties and consequently differences in sensory perception. Such knowledge could provide insights to tailor foods towards specific consumer groups based on consumer characteristics. The aim of this study was to determine the influence of age, gender and ethnicity on consumption time, bolus properties and dynamic texture

perception of sausages. Consumption time was chosen as the variable to quantify oral processing behavior based on previous findings that show that consumption time and bite size are the most relevant parameters for oral processing^{68,69}. Bolus properties (saliva incorporation, particle size distribution and rheological properties) were analyzed and compared between consumer groups varying in age, gender and ethnicity. Temporal dominance of sensations (TDS) was used to compare dynamic texture perception of sausages between consumer groups and to link bolus properties to dynamic sensory perception.

5.2. Materials and methods

5.2.1. Subjects

Sixty-four subjects were recruited through social media and printed advertisements: n=21 young Dutch-Caucasian adults (eleven females and ten males, 22 ± 2.8 yrs); n=21 young Chinese-Asian adults (twelve female and nine males, 23 ± 1.6 yrs) living in The Netherlands and outside China for less than one year; and n=22 older Dutch-Caucasian adults (eleven females and eleven males, 70 ± 4.3 yrs). All participants were healthy (self-reported), without swallowing or mastication disorders and had no missing teeth (except for third molars or wisdom teeth). All subjects gave written informed consent prior to the study and were compensated for their participation. The study was conducted in line with the Declaration of Helsinki.

5.2.2. Test food and serving size

Commercially available canned hotdog sausages (Unox® Hotdogs, Unilever, The Netherlands) were used. For bolus collection and sensory evaluations, hotdog sausages were cut into cylinders of 20mm diameter and 30mm height with a constant weight of 7g and served at room temperature without further preparation.

5.2.3. Consumption time

Consumption time was measured per subject in triplicate to determine consumption time corresponding to 100% of mastication of one sample. Participants were asked to chew it normally and to indicate the main swallowing moment by raising a hand. The time needed

to consume each sausage sample was recorded by the researcher and the average time of three replicates per participant determined. This average was considered 100% of mastication time of the participant.

5.2.4. Bolus collection and characterization

Collection of sausage boli was done in two sessions of 30 min each. During each session, participants were instructed to place the sausage sample (7 g) in their mouth, chew it as they would normally do for their individual 33, 66 or 100% of mastication time, and expectorate the bolus in a coded container. To provide participants with a comfortable atmosphere, bolus collection sessions were held individually. The expectorated sausage boli collected in the first session were used to determine particle size distribution and saliva incorporation. Expectorated boli collected in the second session were used to quantify rheological bolus properties.

Particle number and size analysis

Participants expectorated the sausage bolus directly into a petri dish, then a glycerol-water (1:2) solution was added to the bolus allowing the separation of bolus particles. To improve separation of particles further, they were gently manually separated with a spatula. Petri dishes were placed on a scanner (CanonScan 9000F markII) and images obtained in greyscale (8 bit) with a resolution of 1200 dpi. Images were analyzed using ImageJ (National Institutes of Health, Version 1.51g) and the median particle size in μm (d_{50}) and number of particles determined. This procedure was done in duplicate per participant for each expectoration time point (33, 66 and 100% mastication time).

Moisture content and bolus saliva incorporation

Boli were expectorated into aluminum plates and wet bolus weight was determined. Boli were dried for 16 h at 105°C in an atmospheric oven (Venti-line line, VWR®). After drying, samples were weighed again. This procedure was done in duplicate per participant and for each expectoration time point (33, 66 and 100% mastication time). Saliva content was calculated following the method described by Drago et al ⁵⁷ which takes into account the amount of food that remains in the mouth after oral processing. The mass ratio of saliva

incorporated into the bolus (mg) per gram of food masticated was calculated (h_w) as follows:

$$h_w = \frac{DM_{sample} * 1000}{DM_{spit_bolus}} - 1000$$

Mechanical bolus properties determined by two cycle penetration tests

To obtain boli with cylindrical shapes of similar dimensions, participants expectorated bolus into a 35mm diameter cup with a line marked at 25mm height. Boli surfaces were gently evened with the flat side of the plunger of a 50 mL syringe. Immediately after expectoration, boli were analyzed by a two-cycle penetration test using a Texture Analyzer (TA. XT plus) equipped with a load cell of 5 kg and a cylindrical steel probe of 20mm diameter. Two successive penetration cycles were performed at a constant speed of 5mm/s up to 50% strain with a resting time of 5s between both penetration cycles. Three replicates were performed for all boli expectorated after 33, 66 and 100% of mastication time of each participant. From the two cycle penetration tests, maximum force (N) of first penetration (firmness), negative area under force-time curve (N*s) between the moment that the probe is retrieved after first penetration until second penetration (adhesiveness) and ratio between area under the force-time curve of the second and first compression cycle (cohesiveness) were extracted.

5.2.5. Sensory evaluation

Texture attribute generation

A preliminary list of 13 attributes describing texture perception of sausages was obtained from literature^{75,168–175}. To generate the list of attributes used for Temporal Dominance of Sensation (TDS), these 13 attributes were evaluated by n=43 subjects from the consumer groups using a Check-All-That-Apply evaluation of the sausage. The eight most frequently checked texture attributes (Table 5.1) were selected to be used in the TDS evaluation.

TDS evaluation

A 60 min familiarization session was performed to introduce the concept of temporality of sensations and to explain the dominant sensation as “the attribute associated with the

sensation catching the attention at a given time, and not necessarily the attribute with the highest intensity”⁸⁸. Afterwards, texture attributes were presented to the subjects together with their definitions. In addition, subjects performed a TDS test with a dummy sausage sample to familiarize themselves with the sensory methodology and software used (EyeQuestion v3.9.7). Subjects were encouraged to ask questions at any time during this familiarization session. No further training was done in order to avoid biasing the oral processing behavior of subjects¹⁷⁶.

Table 5.1. Texture attributes and definitions used for TDS evaluation of hotdog sausages.

Attribute	Definition
Firmness	Force needed to bite through the sausage
Chewiness	Amount of work required to chew the sausage into a state that is ready to swallow
Juiciness	Water release from sausage perceived during mastication
Graininess	From crumbly to granular particles in the mouth
Smoothness	Homogeneity of the sausage in the mouth
Fattiness	Perception of fat
Slippery	Easiness to move the sausage in the mouth
Dryness	Rough feeling in the mouth

Sensory evaluation was performed in a well-lit room with a portable separator used to create sensory booths. During one session of 30 min participants (n=21 young Dutch-Caucasian; n=21 young Chinese-Asian adults; n=22 older Dutch-Caucasian adults) received a dummy sausage sample and the hotdog sausage sample in triplicate (6 samples per session per subject). A dummy sample was included for randomization and blinding purposes since we were interested only in the texture evaluation of one type of sausage. Hotdog sausage samples were presented one by one on a plate labeled with three-digit codes following a counterbalanced design. Participants were instructed to put the sausage sample (7 g) into their mouth and click the start button to begin the evaluation. The texture attributes were presented simultaneously on a computer screen. Subjects were free to select an attribute several times or to not select it at all throughout the evaluation. To facilitate the assessment and to avoid confusion, attributes were presented in random order across the panel but remained in the same position for a given panelist during the

whole session. Finally, participants pressed the stop button to indicate the swallowing moment. Between samples participants were asked to neutralize their palate by eating an unsalted cracker and rinsing their mouth with water.

5.2.6. Data analysis

A two-way ANOVA was performed to determine the effect of gender and age and their interaction on consumption time and bolus properties at the swallowing point (100% mastication time). Another two-way ANOVA was performed to determine the effect of gender and ethnicity and their interaction on consumption time and bolus properties at the swallowing point (100% mastication time). Effects were considered statistically significant at $p < 0.05$. When applicable, post-hoc analyses were performed with Bonferroni adjustment.

Mediation analyses were performed to determine the effect of age, gender and ethnicity on bolus properties (saliva incorporation, median particle size, particle number, hardness, cohesiveness, adhesiveness) using consumption time as mediator (Figure 5.1).

Figure 5.1. Mediation model of age, gender and ethnicity as predictors for the outcome variables of bolus properties, mediated by the consumption time. The regression coefficients a , b , and c' estimate the effect of the predictor on the mediator, the effect of the mediator on the outcome variable, and the direct effect of the predictor on the outcome variable, respectively.

The effect of age and gender on bolus properties was determined between the groups of young Dutch ($n=21$) and older Dutch ($n=22$) adults. To determine the effect of ethnicity on bolus properties, young Dutch ($n=21$) adults were compared to young Chinese adults ($n=21$). Indirect effects were estimated by bootstrapping using 5000 bootstrap samples and

reported with bias corrected confidence intervals. When the confidence intervals did not include zero, mediation was considered existent. Data are presented as mean $\pm$ SE.

To illustrate the evolution of sensory perception, TDS curves were built by plotting dominance rate (proportion of subjects who scored each attribute at each point of time as dominant sensation) against consumption time. In order to take into account differences in consumption time between subjects, data used to build the curves were time standardized on a scale from 0 (starting point) to 100 (swallowing moment). Chance and significance level were calculated as described by Pineau ⁸⁸.

To investigate the relationships between bolus properties at three expectoration times and dynamic texture perception from TDS, a Multiple Factor Analysis (MFA) was performed with two data matrices as active datasets. Bolus properties collected at the different expectoration time points (33, 66 and 100% mastication time; see Appendix 5.1) formed one data matrix. The second matrix included the values of the cumulative dominance rate for each attribute at during three time periods 33 (T0 – T33), 66 (T34 – T66) and 100 (T67 – T100) of standardized consumption time. Cumulative dominance rate was calculated by summing the significant dominance rates of each attribute per period. Individuals graphs and correlations circles were plotted for dimensions one and two.

Data analyses were performed in R v3.6.3. Two-way ANOVA analyses were performed using *rstatix* package v0.4.0. TDS curves and sensory trajectories were constructed using *tempR* package v0.9.9.16. MFA analysis were performed with packages *FactoMineR* v2.3 and *factoextra* v1.0.7. Mediation analysis was performed using SPSS v24.0 and the *PROCESS* macro v3.00.

5.3. Results

5.3.1. Effect of age, gender and ethnicity on consumption time

Age had a significant effect [$F(1,125)=27.37$, $p<0.001$] on consumption time among Dutch consumers, with older adults having longer consumption time ($25.6\pm1.4s$) than young adults ($21.0\pm0.9s$) (Table 5.2). Gender had a significant effect on consumption time only for Chinese consumers [$F(1,122)=28.2$, $p<0.001$] with males ($18.8\pm1.1s$) having a shorter consumption time than females ($29.5\pm1.8s$). Ethnicity had a significant effect on

consumption time only within females [$F(1,122)=44.4$, $p<0.001$], with Chinese females having longer consumption time (29.5 ± 1.8 s) than Dutch females (16.8 ± 1.1 s) (Table 5.2).

5.3.2. Effect of age, gender and ethnicity on bolus properties at the swallowing point

Table 5.2 shows descriptive data of all consumer groups for the measured bolus properties at swallowing point. Age had a significant effect on bolus hardness [$F(1,125)=5.79$, $p=0.018$] among Dutch consumers with older adults producing softer bolus (1.95 N) than young adults (2.3 N). Age had a significant effect in Dutch females on bolus adhesiveness [$F(1,122)=6.09$, $p=0.015$], cohesiveness [$F(1,125)=4.32$, $p=0.040$], and number of bolus particles [$F(1,82)=4.27$, $p=0.042$]. Older Dutch females produced a more adhesive (0.05 N*s) and less cohesive (0.37) bolus containing more particles (561) than young Dutch females (0.03 N*s, 0.41 and 381 respectively). Age did not have a significant effect on saliva ratio h_w and bolus particle size d_{50} .

Table 5.2. Descriptive data (Mean $\pm$ SE) of consumption time and bolus properties of consumers differing in age ($n=22$ older adults Dutch, $n=21$ young Dutch), ethnicity ($n=21$ young Dutch, $n=21$ young Chinese), and gender ($n=34$ females, $n=30$ males). Bolus data was collected at the swallowing point (100% mastication time).

	Young adults				Older adults	
	Chinese		Dutch			
	Females	Males	Females	Males	Females	Males
Consumption time (s)	29.5 $\pm$ 1.8	18.8 $\pm$ 1.1	16.8 $\pm$ 1.1	17.2 $\pm$ 1.4	27.6 $\pm$ 2.3	23.5 $\pm$ 1.5
Hardness (N)	1.79 $\pm$ 0.1	2.12 $\pm$ 0.13	2.35 $\pm$ 0.13	2.27 $\pm$ 0.21	2.04 $\pm$ 0.1	1.86 $\pm$ 0.14
Adhesiveness (N*s)	0.04 $\pm$ 0.005	0.04 $\pm$ 0.006	0.03 $\pm$ 0.005	0.03 $\pm$ 0.005	0.05 $\pm$ 0.006	0.03 $\pm$ 0.005
Cohesiveness (-)	0.36 $\pm$ 0.01	0.39 $\pm$ 0.01	0.41 $\pm$ 0.01	0.40 $\pm$ 0.01	0.37 $\pm$ 0.01	0.39 $\pm$ 0.01
Particle size d_{50} (μ m)	1935 $\pm$ 28	1944 $\pm$ 27	2008 $\pm$ 25	1968 $\pm$ 19	1936 $\pm$ 20	1961 $\pm$ 16
Number of particles	623 $\pm$ 32	555 $\pm$ 27	381 $\pm$ 31	526 $\pm$ 40	561 $\pm$ 37	538 $\pm$ 51
Saliva ratio h_w (-)	0.2 $\pm$ 0.02	0.2 $\pm$ 0.01	0.1 $\pm$ 0.02	0.2 $\pm$ 0.01	0.2 $\pm$ 0.02	0.2 $\pm$ 0.04

Ethnicity had a significant effect on bolus hardness [$F(1,125)=6.79$, $p=0.010$], bolus cohesiveness [$F(1,122)=9.93$, $p=0.002$], and particle size d_{50} [$F(1,80)=3.99$, $p=0.049$]. Chinese consumers produced softer (1.95N), less cohesive (0.38) bolus with slightly smaller particles (1940 μm) than Dutch (2.31N, 0.41, 1988 μm). Ethnicity had a significant effect in females on number of particles [$F(1,80)=10.17$, $p<0.001$]. Chinese females produced bolus with more particles (623) than Dutch females (381). Ethnicity did not have a significant effect on bolus adhesiveness and saliva incorporation.

Gender had a significant effect in older Dutch adults on bolus adhesiveness [$F(1,122)=6.09$, $p=0.015$] and cohesiveness [$F(1,125)=4.32$, $p=0.040$], and in young Dutch adults on number of particles [$F(1, 125)=4.32$, $p=0.040$]. Older females produced more adhesive (0.05N*s) and less cohesive (0.37) bolus than older males (0.03N*s and 0.39, respectively). Young Dutch females produced fewer particles (381) than young Dutch males (525). Gender did not have an effect on saliva ratio h_w and particle size d_{50} .

5.3.3. Mediation effect of consumption time on bolus properties of consumers varying in age, gender and ethnicity.

Table 5.3 shows the mediation coefficients that represent the effects of age, gender and ethnicity on the different bolus properties at the swallowing point. Age indirectly influenced saliva ratio, bolus hardness, cohesiveness, adhesiveness, particle size and number of particles through its effect on consumption time but did not influence bolus particle size. Older adults had a longer consumption time than young adults, and longer consumption time increased saliva ratio and number of particles in the bolus, but decreased hardness, cohesiveness, adhesiveness and particle size. The results of the mediation analysis did not provide evidence that age influenced bolus properties independent of its effect on consumption time.

The results of the mediation analysis did not provide evidence that gender had an indirect effect on bolus properties through consumption time in Dutch consumers. This means that gender did not have any effect on bolus properties that was mediated by consumption time.

Ethnicity had an indirect effect on saliva ratio, bolus hardness, adhesiveness, cohesiveness, and number of particles mediated by consumption time. Chinese participants had a longer

consumption time than Dutch participants, and participants with a longer consumption time increased saliva ratio and number of particles in the bolus, but decreased hardness, cohesiveness, adhesiveness. The results of the mediation analysis did not provide evidence that ethnicity influenced bolus properties independent of its effect on consumption time.

5.3.4. Dynamic texture perception of consumers differing in age, gender and ethnicity

The TDS curves of the hotdog sausage for the consumer groups differing in age, gender and ethnicity are shown in Figure 5.2. Three to four texture attributes were selected as dominant sensations throughout the sensory evaluation by all consumer groups. The dominant texture attributes showed a clear dynamic evolution over consumption time. Figure 5.2.A-F shows that all consumer groups perceived the texture of the sausage similar during the beginning (first third of normalized consumption time) and end of mastication (last third of normalized consumption time). The dominant texture sensation of the hotdog sausage perceived by all consumer groups at the beginning of mastication was firmness and at the end of mastication it was graininess. Only in the middle of mastication (second third of normalized consumption time) differences in dominant texture sensations were found between consumer groups. It should be noted that dominant texture sensation perceived in the second third of normalized consumption time were significant but displayed low dominance rates for all consumer groups suggesting a low level of panel agreement.

For young Dutch adults (Figure 5.2.A/F) the dominant texture sensation perceived during the second third of consumption time was fattiness. For older Dutch adults the dominant texture sensation perceived during the second third of consumption time was dryness followed by juiciness (Figure 5.2.B). When comparing the dominant texture sensations between females and males (Figure 5.2.C and D, respectively), differences are neglectable. Only during the second third of consumption time small differences are perceived but attributes barely reach significance level. Figure 5.2.E and F show that Chinese consumers selected chewiness and dryness as dominant texture sensation during the second third of consumption time, whereas Dutch consumers selected fattiness.

Figure 5.2. TDS curves showing texture attribute dominance rates of hotdog sausages in consumers differing in age ($n=22$ older adults Dutch, $n=21$ young Dutch), ethnicity ($n=21$ young Dutch, $n=21$ young Chinese), and gender ($n=34$ females, $n=30$ males) by triplicate. A and F) show Young Dutch; B) Older Dutch; C) Females; D) Males; E) Young Chinese.

Table 5.3. Path regression coefficients and indirect effects for mediation models. Regression coefficients a , b , and c' estimate the effect of the predictor on the mediator, the effect of the mediator on the outcome variable, and the direct effect of the predictor on the outcome variable, respectively (see Figure 5.1). Indirect effect indicates whether or not a predictor variable had an effect on the outcome variable mediated by the consumption time. When the confidence intervals did not include zero, mediation was considered existent. Lower Level Confidence Interval (LLCI), Upper Level Confidence Interval (ULCI).

	a			c'			Indirect effect		
	coeff	p-value	coeff	p-value	coeff	p-value	coeff	LLCI	ULCI
Age									
Saliva ratio h_w	8.62	<0.001	0.01	<0.001	-0.01	0.61	0.04	0.02	0.08
Hardness	8.62	<0.001	-2.97	<0.001	-11.07	0.49	-25.64	-41.78	-13.25
Cohesiveness	8.62	<0.001	0.00	<0.001	0.00	0.82	-0.02	-0.03	-0.14
Adhesiveness	8.49	<0.001	-0.20	<0.001	0.74	0.10	-1.69	-2.60	-0.90
Particle size d_{50}	8.62	<0.001	0.00	0.29	-0.03	0.18	-0.01	-0.03	0.01
Number of particles	8.62	<0.001	7.89	<0.001	31.88	0.46	68.04	27.86	111.57
Gender									
Saliva ratio h_w	-1.77	0.42	0.01	<0.001	0.04	0.08	-0.01	-0.03	0.02
Hardness	-1.77	0.32	-3.30	<0.001	-19.85	0.17	5.83	-5.89	17.89
Cohesiveness	-1.77	0.32	0.00	<0.001	0.00	0.69	0.00	0.00	0.01
Adhesiveness	-2.14	0.24	-0.18	<0.001	0.74	0.07	0.39	-0.21	1.11
Particle size d_{50}	-1.77	0.42	0.00	0.07	-0.01	0.59	0.00	-0.01	0.01
Number of particles	-1.77	0.42	8.91	<0.001	76.56	0.05	-15.74	-58.82	21.09

Ethnicity										
Saliva ratio h _w	7.91	<0.001	0.00	<0.001	0.00	0.92	0.03	0.01	0.05	
Hardness	7.91	<0.001	-3.57	<0.001	-10.12	0.50	-28.28	-44.73	-14.37	
Cohesiveness	7.91	<0.001	0.00	<0.001	-0.01	0.36	-0.02	-0.03	-0.01	
Adhesiveness	7.78	<0.001	-0.11	<0.001	-0.12	0.83	-0.84	-1.39	-0.39	
Particle size d ₅₀	7.91	<0.001	0.00	0.68	-0.04	0.12	-0.01	-0.03	0.02	
Number of particles	7.91	<0.001	6.70	0.00	90.75	0.02	53.01	12.86	99.91	

5.3.5. Relationships between dynamic bolus properties and dynamic texture perception

Multiple Factor Analysis (MFA) was used to explore the relationships between dynamic bolus properties and dynamic texture perception. Figure 5.3 displays the first two dimensions of the MFA, both dimensions together explain 59.1% of the variance in the data. Both groups of data contributed almost equally to Dimension 1, while Dimension 2 was almost exclusively explained by the sensory attributes data. Figure 5.3.A shows that consumer characteristics (age, gender and ethnicity) are close to the origin of the MFA plot indicating that their contribution to the variance in the data is low. In contrast, the two extreme mastication time points (33 and 100% mastication times) at which bolus properties and texture perception were determined (TDS data was split into three time periods 33 (T0 – T33), 66 (T34 – T66) and 100 (T67 – T100) of standardized consumption time, (see section 5.2.6) are the main contributors to the variance in the data. Figure 5.3.B shows the correlation between dynamic bolus properties and dynamic texture perception.

Overall, MFA shows that at 33% of mastication time, bolus properties had high values of hardness, cohesiveness and d_{50} . These bolus properties were positively correlated among them and with perception of texture attributes firmness and chewiness. At 66% of mastication time perception of fattiness and smoothness were positively correlated with each other and negatively correlated with dryness (as seen also in Figure 5.2). Relative to other attributes, fattiness and smoothness were the attributes mostly reported within young Dutch consumers at that point in time, whereas dryness was mainly reported by older (Dutch) consumers. At 100% of mastication time, boli were characterized by high amounts of saliva, high adhesiveness and large number of bolus particles. These bolus properties were positively correlated between them and with the perception of graininess and juiciness.

Figure 5.3. A. MFA space (first two components) from all consumer groups and mastication times 33, 66 and 100%. **B.** Correlation circle displaying the relationships between variables of bolus properties (blue) and texture perception determined by TDS (yellow).

5.4. Discussion

The present study shows that for a fixed bite size of a hotdog sausage, consumers differing in age, gender and ethnicity varied in consumption time. Differences in bolus properties were influenced by age and ethnicity but these effects were mediated by consumption time. This demonstrates that adaptation in consumption time is the underlying mechanism that explains the differences in bolus properties between consumer groups.

We observed that older adults masticated the hotdog sausage samples for longer consumption times than young consumers, which is in line with several previous studies showing that among healthy subjects an increment in age is accompanied by an increment in consumption time regardless of the food characteristics^{27,33,68,163}. This effect has been attributed to a decline of bite^{25,26} and tongue strength with ageing²⁸ as well as a reduction in muscle activity and density^{29,177}. Older adults produced a more degraded bolus than young adults. Thus, consumers differing in age, modify their consumption time and therefore the bolus properties at swallowing point differ considerably in order to reach a bolus with an optimal state for safe and comfortable swallowing. An age related prolongation of consumption time can be an adaptative mechanism not only to overcome

the oral decline but also to compensate for a less efficient digestion¹⁷⁸. We note that in our study bite size was fixed to 7g of hotdog sausage; however, under natural eating conditions, consumers might also adapt their bite size to compensate for a decline in oral capabilities, for example by taking smaller bites leading to shorter consumption times. Our results differ from previous studies by Mioche and colleagues. They observed that older populations swallow a bolus with lower degree of food structural breakdown³². There is a major difference between our study and the study by Mioche et al. regarding the selection criteria for the dental status of the older adults. In our study only older adults with full denture participated whereas in the study by Mioche et al. older adults with at least six pairs of post-canine teeth participated. The worse dental status of the older adults participating in the Mioche et al. study might have contributed to the lower degree of structural breakdown of the foods at the moment of swallowing.

Despite the observed changes in bolus properties between young and older adults, dynamic texture perception of the sausage was similar between both groups. Both consumer groups perceived firmness as the first dominant sensation for the first third of consumption time, and with similar dominance rate. The second third of consumption time showed minor differences between young and older adults in dynamic texture perception. In this period, older adults mainly perceived dryness as dominant sensation, whereas for the young group fattiness was dominant sensation. This period may provide important sensory input to decide if longer mastication is needed in order to reach the bolus lubrication threshold needed for swallowing. Older adults have decreased saliva flow and lower amounts of mucins (salivary proteins that contribute to bolus formation) than younger adults^{179,180}. This means that to reach the same amount of saliva incorporated in a bolus, older adults would need to process the bolus for a longer period of time. This explains why despite significant differences in consumption time, the amount of saliva incorporated into the bolus at the swallowing point was not different between both age groups. During the last third of consumption time graininess was dominant sensation until the swallowing moment. Graininess is an attribute that reflects the increased number of fragments generated during mastication, where particles' size and shape are perceived assessing if they are small enough to be swallow¹⁸¹. The size of bolus particles is another factor that

has been suggested to influence the swallowing moment. However, in our study size of bolus particles at the moment of swallowing did not differ between the two age groups.

Gender influenced consumption time but only in Chinese consumers, with males having shorter consumption time than females. Consumption time differed between Dutch and Chinese but only in females with Chinese having longer consumption time than Dutch. Despite the often reported oral physiological differences between males and females and between ethnic groups,^{25,29,34,40,182,183} differences in food oral processing behavior related to gender and ethnicity frequently show contrasting results with some studies showing differences in food oral processing behavior^{38,68,152,153,182} and others not^{31,184}. Our study found an interaction effect between gender and ethnicity which may help to explain why conflicting results are found in literature. It is probable that (oral) physiological variations between genders and ethnicities combined with cultural or environmental differences contribute to adaptation of consumption time. For example, females are frequently taught to slow down their eating rate and chew thoroughly, behavior that might not be encouraged in males as often^{37,38,185,186}. Nevertheless, this behavior might be encouraged more often in traditional cultures. Based on the observations made in this study, in order to find more consistent results, investigations about oral behavior should balance the selection of subjects by gender and report or homogenize ethnicity in order to avoid confounding effects.

The comparison between the bolus properties of Dutch and Chinese showed that Chinese expectorated bolus that were softer, less cohesive and contained more particles of slightly smaller size than Dutch whereas the amount of saliva incorporated into the bolus did not differ between both groups. The differences found in bolus texture and bolus particle characteristics might be related to lower mastication efficiency of Chinese compared to Dutch¹⁸⁷. Thus, the elongation of consumption time can be a strategy to adapt for lower mastication efficiency.

Dynamic texture perception differed between ethnic groups, only during the second third of consumption time. Dutch consumers perceived the sausage as fatty and Chinese as dry. The difference in texture perception between the ethnicities may be related to physiological factors and cultural expectations. The first factor refers to differences in saliva

flow rate between these groups which have been reported previously with Chinese having lower saliva flow rates than Dutch consumers ¹⁸⁷. Perception of dryness by Chinese, similarly to what was observed in older consumers, might contribute to prolongation of consumption time to compensate for low saliva production. In a way that at the swallowing point both ethnicities reach a bolus with the same amount of saliva. The second factor, cultural expectation, may be related to differences in sensory properties between sausages consumed in China and The Netherlands. Many sausages available in China might contain a broad range of fat contents and fat particles might be visible and large. Many sausages available in The Netherlands tend to have lower fat content and typically contain finely ground meat and emulsified fats ¹⁸⁸. Thus, the expectation of sensory properties of the sausage may be different between the Chinese and Dutch and may drive the attention of both consumers towards different texture attributes.

Gender was the consumer characteristic that had the weakest influence on bolus properties in this study. When gender influenced bolus properties, the effect was always interacting with age or ethnicity. For example, older females produced a more adhesive and cohesive bolus than older males. Furthermore, among young Dutch consumers, females produced fewer bolus particles than young Dutch males. Similarly to age and ethnicity, gender did not influence the amount of saliva incorporated into the bolus and bolus particle size. It is possible that both saliva incorporation and bolus particle size are key determinants to trigger a swallow. Furthermore, dynamic texture perception did not differ considerably between females and males.

Overall, for all consumer groups, relationships between bolus properties and texture perception were found especially at the beginning and end of consumption time (33 and 100% mastication time). The first third of consumption time was associated with bolus hardness, cohesiveness, bolus particle size (d_{50}) and with perception of firmness and chewiness. The bolus properties observed at the beginning of consumption time mainly represent the response of the food structure to mechanical disruption imposed upon chewing ¹⁸¹. The positive correlation between instrumental bolus hardness and perception of firmness is in agreement with previous studies ^{189,190}. Moreover, large particle sizes in foods have been associated with an increment in perception of firmness and chewiness ¹⁹¹.

The end of consumption time was associated with bolus properties such as saliva ratio, adhesiveness, number of bolus particles and with perception of graininess and juiciness. The increased presence of saliva in the bolus is accompanied by mucins and water, which together can increase the adhesiveness of the bolus contributing to agglomeration of bolus particles ^{192,193}. The large number of bolus particles produced during the mastication process can lead to a grainy perception as shown in the present study. To summarize, at the beginning and end of consumption time dynamic texture perception of sausages was similar for all consumer groups and strongly correlated with bolus properties. Minor differences in dynamic texture perception between consumers groups were observed only during the middle stages of mastication with low dominance rates. Consumers differing in age, gender and ethnicity adapt oral processing time of sausages to safely swallow bolus with textural properties optimized for their needs.

5.5. Conclusion

We conclude that consumers differing in age, gender or ethnicity differ in consumption time and that consumption time is adapted in order to reach a bolus with optimized textural properties that guarantee a safe and comfortable swallow. The effect of consumer characteristics such as age, gender and ethnicity on bolus properties is mediated by consumption time. While adaptation in consumption time of sausages leads to differences in bolus properties, it does not lead to large differences in dynamic texture perception. Bolus properties and texture perception were mainly correlated at the beginning and end of consumption time. We suggest that the information provided in this study, showing the bolus properties that are needed to enable a safe and comfortable swallow in different consumer groups, helps to optimize foods by tailoring food texture properties towards the needs of specific target groups.

Appendix 5.1. Descriptive data (Mean±SE) of consumption time and bolus properties of consumers differing in age (n=21 young Dutch, n=21 young Chinese), ethnicity (n=22 older adults Dutch, n=21 young Dutch), and gender (n=34 females, n=30 males).

	Young adults				Older adults	
	Chinese		Dutch			
	Females	Males	Females	Males	Females	Males
Consumption time (s)	29.5±1.8	18.8±1.1	16.8±1.1	17.2±1.4	27.6±2.3	23.5±1.5
33% of consumption time						
Hardness (N)	3.08±0.19	3.59±0.26	3.65±0.26	3.63±0.23	3.24±0.18	3.22±0.19
Adhesiveness (N*s)	0.012±0.002	0.018±0.003	0.012±0.004	0.011±0.002	0.013±0.002	0.013±0.004
Cohesiveness (-)	0.48±0.01	0.50±0.01	0.52±0.01	0.52±0.01	0.48±0.01	0.50±0.01
Particle size d ₅₀ (µm)	2146±45	1994±31	2142±40	2025±19	2103±42	2122±41
Number of particles (-)	325±48	302.5±48	172±19	287±37	323±32	292±34
Saliva ratio h _w (-)	0.1±0.01	0.1±0.01	0.1±0.01	0.1±0.01	0.1±0.01	0.1±0.01
66% of consumption time						
Hardness (N)	2.14±0.18	2.65±0.15	3.0±0.19	2.89±0.23	2.51±0.13	2.54±0.17
Adhesiveness (N*s)	0.024±0.004	0.028±0.006	0.021±0.004	0.02±0.003	0.037±0.004	0.02±0.003
Cohesiveness (-)	0.40±0.01	0.42±0.01	0.45±0.01	0.45±0.01	0.40±0.01	0.44±0.01
Particle size d ₅₀ (µm)	1960±23	1958±27	2034±33	1981±32	1946±27	2027±28
Number of particles (-)	494±35	396±49	316±31	427±45	510±22	489±49
Saliva ratio h _w (-)	0.1±0.01	0.1±0.01	0.1±0.02	0.1±0.01	0.1±0.01	0.2±0.03

100% of consumption time							
Hardness (N)	1.79±0.1	2.12±0.13	2.35±0.13	2.27±0.21	2.04±0.1	1.86±0.14	
Adhesiveness (N*s)	0.04±0.005	0.04±0.006	0.03±0.005	0.03±0.005	0.05±0.006	0.03±0.005	
Cohesiveness (-)	0.36±0.01	0.39±0.01	0.41±0.01	0.40±0.01	0.37±0.01	0.39±0.01	
Particle size d ₅₀ (µm)	1935±28	1944±27	2008±25	1968±19	1936±20	1961±16	
Number of particles (-)	623±32	555±27	381±31	526±40	561±37	538±51	
Saliva ratio h _w (-)	0.2±0.02	0.2±0.01	0.1±0.02	0.2±0.01	0.2±0.02	0.2±0.04	

6

How addition of peach gel particles to yogurt affects oral behavior, sensory perception and liking of consumers differing in age

This chapter has been published as:

Aguayo-Mendoza M. *, Santagiuliana M. *, Ong X., Piqueras-Fiszman B., Scholten E., Stieger M. How addition of peach gel particles to yogurt affects oral behavior, sensory perception and liking of consumers differing in age. *Food Research International* 1;134:109213 (2020).(*The authors contributed equally to this work)

Abstract

Addition of particles to foods, such as fruit pieces to dairy products or vegetable pieces to soup, is a convenient approach to alter nutritional composition, appearance, perception and acceptance. This study aimed to investigate the effect of addition of peach gel particles to yogurt on oral behavior, sensory perception and liking of consumers differing in age. One homogeneous yogurt and seven yogurts with peach gel particles were prepared. The added peach gel particles varied in size, fracture stress, or concentration. Oral behavior of healthy participants was characterized by video recordings (young adults, $n=62$, 21 ± 2 years; elderly, $n=62$, 70 ± 5 years). Yogurts' sensory properties and liking were scored on nine-point scales. Elderly consumed yogurts with more chews and longer consumption time leading to lower eating rate than young adults. Addition of particles, regardless of characteristics, increased number of chews, consumption time, and decreased eating rate up to 60% for both consumer groups, with an average decrement of 110 g/min for young and of 63 g/min for elderly consumers. With increasing peach gel hardness and concentration, the number of chews and consumption time increased while eating rate decreased. Sensory properties and liking of yogurts with added peach gel particles were similar for healthy young adult and healthy elderly. Thus, healthy ageing seems to affect sensory perception of semi-solid foods to a limited extent only. We conclude that changes in food texture by addition of particles can be used as a strategy to steer eating rate and potentially impact food intake of young adult and elderly consumers while maintaining or enhancing food palatability. Additionally, particle characteristics can be modified to target specific consumer groups that might differ in eating capabilities.

6.1. Introduction

The principal role of oral processing is to transform food into a bolus that can be safely swallowed to continue through the digestive system. It involves food structural changes and physiological actions, making oral processing considerably different between foods and subjects ¹⁹⁴. Several studies investigated how physical differences between homogeneous foods and differences in consumer physiology related to aging affect oral processing. For instance, Koç et al. showed for food gels that an increment in fracture stress of 6.5 folds can double consumption time and number of chews ⁴⁷. Similarly, Lasschuijt observed that an increment in fracture stress of seven folds yielded a 42% decrement of eating rate ¹⁹⁵. Wee et al. stated that an increment of the physical characteristics associated with food elasticity i.e. springiness, cohesiveness, chewiness and resilience (derivate from Texture Profile Analysis) can reduce eating rate of a broad range of solid foods ¹⁴¹, however, measurements obtained by TPA should be interpreted with caution as suggested by Nishinary ¹⁹⁶. For fluid foods, Aguayo-Mendoza et al. observed that bite size of yogurts decreased by 20% when the consistency K (Pa·s) increased by 16 folds ⁶⁹. These observations indicate that large variations in rheological and mechanical properties of foods have a significant impact on oral behavior. The studies of Ketel, Kohyama, and Mioche reported that elderly chewed foods such as rice, cheese, bread and meat, for longer time and with more chews than young adult consumers ^{27,58,68}. Aging might have an impact on oral physiology as muscle activity can decrease and dental status can deteriorate with age. These changes have several consequences on eating capability, sensory perception, and food enjoyment ⁶⁵, potentially leading to a reduced food intake and a weakened nutritional status of the elderly population. Food developers aiming to boost satisfaction and to increase food intake in elderly need to find new strategies to provide products that are more pleasant and easier to consume; thus, better understanding the ability of elderly consumers to orally process foods and gaining further insights into their sensory perception is of critical importance.

The addition of food particles into macroscopically homogeneous food matrices, such as fruit pieces in yogurt or vegetable pieces in soups, is a convenient approach to alter nutritional composition, sensory perception, acceptance and food intake. Depending on the

properties of the particles, this addition might lead to the perception of texture contrast. Such texture contrast has been suggested to be the main reason for the high palatability of many composite foods ^{197,198}. Recent studies have shown that addition of particles can largely affect consumer expectations, sensory perception, and liking of soups and processed cheeses ^{191,199,200}. When considering a liquid matrix, the addition of carrot pieces to chicken soups moved the sensory profile closer to the ideal product profile compared with chicken soups without particles ²⁰⁰. Thus, particle addition can be a valuable approach to change sensory perception, while enhancing consumer appreciation.

However, consumers' response to the addition of particles in foods may have a different effect for consumers differing in age. For macroscopically homogeneous products (e.g. soups, yogurts, beverages), differences between young and elderly consumers were found in terms of sensory properties and preferences ^{201–203}. For instance, Forde and Delahunty demonstrated that the discriminability of chemical and textural stimuli in liquid, semi-solid and solid foods was reduced for old consumers (>65 years) in comparison to young consumers (20–35 years) ²⁰³. The same study showed that the two consumer groups had comparable preferences for the majority of food products tested. Nevertheless, taking orange juice as example, Forde and Delahunty described that the product characteristics (i.e. taste, smell, texture) responsible for the determination of preferences can vary across groups of different age cohorts ²⁰¹. Laguna studied the relationships between eating capability and difficulty to orally process model foods varying in hardness and homogeneity in elderly ¹⁵⁴. Calcium alginate beads differing in size were added to flavorless k-carrageenan gels. Consumption time of gels increased upon addition of beads in the elderly. Bead size did not influence number of chews and consumption time. However, the authors reported that elderly consumers struggled to consume the model foods due to their unfamiliarity and low acceptability. Although these conclusions are expected to be valid also for heterogeneous foods, little information is currently available about sensory properties and preferences of foods with added particles for consumers differing in age.

Several studies have demonstrated that addition of particles to homogeneous foods can affect expected satiation ²⁰⁴ and reduce food and energy intake of a later meal ^{205,206}. Reduction of energy intake within a meal can be achieved by product texture modifications

^{125,126,132,207}. These studies have demonstrated that increasing the hardness or thickness or reducing the size of particles added to yogurt can alter sensory stimulation and/or longer oro-sensory exposure time, which reduces energy intake. Addition of particles to a product might also be used as a means to introduce texture modification to provide a prolonged oral processing and induce earlier satiation and hence potentially reduce energy intake within a meal. However, when differences in texture are too subtle or when consumers are distracted while eating, intake may remain unaffected ²⁰⁸.

To summarize, adding particles to foods seems to be a promising and convenient way to steer eating behavior, improve palatability, and influence energy intake. Yet, the applicability of this approach of texture modification by particle addition to foods has not been investigated yet for elderly consumers. Therefore, the aim of this study was to investigate the effect of the addition of peach gel particles varying in size, fracture stress and concentration to yogurt on oral processing behavior, sensory properties and liking of consumers differing in age. We hypothesize that oral processing is influenced by size, fracture stress, and concentration of added particles. Elderly consumers are expected to display longer oral processing time than young, adult consumers. We also hypothesize that sensory perception and liking of heterogeneous yogurts might differ between young adults and elderly.

6.2. Material and methods

6.2.1. Materials

Optimel® Greek style peach yogurt was provided by FrieslandCampina (Amersfoort, The Netherlands). Agar was purchased from Caldic Ingredients B.V. (Rotterdam, The Netherlands). Holland Ingredients B.V. (Meppel, The Netherlands) kindly provided annatto (orange food colorant, WS 2.5%, E160b). Titanium dioxide (TiO₂, E171), riboflavin (yellow food colorant, 10% PWS, E101) and peach aroma were purchased from Pomona Aroma B.V. (Hedel, The Netherlands). Canned peaches (PLUS, Utrecht, The Netherlands) and crackers without salt (Bayman Barendrecht, The Netherlands) were purchased from a local supermarket. All ingredients were food safe and samples were prepared under food safe conditions.

6.2.2. Sample preparation

Peach gel preparation

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

Peach gels were prepared by combining the peach extract with agar in different concentrations as shown in Table 6.1. The concentration of agar was varied to obtain gels with different target fracture stresses (σ_F : 20, 60, and 100 kPa). Peach aroma, TiO₂, riboflavin and annatto were added to resemble the appearance and flavor of real peach pieces. The concentrations used are provided in Table 6.1. To prepare the gels, solutions were heated under continuous stirring in a water bath at 95°C for 45 min. The heated solutions were poured either in disposable plastic containers to obtain samples for the sensory evaluation or in 30 ml syringes (Terumo, Leuven, Belgium) for instrumental sample characterization. Solutions were placed on ice for 1 h to initiate gel formation. After cooling, gels for the sensory evaluation were cut in cubes of 3x3x3, 7x7x7, and 10x10x10mm using a mandolin (Michel BRAS, Laguiole, France) (Figure 6.1). The gels for instrumental characterization were cut into cylinders with a diameter of 23mm and a height of 15mm and measured ~24 hrs after preparation. Gels for the sensory evaluation were stored at 4°C for a maximum of one week.

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

Target fracture stress (kPa)	Peach extract	Agar	Peach aroma	TiO ₂	Riboflavin	Annatto
20	98.5	1.4	0.049	0.039	0.025	0.024
60	97.3	2.5	0.049	0.039	0.024	0.023
100	96.3	3.6	0.048	0.039	0.024	0.023

Figure 6.1. Peach gels varying in size; (a) small 3x3x3mm, (b) medium 7x7x7mm and (c) large 10x10x10mm peach gel particles.

Figure 6.2. Pictures of yogurts provided during the sensory study. A. Homogeneous yogurt without peach gel particles (HO). B. Yogurt with low concentration (10% w/w) of peach gel particles of medium size (7x7x7mm; Me-10). C. Yogurt with medium concentration (15% w/w) of peach gel particles of medium size (7x7x7mm; Me-15). D. Yogurt with high concentration (20% w/w) of peach gel particles of medium size (7x7x7mm; Me-20). E. Yogurt with medium concentration (15% w/w) of large peach gel particles (10x10x10mm; La-15). F. Yogurt with medium concentration (15% w/w) of small peach gel particles (3x3x3mm; Sm-15).

Yogurt preparation

Optimel® Greek style peach flavored yogurt was sieved to remove the peach pieces present in the commercially available yogurt and then stored at 4°C for a maximum of one week.

Eight yogurts were obtained by adding peach gel particles to the yogurt matrix in different concentration and with different size and hardness (Figure 6.2). The properties of the different samples and the corresponding codes are depicted in Table 6.2. The sample codes consist of four letters and one number. The first two letters indicate particle size, Sm(-), Me(-), and La(-) for small, medium, and large particles respectively, the next two letters indicate the fracture stress, (-)So, (-)Me, and (-)Ha for soft, medium, and hard particles, whereas the subscript number indicates the particle concentration, 10, 15, and 20 for low (10%), medium (15%), and high (20%). The sample code for the homogeneous yogurt without particles is HO.

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

Sample code	Particle size (mm)	Fracture stress σ_f (kPa)	Particle concentration (% w/w)
HO	-	-	-
SmMe15	3x3x3	60	15
MeSo15	7x7x7	20	15
MeMe15	7x7x7	60	15
MeMe10	7x7x7	60	10
MeMe20	7x7x7	60	20
MeHa15	7x7x7	100	15
LaMe15	10x10x10	60	15

This incomplete factorial experimental design was chosen to reduce the number of evaluated samples yet allowing for an investigation of the different variables considered. By comparing (HO), SmMe₁₅, MeMe₁₅, and LaMe₁₅ the effect of particle size on oral behavior and perception was studied while keeping peach gel particle fracture stress and concentration constant; by comparing (HO), MeSo₁₅, MeMe₁₅, and MeHa₁₅ the effect of particle hardness (fracture stress) on oral behavior and perception was studied while particle size and concentration were constant; and finally by comparing (HO), MeMe₁₀,

MeMe₁₅, and MeMe₂₀ the effect of particle concentration on oral behavior and perception was studied while particle size and fracture stress were constant.

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

6.2.3. Sample characterization

Uniaxial compression tests of model peach gels

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

Viscosity measurements of yogurt

Rheological properties of yogurt were determined using a rheometer (MCR 302, Anton Paar GmbH, Graz, Austria) with a C-CC17/T200/TI cup (diameter of 18.08mm) and a CC17/TI cylinder (diameter of 16.66mm and length of 24.95mm). The rheometer was set in a rotational mode with shear rates increasing from $1-1000\text{ s}^{-1}$ and then decreasing from $1000-1\text{ s}^{-1}$ in a time period of 2.5 min. After pouring the yogurt into the cup, a waiting time of 2 min was applied to reach equilibrium prior to measuring. The yogurt was measured in

triplicate at 4°C (storage/serving temperature) and 20°C (room temperature). Flow curves were obtained by measuring viscosity as a function of the shear rate. The obtained results at a shear rate from 1 to 1000 were then fitted using the Ostwald-de Waele model:

$$\eta = k\dot{\gamma}^{n-1}$$

where η is the viscosity (Pa·s), k the consistency (Pa·s), $\dot{\gamma}$ the shear rate (s^{-1}) and n the flow behavior index (-). The yogurt measured at 4°C displayed a consistency k of 3.45 ± 0.03 Pa·s and had a power law index $n=0.38$. At 20°C, the consistency significantly decreased ($p < 0.001$) to $k=2.92 \pm 0.05$ Pa·s, while power law index remained unchanged as $n=0.38$.

6.2.4. Characterization of oral processing behavior and sensory evaluation

Participants

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

Oral processing behavior characterization

To determine the oral processing behavior, each participant was individually video recorded in a well-lit room while consuming yogurts at a serving temperature of 4°C. Before starting

the video recording, the researcher placed four circular stickers on the participant's face, serving as markers, to perform the analysis of the video recordings. Two stickers were placed on the forehead spaced 5 cm apart horizontally, one on the tip of the nose (reference point), and one on the center of the chin (mobile point).

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

From the video recording, consumption time (s), number of chews (-), number of swallows (-), chewing rate (chews/s) and eating rate (g/min) were extracted. Changes in position of the stickers placed on each participant's face over time were extracted as X-Y coordinates using Kinovea software (version 0.8.12) as described previously^{68,69}. Coding of the videos, *i.e.* placing a digital marker in each sticker and indicating with a label at each swallow and at the beginning and end of consumption time in the videos, was divided between two researchers. To standardize the coding procedures, the researchers coded a set of 10 videos together. After all videos of the study were coded, approximately 10% of the videos were randomly selected and codification was validated by the other researcher. Jaw's vertical displacement was computed as the Y-coordinate difference between the nose and chin markers at each time point. The number of chews was calculated by detecting the zero-crossing of peaks using a smoothed first derivative of the jaw's vertical displacement. Consumption time was defined as the time period when participants placed the sample in the mouth until the last swallow. Number of swallows were recorded by counting the number of times the participant raised their hand. Chewing rate indicates the number of

chews per second whereas eating rate indicates the amount of food consumed per time unit (g/min). These calculations were processed using a custom-made Excel macro.

Sensory evaluation of heterogeneous yogurts

The sensory evaluation was divided into two separate sessions of 45 min each with a break of one week between sessions. Participants indicated perceived intensities of 13 attributes using a nine-point scale ranging from “not” to “very” after tasting the yogurts samples at a serving temperature of 4°C. The list of sensory attributes, which were selected and tested during feasibility tests (data not shown), and their definitions are reported in Table 6.3.

Table 6.3. Sensory descriptors and definitions used for quantification of sensory profile.

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

Participants also evaluated all samples on liking (overall liking, flavor liking, texture liking) using a nine-point hedonic scale. Participants were asked not to eat for one hour prior to the sensory sessions. In each session, they were provided with four different samples of

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

6.2.5. Data analysis

Oral processing behavior data were analyzed conducting factorial ANOVA analyses using IBM® SPSS® Statistics (version 24.0). The effect of age on oral behavior (consumption time, number of chews, number of swallows, chewing rate, and eating rate) was determined using all samples. The effect of particle size, particle fracture stress and particle concentration on oral behavior was determined using only the samples differing in the parameter of interest, while maintaining the other parameters constant (e.g. effect of particle fracture stress at 20, 60, and 100 kPa, with a constant particle size of 7x7x7mm and particle concentration of 15% w/w). Main effects were considered statistically significant at $p < 0.05$. When effects were significant, post hoc pairwise comparisons were performed using Bonferroni's adjustment.

Results with respect to sensory perception were analyzed using R language (version 3.2.3). First the data were analyzed separately by ANOVA considering young and elderly participants independently. Such analysis was performed to allow a comparison between all products, and when effects were significant, post-hoc pairwise comparisons were conducted with Tukey's HSD test ($p < 0.05$). Two separate approaches were used to compare perception between participant groups. As a multivariate approach, sensory perception data were analyzed by Multiple Factor Analysis (MFA) to assess the configurational similarity of product spaces obtained from the young adult and elderly participants separately. As a univariate approach, t-tests between the two participant groups were performed on the intensity scores of each product. This approach allowed to identify the effect of participant age on specific sensory attributes per product type.

To check for similarities between the heterogeneous yogurt samples and to investigate the relationship between oral behavior, sensory perception and liking, data from both

consumer groups were pooled and MFA was performed with the three data matrices (oral behavior data, sensory data, and liking). The data regarding mechanical properties were analyzed using Analysis of Variance (ANOVA) with $p < 0.05$ and Tukey's HSD as post-hoc test. Two-tailed paired sample t-tests were used to compare viscosity measurements of each yogurt at different temperatures.

6.3. Results and discussion

6.3.1. Oral processing behavior

Effect of age on oral processing behavior of yogurts

Oral processing behavior was characterized and compared between healthy young adult ($n=62$, age 21 ± 2 years) and healthy elderly ($n=62$, age 70 ± 5 years) participants. Age had a significant effect on consumption time [$F(1,911)=54.60$, $p < 0.001$], number of chews [$F(1,911)=50.95$, $p < 0.001$] and eating rate [$F(1,911)=29.31$, $p < 0.001$]. Figure 6.3 shows that elderly required significantly longer time (11.2 ± 5.2) and more chews (15.3 ± 7.6) than young adults (consumption time: 9.0 ± 4.1 ; number of chews: 12.3 ± 6.1). Moreover, elderly consumed yogurts with a lower eating rate ($68.0 \text{ g/min} \pm 0.6$) than young adults ($90.4 \text{ g/min} \pm 87$). These differences between young adults and elderly in oral processing behavior may be explained by physiological changes related to aging such as the decrease of density of the mastication muscles and consequently the weakening of bite force. This reduction of bite force induces the subject to increase the number of chews and the consumption time until the bolus reaches a swallowable consistency^{33,68,209,210}. It should be noted that the young adult and elderly consumers were healthy and had good dental status with a maximum of two missing teeth or implants. Hence, the observed differences in eating behavior between the two groups are probably not caused by differences in dental status between groups. The number of swallows significantly differed between groups [$F(1,911)=24.61$, $p < 0.001$]. It was observed that young adults swallowed more times than elderly, probably because the threshold volume to trigger a swallow is lower in young adults than in elderly²¹¹. In contrast, chewing rate did not differ significantly between young adults and elderly [$F(1,911)=.59$, $p=0.442$] suggesting that the central pattern generator in the brain, that controls chewing frequency, might not have been affected by aging²¹².

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

Effect of particle size on oral processing behavior of young adults and elderly

To investigate the effect of peach gel particle size added to yogurts, we compared the homogeneous yogurt, the yogurts with peach gel particles of 3x3x3mm (small), 7x7x7mm (medium), and 10x10x10mm (large), while keeping the fracture stress and concentration constant at 60kPa and 15% (w/w), respectively. The addition of peach gel particles to yogurt had a significant effect on consumption time [$F(3,451)=55.28$, $p<0.001$], number of chews [$F(3,451)=55.78$, $p<0.001$], number of swallows [$F(3,451)=11.65$, $p<0.001$], eating rate [$F(3,451)=41.71$, $p<0.001$], and chewing rate [$F(3,451)=9.62$, $p<0.001$] (Figure 6.4). The addition of peach gel particles more than doubled the number of chews and consumption time, and decreased eating rate by up to 60% compared to yogurts without particles, with an average decrement of 110 g/min for young adults and of 63 g/min for elderly consumers. We suggest that addition of particles to yogurts is a feasible and convenient strategy that can potentially be used to manipulate food and energy intake within a meal since changes in oral behavior caused by modification of food texture have been related to satiation responses^{126,204}.

Although the presence of peach gel particles affected oral behavior, changes in particle size did not significantly affect any of the parameters describing oral processing behavior. Similarly, Laguna et al. reported that addition of alginate beads to k-carrageenan gels increased consumption time in the elderly. Size of alginate beads did not influence number of chews and consumption time¹⁵⁴. In our study, all yogurts had a constant particle weight concentration (15% w/w). Therefore, increasing the size of the particle was accompanied by a decrease in the number of particles in the yogurt. Consequently, yogurts with the largest particle size (10x10x10mm) had fewer particles whereas yogurts with the smallest particles (3x3x3mm) had more particles present. Size and number could have induced counteracting effects in this study, and therefore no overall changes might have been observed.

Figure 6.4. Parameters related to Oral processing behavior of yogurts without and with peach gel particles differing in particle size: (HO) yogurt without particles, (Sm) yogurt with particles of 3x3x3mm, (Me) yogurt with particles of 7x7x7mm and (La) yogurt with particles of 10x10x10mm. All particles had a fracture stress of 60kPa and were added at a concentration of 15% (w/w). Mean±SD values are shown for A) consumption time, B) number of chews, C) number of swallows and D) eating rate. Different superscript letters indicate significant differences between samples within each oral behavior descriptor (p<0.05). Dark bars indicate young adult consumers (n=62, age 21±2 years) whereas light bars depict elderly consumers (n=62, age 70±5 years).

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

To investigate the effect of particles hardness on oral processing behavior, the three samples with particles that varied in fracture stress (20, 60, and 100 kPa) with constant particle size of 7x7x7mm at concentration of 15% w/w, were compared to each other together with the HO sample. The addition of peach gel particles significantly influenced all oral processing parameters. Between the yogurts with particles differing in fracture stress, a significant effect was found on consumption time [$F(3,452)=62.05$, $p<0.001$], number of chews [$F(3,452)=66.96$, $p<0.001$], and eating rate [$F(3,452)=38.59$, $p<0.001$] (Figure 6.5). We observed in average for both consumer groups, an increment of 80 kPa (from 20 to 100 kPa) in fracture stress of the particles increased consumption time and number of chews by approximately 40% whereas eating rate decreased by 30%. These findings demonstrate that oral behavior adapted to fracture stress of the particles. These results are in line with other studies that demonstrated that with increasing food hardness, consumption time and number of chews increase and eating rate decreases^{50,69}. Furthermore, the results show that between groups elderly consumers are slightly less affected by the increments in particle fracture stress than young adults.

For number of swallows and chewing rate, the results are slightly different. Although particle fracture stress had a significant effect on the number of swallows [$F(3,452)=11.15$, $p<0.001$], this effect was present only when medium or hard particles were added to the yogurt, but not when soft particles were added. Soft particles may be easier to deform and compress between the tongue and palate, and therefore fewer chews are required. Subjects are therefore not required to increase the number of swallows since these particles may directly be swallowed without the need to remain in the mouth for further chewing. Medium and hard particles needed a longer oral processing time due to a mechanism that involves continuous chewing of large particles until they are softened and reducing in size to the point that they are ready to be swallowed. This long process of chewing leads to several swallows. Chewing rate was least influenced by particle hardness. While the addition of particles had a significant influence [$F(3,452)=11.26$, $p<0.001$], there was no difference between yogurts containing particles varying in particle hardness. This is

consistent with other literature that shows that chewing rate is relatively constant and independent of the food properties^{69,213}.

Figure 6.5. Oral processing behavior of yogurts without and with added peach gel particles differing in particle fracture stress (kPa): (HO) yogurt without particles, (So) yogurt with particles with fracture stress of 20kPa, (Me) yogurt with particles with fracture stress of 60kPa and (Ha) yogurt with particles with fracture stress of 100kPa. All particles had a size of 7x7x7mm and were present at a concentration of 15%(w/w). Mean±SD values are shown for A) consumption time, B) number of chews, C) number of swallows and D) eating rate. Different superscript letters indicate significant differences between samples within each oral behavior descriptor ($p<0.05$). Dark bars indicate young adult consumers ($n=62$, age 21 ± 2 years) whereas light bars depict elderly consumers ($n=62$, age 70 ± 5 years).

Effect of particle concentration on oral processing behavior of young adults and elderly

Particle concentration had a significant effect on consumption time [$F(3,451)=56.48$, $p<0.001$] and number of chews [$F(3,451)=61.06$, $p<0.001$]. Figure 6.6 shows that in yogurts with peach gel particles, an increment in concentration (w/w) by 10% from 10 to 20% caused an increment of the number of chews and consumption time of 20%. From 11.8 to 14.3 chews and 8.8s to 10.6s for young adults and from 14.6 to 17.7 chews and 11.0s to 12.8s for elderly. However, smaller increments on particle concentration of 5% (w/w) (e.g.

10 – 15% or 15 – 20%) did not cause significant differences in number of chews nor consumption time. Eating rate [$F(3,451)=34.44$, $p<0.001$], number of swallows [$F(3,451)=12.01$, $p<0.001$] and chewing rate [$F(3,451)=9.72$, $p<0.001$] significantly differed between the homogeneous yogurt and the heterogeneous yogurts with peach gel particles, but not between yogurts with particles differing in concentration.

Figure 6.6. Oral processing behavior of yogurts without and with peach gel particles differing in particle concentration: (HO) yogurt without particles, (10) yogurt with a particle concentration of 10%, (15) yogurt with a particle concentration of 15%, and (20) yogurt with a particle concentration of 20% (w/w). All particles had a size of 7x7x7mm and fracture stress of 60 kPa. Mean±SD values are shown for A) consumption time, B) number of chews, C) number of swallows and D) eating rate. Different superscript letters indicate significant differences between samples within each oral behavior descriptor ($p<0.05$). Dark bars indicate young adult consumers ($n=62$, age 21 ± 2 years) whereas light bars depict elderly consumers ($n=62$, age 70 ± 5 years).

6.3.2. Sensory properties and liking

Sensory properties of yogurts without and with added peach gel particles by young adults and elderly

Multiple Factor Analysis (MFA) was used to compare the perceived sensory properties of all products for the two consumer groups. The consensus MFA map considering the first

two dimensions (explaining 68.70% of the total variance) is depicted in Figure 6.7.A, while the correlation plot of the two groups is reported in Figure 6.7.B. Overall, in both Figure 6.7.A and B, very similar sensory profiles can be observed for the two consumer groups as both product locations and sensory attributes showed only a few and small differences between the two consumer groups.

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

The minor discrepancies across all products between healthy young adults and elderly can be further examined by looking at the comparison between averaged values of perceived attributes intensities (across-attribute comparison; Appendix 6.1). Consumer groups varying in age differed in sweetness and sourness perception, as elderly perceived most of the yogurts as less sweet and sour than the young adults. Regarding textural attributes, differences between groups in the averaged scored intensities across products were only observed for crumbliness and particle size, for which elderly participants gave significantly lower scores than young participants. This might suggest that the aging of healthy participants mainly affects taste perception but influences texture perception only marginally.

The mean values of the different sensory attributes (Appendix 6.2 and Appendix 6.3) show that a variation in particle size influenced perception of creaminess, thickness, and particle

size for young adults, while for elderly, such a variation only significantly affected crumbliness and particle size. No significant effects of particle size on chewiness, dryness, hardness, juiciness, smoothness, sourness, sweetness, dairy and peach flavor were observed in either group. For both consumer groups, increasing the particle fracture stress from 20 to 60 to 100 kPa (MeSo₁₅, MeMe₁₅, MeHa₁₅) resulted in a significant increase in perceived chewiness and hardness, while it significantly decreased smoothness. Yogurts containing soft particles were perceived as smoother, less chewy and hard compared to the yogurts containing hard particles (MeHa₁₅) for both young and elderly participants. For both consumer groups, a variation in particle concentration (10, 15 or 20% w/w) did not yield any significant difference in product perception.

We conclude that healthy aging has only a very limited effect on perceived sensory properties of yogurts without and with added peach gel particles. For both healthy young adults and elderly, an increase in particle size led to a decrease in creaminess and thickness perception, while higher hardness and chewiness were perceived with an increase in particle hardness and concentration, respectively. We conclude that aging marginally affected texture perception of semi-solid heterogeneous products (i.e. lower crumbliness and particle size for elderly), whereas somewhat larger effects were found for taste perception (e.g. perceived sourness and sweetness). As described in section 6.2.4, we emphasize that the young adults as well as the elderly had good general health (self-reported) and good dental status (a maximum of two dental implants or missing teeth) which might explain that only a few and minor differences were found in sensory perception of the yogurts with and without added peach gel pieces.

Liking of yogurts without and with added peach gel particles by young adults and elderly

Table 6.4 reports the averaged values for overall liking, flavor liking, and texture liking for young adults and elderly. The results of each consumer group were analyzed separately to determine the effect of particle addition, particle size, particle hardness and concentration on liking. Considering the similar perception of the yogurts with and without added peach gel pieces observed in the previous sections, we expected small differences between the age groups also in terms of preferences.

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

Liking										
	F	p	SmMe15	MeSo15	MeMe15	MeMe10	MeMe20	MeHa15	LaMe15	HO
Young										
Overall liking	11.43	<0.001	5.1 ^d	6.0 ^b	5.9 ^{bc}	5.6 ^{bcd}	5.3 ^{cd}	5.4 ^{bcd}	5.4 ^{bcd}	6.8 ^a
Flavor liking	2.97	0.004	5.9 ^{ab}	6.4 ^a	5.8 ^{ab}	6.0 ^{ab}	5.5 ^b	5.8 ^{ab}	5.8 ^{ab}	6.4 ^a
Texture liking	24.32	<0.001	3.6 ^d	5.7 ^b	5.4 ^{bc}	5.4 ^{bc}	5.0 ^{bc}	4.8 ^c	4.9 ^c	6.9 ^a
Elderly										
Overall liking	3.82	<0.001	5.2 ^{ab}	5.8 ^a	5.1 ^{ab}	5.4 ^{ab}	5.1 ^{ab}	4.7 ^b	5.9 ^a	5.9 ^a
Flavor liking	2.91	0.005	5.3 ^{ab}	5.7 ^a	5.1 ^{ab}	5.4 ^{ab}	5.0 ^{ab}	4.5 ^b	5.7 ^a	5.5 ^{ab}
Texture liking	3.22	0.002	4.9 ^b	5.6 ^{ab}	5.3 ^{ab}	5.4 ^{ab}	5.3 ^{ab}	4.9 ^b	5.9 ^a	5.9 ^a

From Table 6.4, it can be seen that homogeneous yogurts were preferred over yogurts with hard particles in terms of overall liking, flavor and texture by both consumer groups. Young adults liked the texture of homogeneous yogurts more than yogurts containing soft, medium and hard peach gel particles and evaluated the texture of yogurts containing small particles as the least liked in texture.

Also for the elderly, yogurts containing small (SmMe₁₅) or hard particles (MeHa₁₅) were significantly less liked than the homogeneous yogurt and the yogurts with medium or soft particles. For the young adults, variation in particle size affected significantly the hedonic response as yogurt with medium-sized particles was liked more than products containing small and large particles. Such effect of particle size was not observed for the elderly group. In this group, the effect of particles hardness was more prominent; an increase in particle hardness (MeHa₁₅) decreased overall liking significantly. Interestingly, for elderly consumers, addition of medium or soft gel particles to yogurt did not decrease liking in comparison to the homogeneous version of the product. For both consumer groups, particle concentration did not affect hedonic responses. We conclude that for young consumers, liking was mainly affected by variation in particle size, whereas for elderly, liking was mostly affected by particle hardness.

Overall, we conclude that these minor differences in preferences between the groups differing in age were probably due to the fact that both groups were in good health and had good dental status. Larger differences may be observed for elderly with a different health status. This suggests that the assumption for which age-related declines always impair sensory and preferences might be not always true. Therefore, this research suggests that other factors than age might be more suitable to identify clusters of consumers and the related drivers of liking.

6.3.3. Relationships between mechanical properties, oral behavior, sensory perception and liking of yogurts with added peach gel particles

MFA was performed to understand the relation between oral behavior, sensory perception and liking of the heterogeneous yogurts with added peach gel pieces. Figure 6.8.A shows the position of the heterogeneous yogurts relatively to each other within a two-dimensional

space (explaining 77.5% of the total variance) whereas Figure 6.8.B depicts the variables. The oral behavior data, sensory data and liking data was pooled over the young adults and elderly consumers in order to show only the yogurts' effect.

Figure 6.8. A. MFA sample space (first two components) from pooled data of both consumer groups. B. Correlation circle displaying the relationship between variables from oral behavior (gray), sensory perception (blue) and liking (yellow).

From Figure 6.8.B, it can be observed that consumption time and number of chews are positively correlated and that both are correlated with sensory attributes hardness, chewiness, dryness (upper left quadrant) and crumbliness (lower left quadrant). The observed relationships between perceived hardness, chewiness and a prolonged consumption time are in line with previous studies^{125,132}. The aforementioned attributes describe, in the upper left quadrant, yogurt containing peach gel particles with high fracture stress, and yogurt containing peach gel particles with high concentration; whereas in the lower left quadrant, crumbliness describes yogurt with small peach gel particles. Hardness, chewiness and dryness have been associated with a greater expected fullness⁵², which is one of the contributors in determining portion size selection due to learned associations by previous experiences²¹⁴. Thus, it could potentially be possible to achieve a reduction in energy intake through a combination of food texture modifications that decrease eating rate and increase satiation.

Furthermore, consumption time and number of chews were negatively correlated with eating rate, which in turn was positively correlated to liking and sensory attributes such as smoothness, creaminess, dairy flavor, juiciness and peach flavor. These characteristics describe the yogurts that contained peach gel particles with a low fracture stress. The observed increment in overall liking might be explained by the high scores of creaminess and smoothness which have previously been reported to be drivers for consumer acceptance of dairy products ²¹⁵. Both attributes, creaminess and smoothness, are attributes that may resemble a more bolus like structure. Thus, it might be possible that in the presence of these sensory cues, consumers perceive these foods as easy to orally process and consequently reduce consumption time affecting eating rate accordingly.

6.3.4. Practical implications

Particle addition to yogurt is a convenient approach that can be applied in different manners depending on the targeted consumer group. Consumers aiming to reduce energy intake can benefit from the reduction of eating rate generated upon particle addition and an increase in particle fracture stress. A reduced eating rate has been demonstrated to decrease meal portion size and *ad libitum* food intake within a meal ^{125,126,132,139}. In order to benefit from the aforesaid approach, the particles added should not increase the food energy density and should preferably be low caloric.

The approach of adding particles to foods can also be used to improve nutritional value of the product while maintaining consumers' acceptance and intake. This may especially be relevant for the elderly population. The elderly consumers equally liked yogurts containing soft-medium size particles, hard-medium size particles and homogeneous yogurts with no added particles. Pleasantness of food is an important determinant of food choice and food intake ²¹⁶. Thus, manufacturing yogurts containing nutrient-rich particles that meet the preferred particle characteristics may be an appropriate strategy to increase elderly's food enjoyment and boost nutrient intake.

6.4. Conclusions

This study highlights that particle addition to macroscopically homogeneous products such as yogurt prolongs oral processing time and decreases eating rate in healthy young adult

and elderly consumers. The present study showed that in heterogeneous yogurts, elderly had a lower eating rate and higher number of chews than young participants. Particularly, increasing particle concentration and particle fracture stress increased consumption time and number of chews. Only few and small differences in perceived sensory properties of heterogeneous yogurts were found between young adults and elderly consumers. Liking of the heterogeneous products differed slightly between the two age groups as for young consumers, liking was mainly affected by variation in particle size, whereas for elderly, liking was mainly affected by particle hardness.

We conclude that addition of soft-solid particles to yogurts can be used as an effective strategy to change oral processing behavior and possibly impact food and energy intake within a meal. This approach can be used to tune sensory perception and enhance product palatability especially in products directed to the elderly population.

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

	Chewiness	Creaminess	Crumbliness	Dryness	Hardness	Juiciness	Particle size	Smoothness	Thickness	Dairy flavor	Peach flavor	Sourness	Sweetness
HO											↓	↓	↓
SmMe ₁₅						↓							↓
MeSo ₁₅			***↑				***↑					**↑	***↓
MeMe ₁₅			*↑				*↑					***↓	***↓
MeMe ₁₀			*↑		*↑							***↓	***↓
MeMe ₂₀			*↑				*↓				*↓	**↓	**↓
MeHa ₁₅											*↓	**↓	***↓
LaMe ₁₅			*↑				**↑						*↓

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

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

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

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

7

Linking oral processing behavior to bolus properties and dynamic sensory perception of processed cheeses with bell pepper pieces

This chapter has been published as:

Aguayo-Mendoza, M. G., Chatonidi, G., Piqueras-Fiszman, B., Stieger, M. Linking oral processing behavior to bolus properties and dynamic sensory perception of processed cheeses with bell pepper pieces. *Food Quality and Preference* 104084 (2020).

Abstract

The addition of food particles to food matrices is a convenient approach that allows to steer oral behavior, sensory perception and satiation of heterogeneous foods. The aim of this study was to determine the influence of physical-chemical properties of heterogeneous foods on oral processing behavior, bolus properties and dynamic sensory perception. Bell pepper gel pieces varying in fracture stress and concentration were added to processed cream cheese matrices differing in texture. Addition of bell pepper gel pieces to processed cheeses increased consumption time, decreased eating rate and led to harder and less adhesive bolus with more saliva incorporated. Addition of bell pepper gel pieces to processed cheeses decreased dominance rate and duration of creaminess, smoothness, melting and dairy flavor and increased graininess and bell pepper flavor. Increasing fracture stress of bell pepper gel pieces from 100 to 300 kPa resulted in longer consumption time, lower eating rate, and for hard/non-adhesive processed cheese matrices in formation of bolus with larger particles and more saliva. These changes were accompanied by decreased perception of dominance of creaminess and bell pepper flavor and increased dominance of graininess. Increasing the concentration of bell pepper gel pieces from 15 to 30% did not affect oral behavior but led to the formation of harder and less adhesive bolus with larger particles and less saliva that were perceived with reduced dominance of creaminess, melting and dairy flavor while dominance of graininess and bell pepper flavor increased. Changing the texture of the cheese matrix from soft/adhesive to hard/non-adhesive decreased consumption time, increased eating rate, did not influence bolus properties and decreased dominance rate of creaminess, smoothness and melting sensations. Number of chews and total consumption time were positively correlated with saliva content of the bolus, number of bolus particles, bolus hardness, dominance of firmness, chewiness and graininess. We conclude that the modification of physical-chemical properties of processed cheeses and embedded bell pepper gel pieces can be a strategy to steer oral behavior and bolus properties which consequently determine dynamic sensory perception.

7.1. Introduction

Throughout oral processing the bolus structure changes continuously as a result of food comminution, hydration and agglomeration ²¹⁷. These changes in bolus structure during oral processing cause dynamic changes in sensory perception and ultimately determine food liking ⁵. A detailed mechanistic understanding of how structural transitions of food bolus are perceived, so how structural transitions contribute to sensory properties, is still missing. It is important to understand how oral processing behavior, bolus properties and sensory perception change depending on structural and physical-chemical properties of foods. Based on this understanding foods with specific structural and physical-chemical properties might be designed with enhanced eating experiences.

Numerous studies demonstrated that consumers adapt oral behavior to the texture and mechanical properties of homogeneous foods. Positive relationships have been reported between viscosity of a broad range of liquid and semi-solid foods and consumption time. For a broad range of solid foods, consumption time and number of chews have been positively correlated with mechanical food properties such as fracture stress, fracture strain and other food texture properties ^{39,45–47,49,50,69,113,167,218–220}. Altering texture and mechanical properties of foods not only changes oral behavior but also leads to changes in bolus properties. Bolus particles of hard foods are smaller compared to those of soft foods ⁵⁶. Reduction of bolus particle size facilitates incorporation of saliva into the bolus often leading to an increase in bolus cohesiveness, holding bolus fragments together and enabling a safe swallow. During bolus formation structural changes can be continuously sensed by the consumer providing dynamics to texture and flavor perception. Thus, food structure can be modified to control mechanical, texture and physical-chemical properties which impact oral behavior and bolus properties, and consequently sensory perception ⁷⁵.

The majority of studies so far focused on understanding relationships between structure and physical-chemical food properties and oral behavior, bolus properties and sensory perception of homogeneous foods. Limited knowledge is available about these relationships for heterogeneous foods. Here, heterogeneous foods refer to foods that are composed of two food components that differ considerably in texture or mechanical properties, like foods that are composed of a matrix in which particles are embedded, such

as chocolates with nuts, yogurts with granola pieces and cheeses with pieces of herbs or vegetables. Although heterogeneous foods are commonly consumed, since the contrast in texture and flavor can lead to high palatability ²²¹, the effect of food heterogeneity on oral behavior, bolus properties and sensory perception is less well documented. The first of only few studies done with solid, heterogeneous foods investigated oral processing behavior and bolus properties of chocolate and gelatin gels with embedded peanuts differing in moisture content ⁵⁵. The matrix in which peanuts were embedded was responsible for differences in oral behavior whereas moisture content of peanuts did not influence oral behavior. Differences in particle size distribution of bolus peanut fragments were explained by differences in peanut moisture content rather than matrix type. It is possible that the peanuts characteristics might not have affected oral behavior because the contrast in mechanical properties between matrices and peanuts might have been not large enough. The study did not explore how addition of peanuts to chocolate and gelatin gels effects oral behavior since these matrices without peanuts were not investigated nor was sensory perception of the heterogeneous foods quantified. Several other studies focused on the effect of particle addition on sensory perception and liking of heterogeneous foods. The influence of size and fracture stress of dispersed K-carrageenan particles added to model soups and protein-based model gels on sensory perception and hedonic responses has been described ¹⁹⁹. It has been shown that sensory properties of soups can be optimized by addition of congruent and familiar particles such as carrot pieces that match consumer' expectations ²⁰⁰. These studies did not investigate how addition of particles to the matrix change oral behavior and consequently bolus properties and sensory perception, thus a comprehensive understanding of these relationships is lacking.

The addition of food particles to a food matrix is a convenient approach that allows to steer oral behavior, sensory perception and satiation of heterogeneous foods. The properties of particles can be varied independently from properties of the matrix. Previously, it was demonstrated that oral behavior of yogurts can be modified considerably by addition of peach gel particles ²²². The addition of peach gel particles to yogurt was sufficient to double consumption time and number of chews and thereby decreasing eating rate up to 60%. Another study indicated that addition of lyophilized pineapple cubes to yogurts changed

oral behavior by lengthening consumption time, leading to an increase of expected satiating capacity²⁰⁴. Furthermore, Mosca et al. showed that decreasing the size of granola particles added to yogurts, decreased eating rate and *ad libitum* food intake²⁰⁷. The differences in eating rate and *ad libitum* intake between yogurts containing many small and fewer large granola particles (constant weight concentration) were 5 g/min (7%) and 17g (5%), respectively. These studies highlight that in liquid foods addition of solid food particles can largely modify oral processing behavior and consequently impact expected satiety and *ad libitum* food intake.

To summarize, a comprehensive understanding of the influence of particle addition to foods on the relationships between oral behavior, bolus properties and dynamic sensory perception is lacking. The aim of this study was to determine the influence of physical-chemical properties of processed cream cheeses with bell pepper gel pieces on oral processing behavior, bolus properties and dynamic sensory perception. We hypothesize that the magnitude of the difference in mechanical properties between processed cheese matrix and added particles determines oral behavior and bolus properties.

7.2. Materials and methods

7.2.1. Participants

Thirty-four participants (11 male / 23 females) with an average age of 23±3 years were recruited via social media and printed advertisements at Wageningen University. Inclusion criteria were Europeans, age between 18 - 30 years, BMI (18.5 - 25 kg/m²), good general health and full denture. Exclusion criteria were dental braces, mouth piercings, use of medication, food allergies or intolerances, pregnancy, breastfeeding and smoking. Before taking part in the study, all participants signed an informed consent form. After completion of the study participants received a financial reimbursement.

7.2.2. Samples

Eight processed cream cheeses with bell pepper gel pieces were prepared following a 2x2x2 full factorial design. Two processed cream cheeses varying in texture were prepared (soft/adhesive and hard/non-adhesive). Bell pepper gel pieces differing in fracture stress (low and high) were added at different concentrations (low and high) to processed cream

cheeses. In addition, two processed cream cheeses without bell pepper gel pieces were prepared. Table 7.1 provides a summary of all samples.

Materials

Processed cream cheese (Kiri®) was kindly provided by Bel Group (Fromageries Bel, Suresnes, France), κ -carrageenan (GENUGEL type CHP-2) and low acyl gellan gum (KELCOGEL® gellan gum) were purchased from CP Kelco (Rotterdam, The Netherlands). Food colorant (Paprika Oleoresin WS, E160c) was purchased from Holland Ingredients (Meppel, The Netherlands). Red bell peppers, salt, sunflower oil, white bread and sparkling water were purchased from a local supermarket. All ingredients were food grade and samples were prepared under food safe conditions.

Preparation of processed cream cheeses and instrumental texture characterization

Soft processed cream cheese matrices with high adhesiveness were prepared by placing 100g of cream cheese into a vacuum sealed bag in a water bath at 65°C for 30 min to allow the cream cheese to melt. Molten cream cheeses were poured into a vessel kept at 65°C. To obtain hard processed cream cheese matrices with low adhesiveness, 12.5g of κ -carrageenan gel was added to cream cheese. Molten cream cheese κ -carrageenan mixtures were poured into a vessel kept at 65°C and manually mixed avoiding incorporation of air. κ -carrageenan gel was prepared by dissolving κ -carrageenan with tap water at 2% (w/v). The κ -carrageenan solution was heated in a water bath at 90°C for 30 min under continuous stirring. Subsequently, the solution was placed in an ice bath for 20 min to cool and set. To produce heterogeneous cheeses, bell pepper gel pieces were added at 15% or 30% (w/w).

Table 7.1. Sample codes, texture properties of processed cream cheese matrices and mechanical properties and concentration of bell pepper gel pieces of eight heterogeneous cheeses. First two letters of the sample codes indicate cheese matrix (Sa, soft/adhesive; Hn, hard/non-adhesive), second two letters of the sample codes indicate fracture stress of embedded bell pepper gel pieces (So, soft and Ha hard bell pepper gel pieces) and subscript numbers of the sample codes indicate concentration of added bell pepper gel pieces (15 and 30% w/w for low and high respectively). Data are reported as mean±SE.

Processed cream cheese matrix					Bell pepper gel pieces	
Sample code	Description	Hardness (N)	Adhesiveness (N*s)	Target fracture stress (kPa)	Measured fracture stress (kPa)	Bell pepper gel concentration (% w/w)
Sa (-)	Soft/adhesive cheese without bell pepper gel pieces	6.9±0.7	2.3±0.2	-	-	-
Hn (-)	Hard/non-adhesive cheese without bell pepper gel pieces	13.7±0.5	0.8±0.1	-	-	-
SaSo ₁₅	Soft/adhesive cheese with soft bell pepper gel pieces embedded at 15%	6.9±0.7	2.3±0.2	100	106±1	15
SaSo ₃₀	Soft/adhesive cheese with soft bell pepper gel pieces embedded at 30%	6.9±0.7	2.3±0.2	100	106±1	30
SaHa ₁₅	Soft/adhesive cheese with hard bell pepper gel pieces embedded at 15%	6.9±0.7	2.3±0.2	300	295±11	15
SaHa ₃₀	Soft/adhesive cheese with hard bell pepper gel pieces embedded at 30%	6.9±0.7	2.3±0.2	300	295±11	30
HnSo ₁₅	Hard/non-adhesive cheese with soft bell pepper gel pieces embedded at 15%	13.7±0.5	0.8±0.1	100	106±1	15
HnSo ₃₀	Hard/non-adhesive cheese with soft bell pepper gel pieces embedded at 30%	13.7±0.5	0.8±0.1	100	106±1	30
HnHa ₁₅	Hard/non-adhesive cheese with hard bell pepper gel pieces embedded at 15%	13.7±0.5	0.8±0.1	300	295±11	15
HnHa ₃₀	Hard/non-adhesive cheese with hard bell pepper gel pieces embedded at 30%	13.7±0.5	0.8±0.1	300	295±11	30

The mixture was subsequently poured into a squared petri plate coated with a thin layer of sunflower oil and stored in a fridge at 4°C for 16-18 hours. Cheeses were removed from petri dishes and cut with a custom-made cutting frame to obtain 20x20x12mm cubes weighing approx. 5g which were used for determination of oral behavior and sensory evaluations. Cheese cubes were stored at 4°C.

Spreadability tests were performed on both homogenous processed cream cheese matrices (Sa and Hn) using a Texture Analyzer (TA. XT plus, Stable Micro Systems-SMS) equipped with a 5 kg load cell and a 90° conical stainless-steel probe of 26mm diameter and 12mm height of the conical trunk. Processed cream cheeses were removed from the petri dish in which they were prepared and placed on a flat surface. A stainless-steel cylindrical mold (30mm internal diameter and 10mm height) was put on top of the cheese surface and slowly inserted in the cheese. Excess cheese was gently removed with a knife to obtain a flat surface. The sample was placed in the fridge at 5°C for 10 minutes. After that, the filled mold was fixed in the middle of the plate of the Texture Analyzer underneath the cone. The cheeses were penetrated at 0.5mm/s to a target depth of 9mm. Then the probe was retracted from the cheese speed of 0.5mm/s until the starting position was reached. Force-time curves were recorded. Force (N) at maximum penetration depth (9mm) was taken as hardness and negative area under the force-time curve (N*s) as adhesiveness. Seven replicates were performed, and hardness and adhesiveness calculated by averaging over replicates. Hardness between the hard/non-adhesive cheese matrix and the soft/adhesive matrix differed by a factor of 2x (Table 7.1). With regards to adhesiveness, as the hardness of the cheese increased, adhesiveness decreased.

Preparation of bell pepper gel pieces and characterization of mechanical properties

Bell pepper gel pieces varying in fracture stress (σ_F) were prepared following the methodology described by Santagiuliana et al.¹⁹¹. Gel pieces were prepared using low acyl gellan gum and two bell pepper concentrates to provide a realistic bell pepper flavor. For the first concentrate, bell peppers were roasted for 13 min at 270°C in an oven and then cooled down to room temperature for about 1h. After removal of skin and seeds, bell peppers were pureed using a hand blender (Braun Multiquick 7, MQ 745) for 5 min and then centrifuged (Allegra X-30R Centrifuge) for 15 min at 4500 rpm. The supernatant was

passed through a sieve (64 μm mesh size) and stored at -18°C . For the second concentrate, bell peppers were cut, deseeded, juiced (Philips HR 1861, Eindhoven, The Netherlands) and poured in an open pan reducing to 66% of its initial weight by heating in a stove. The concentrate was sieved (64 μm mesh size) and cooled down in an ice bath for 20 min and stored at -18°C . 50:50 (v/v) solutions of both concentrates were prepared and mixed with 0.5% colorant (E160c paprika oleoresin), 0.2% salt and either 1.5 or 3.6% low acyl gellan gum (Kelcogel F) to obtain soft and hard gel pieces (target fracture stress σ_F : 100 and 300 kPa, respectively). Solutions were placed in a water bath at 95°C for 45 min under continuous stirring which then were poured in either 500 ml squared plastic containers and placed in an ice bath for 20 min to cool and set. Gels were cut into slices using a mandolin (Ernesto, The Netherlands) and then with a custom-made cutter frame into cubes of 4x4x4mm. These bell pepper gel cubes were added to the processed cream cheese as described in section 7.2.2.

To characterize the fracture behavior, gels were prepared in 30 ml syringes (Terumo, Leuven, Belgium). Cylindrical pieces of gels were cut with a diameter of 23mm and height of 15mm. A Texture Analyzer (TA.XT. plus, Stable Micro Systems-SMS) equipped with a load cell of 50 kg and a compression plate of 100mm diameter was used to perform uniaxial compression tests on the bell pepper gels (-So and -Ha). Samples were lubricated with paraffin oil to prevent friction with the plate during compression. Four replicates per sample were measured at 20°C at constant compression speed of 1mm/s up to a strain of 30%. Average true fracture stress (kPa) and true fracture strain were calculated by averaging over replicate measurements. Low and high fracture stress gels exhibited a true fracture stress of 106 ± 1 kPa and 295 ± 11 kPa and a true fracture strain (-) of 0.13 ± 0.01 and 0.14 ± 0.01 , respectively (Table 7.1).

7.2.3. Oral behavior characterization

Oral behavior was characterized by video recording the 34 participants while consuming the cheeses as previously described by Aguayo-Mendoza et al.⁶⁹ and Ketel et al.⁶⁸. In short, four round stickers were placed on the participant's face, two on the forehead spaced horizontally 5 cm, one on the tip of the nose, and one on the center of the chin. Participants were seated in a chair in front of a table with a video camera (Canon IXUS-500HS),

approximately 50 cm from the participant's face. Videos were recorded, in a well-lit room, isolated from external noise or any other distractions. Cheese cubes (20x20x12mm; 5g) were served on a spoon and subjects were instructed to consume the samples as they would normally do, while being video recorded. Subjects were instructed to indicate every moment of swallowing by raising their hand. All 10 cheeses were presented in a randomized order and in monadic sequence at a serving temperature of 8°C and consumed over two test sessions of 60 min each. Videos were analyzed using Kinovea software (version 0.8.15). The parameters extracted from the videos were consumption time (s), number of chews, number of swallows, and eating rate (g/min).

7.2.4. Bolus collection and analyses at moment of swallowing

Boli were collected from the 34 participants during six sessions of 30 min each. In all sessions, participants received samples in a monadic sequence and randomized order. Overall, participants were asked to chew every sample as they would normally do and expectorate the bolus when they hear the alarm of a timer. The timer was set at 100% of the average total consumption time of all 34 subjects.

Particle size and number of bell pepper gel pieces in expectorated bolus

Participants chewed and expectorated bolus of the 8 heterogeneous cheeses in a 120 ml cup. To collect particles that might be left in the mouth, participants took a sip of water and expectorate it in the same cup. Gel fragments in bolus were separated from the cheese matrix by rinsing the bolus for one minute under running lukewarm water and then dried with cold air and gently spread in a plastic petri dish (120x120x17mm, Greiner Bio). Petri dishes were scanned (CanonScan 9000F markII) to obtain images in greyscale (8 bit) with a resolution of 1200 dpi which were analyzed using ImageJ software (National Institutes of Health, Version 1.51). The total number of particles and their median diameter (d_{50}) were quantified.

Saliva incorporation in expectorated bolus

Boli from all 10 cheeses were directly expectorated in aluminum plates and immediately weight was determined. Boli samples were dried for 16 h at 105°C in an atmospheric oven (Venti-line line, VWR®). After drying, samples were weighed. Dry matter of cheeses

(DM_{sample}) and the dry matter of spit-out bolus ($DM_{\text{spit_bolus}}$) were determined and used to calculate saliva content of expectorated boli following the procedure described by Drago⁵⁷. The ratio of milligrams of saliva incorporated in the bolus per gram of food masticated (h_w) was calculated as:

$$h_w = \frac{DM_{\text{sample}} * 1000}{DM_{\text{spit_bolus}}} - 1000$$

Instrumental hardness and adhesiveness of expectorated bolus

Bolus from the 10 cheeses were collected in a cup in triplicate. Immediately after expectoration the bolus was transferred to a stainless-steel cylindrical mold (30mm internal diameter and 10mm height) where the bolus was gently pressed to avoid air incorporation and product above the mold's height was removed with a spatula to obtain a flat surface. The mold containing the bolus was fixed to the plate of the texture analyzer (TA. XT plus, Stable Micro Systems-SMS). The latter was equipped with a 5 kg load cell and a cylindrical aluminum probe of 20mm diameter. The probe penetrated the bolus (back extrusion) with a test speed of 0.5mm/s to a target distance of 9mm, then the probe was retracted from the bolus at a speed of 0.5mm/s until the starting position was reached. From force distance curves, bolus hardness and adhesiveness were obtained as described in section 7.2.2.

Sensory evaluation using Temporal Dominance of Sensations

All 10 cheeses were evaluated by the n=34 subjects in duplicate using Temporal Dominance of Sensations (TDS). Before the evaluation sessions took place, all participants underwent a familiarization session of 90 min where participants were introduced to the TDS methodology, sensory attributes, definitions and the software used to collect their responses. Dominance was defined as: "Attribute that is catching the attention at a given time, not necessarily the attribute with the highest intensity". Attributes and definition were obtained from literature using similar foods¹⁹¹ and by discussion between the researchers (Table 7.2). TDS data was collected over 3 sessions of 60 min each using EyeQuestion (Version 3.9.7, Logic 8 BV, Elst, The Netherlands). Subjects were instructed to put the cheese cube in their mouth and click the "start" button as soon as they began to chew. Participants could only select one attribute at a time. Participants were instructed to

click on a new dominant attribute each time that their perception changed, and that it was possible to repeat attributes or not to select an attribute at all. Finally, when participants swallowed, the “stop” button was pressed. After each sample, participants neutralized their mouth with sparkling water and a piece of white bread. Samples were presented in a randomized order according to a Latin square scheme. The attribute list was randomized across participants but was kept constant for all samples and for an individual panelist.

Table 7.2. Sensory attributes and definitions used during Temporal Dominance of Sensations analysis (TDS) of processed cream cheeses with and without bell pepper gel pieces.

Attribute	Definition
Creamy	Thick, velvety texture
Sticky	Adhesive sensation on tongue, palate and teeth
Firm	Amount of force required by the tongue to flatten the sample
Grainy	Perception of large irregularities in the sample. Mass of solid matter of no particular shape
Melty	Loss of structure in the mouth
Smooth	Uniform perception of the product during consumption
Chewy	The degree of elasticity of the sample
Powdery	The sensation of small particles like flour
Bell pepper flavor	Perception of bell pepper aroma and taste
Dairy flavor	Aroma and taste associated with cream/milk

7.2.5. Data analysis

To determine the effect of addition of bell pepper gel pieces to each cheese matrix (Hn or Sa) on oral behavior (consumption time, number of chews, number of swallows, eating rate), one-way analysis of variance (ANOVA) was performed comparing the homogeneous cheese with their respective heterogenous cheeses. Furthermore, three-way repeated measures ANOVA was performed to determine the effects of cheese matrix type, fracture stress, and concentration of gel pieces on oral behavior (consumption time, number of chews, number of swallows, eating rate) and bolus properties (particle size, particle number, saliva incorporation, bolus hardness and adhesiveness). Effects were considered statistically significant at $p < 0.05$. When applicable, post-hoc analyses were performed with Bonferroni adjustment.

TDS curves were constructed by plotting the dominance rate (proportion of subjects who scored each attribute at each point of time) against consumption time. In order to take into account differences in consumption time between subjects, consumption time was standardized on a scale from 0 (starting point) to 100 (swallowing moment). Chance and significance level were calculated as described by Pineau ⁸⁸.

To investigate the relationships between oral behavior, bolus properties at the moment of swallowing, and sensory perception a Multiple Factor Analysis (MFA) was performed with three data matrices as active datasets (oral behavior, bolus properties, sensory perception) including only cheeses with bell pepper gel pieces. Individuals graphs and correlations circles were plotted for dimensions one and two, and dimensions one and three.

All data analyses were performed in R (v3.6.3; R Core Team, 2019). One-way ANOVA and three-way repeated measures ANOVA analyses were performed using *rstatix* package (v0.4.0). TDS curves and sensory trajectories were constructed using *tempR* package (v0.9.9.16). MFA analysis and graphs were performed with packages *FactoMineR* (v2.3) and *factoextra* (v1.0.7)

7.3. Results

7.3.1. Oral behavior

Table 7.3 shows descriptive data of all parameters characterizing oral processing behavior of the processed cream cheeses with and without bell pepper gel pieces. Upon incorporation of gel pieces into soft/adhesive cheese matrices consumption time [$F(4,128)=5.45$, $p<0.001$], number of chews [$F(4,128)=13.59$, $p<0.001$] and number of swallows [$F(4,128)=3.02$, $p=0.02$] increased significantly, and eating rate [$F(4,128)=7.14$, $p<0.001$] decreased significantly. Incorporation of bell pepper gel pieces into hard/non-adhesive cheese matrices significantly increased consumption time [$F(4,128)=5.91$, $p<0.001$] and number of chews [$F(4,128)=11.62$, $p<0.001$] and significantly decreased eating rate [$F(4,128)=3.84$, $p=0.006$]. In average, the addition of bell pepper gel pieces to soft/adhesive cheeses increased consumption time by 20.6% (from 10.9 to 13.2 s) and number of chews by 41.7% (from 13.3 to 18.9). Addition of bell pepper gel pieces to hard/non-adhesive cheeses increased consumption time by 12.0% (from 11.2 to 12.6 s) and

number of chews by 28.7% (from 14.1 to 18.2). Addition of bell pepper gel pieces decreased average eating rate by 14.5% (4.4 g/min) for soft/adhesive cheeses and by 8.9% (2.7 g/min) for hard/non-adhesive cheeses.

Regarding the effect of matrix type, particle fracture stress and particle concentration, the results showed that, among the heterogenous cheeses, those with soft/adhesive matrix were consumed for significantly longer time (13.2 s) [$F(1,32)=5.98$, $p=0.02$] and with lower eating rate (25.8 g/min) [$F(1,32)=7.38$, $p=0.011$] than cheeses with hard/non-adhesive matrix (12.6s and 27.6 g/min, respectively). A similar effect was seen in cheeses that had bell pepper gel pieces with high fracture stress which were consumed for longer time (13.2 s) [$F(1,32)=6.04$, $p=0.02$] and with lower eating rate (25.9 g/min) [$F(1,32)=4.88$, $p=0.034$] than cheeses with gel pieces with low fracture stress (12.5s and 27.5 g/min, respectively). The relative difference in consumption time between the matrices was 4.5%, and 5.3% between fracture stress of bell pepper gels. Cheeses with high fracture stress gel pieces had significantly higher number of chews (19.4) than cheeses with gel pieces with low fracture stress (17.4) [$F(1,32)=21.26$, $p<0.001$]. Fracture stress of bell pepper gel pieces had also a significant effect on number of swallows [$F(1,32)=4.86$, $p=0.035$] but only in cheeses with soft/adhesive matrix. The concentration of gel pieces did not have a significant effect on any oral processing behavior parameters.

7.3.2. Bolus properties at moment of swallowing

Table 7.4 shows descriptive data of bolus properties of cheeses expectorated after 100% mastication time. Upon incorporation of gel pieces into soft/adhesive cheese matrices saliva incorporation increased significantly from 182 to 285 mg/g [$F(4,124)=13.50$, $p<0.001$], and bolus hardness increased significantly from 2.9 to 5.9 N [$F(4,92)=20.73$, $p<0.001$], whereas bolus adhesiveness decreased significantly from 14.7 to 8.2 N*s [$F(4,92)=34.14$, $p<0.001$]. Same trends were found after incorporation of bell pepper gel pieces into hard/non-adhesive cheese matrices where saliva incorporation increased from 202 to 227.5 mg/g [$F(4,120)=5.41$, $p<0.001$], bolus hardness increased from 2.0 to 4.15 N [$F(4,112)=21.15$, $p<0.001$], and bolus adhesiveness decreased from 13.7 to 7.7 N*s [$F(4,112)=44.42$, $p<0.001$].

Cheeses with soft/adhesive matrix and high concentration of gel pieces (Sa--30) produced boli with significantly more particles than cheeses with hard/non-adhesive matrix and low concentration of bell pepper gel pieces (Hn--15) [$F(1,28)=17.2$, $p<0.001$]. Gel pieces fracture stress had a significant effect on d_{50} [$F(1,28)=5.71$, $p=0.024$]. Cheeses with hard/non-adhesive matrix and gel pieces of high fracture stress (HnHa..) had larger d_{50} compared to cheeses with similar matrix but with gel pieces of low fracture stress (HnSo..). On the other hand, concentration of gel pieces had a significant effect on d_{50} [$F(1,28)=6.77$, $p=0.015$] with cheeses with high concentration of gel pieces having larger d_{50} .

For the mass ratio of saliva incorporated in the bolus (h_w), it was found that high concentration of soft gel pieces caused a higher saliva incorporation in the bolus of cheeses with hard/non-adhesive matrix [$F(1,30)=9.27$, $p=0.02$]. On the other hand, there was significantly higher saliva incorporation in the bolus of cheeses with a hard/non-adhesive matrix, high fracture stress, and bell pepper gel pieces present in low concentration (HnHa15) than in similar cheeses but with low fracture stress bell pepper gel pieces (HnSo15) [$F(1,31)=12.31$, $p=0.004$].

Bolus hardness significantly increased when gel pieces fracture stress and concentration increased [$F(1,22)=12.73$, $p=0.002$]. Cheeses with hard/non-adhesive matrices produced bolus with significantly lower hardness [$F(1,22)=18.02$, $p<0.001$] than cheeses with soft/adhesive matrices. Cheeses with high concentration of particles (30%) had significantly lower bolus adhesiveness [$F(1,22)=87.29$, $p<0.001$] than cheeses with low concentration of particles (15%).

Table 7.3. Descriptive data of oral processing behavior parameters of all processed cheeses varying in cheese matrix texture, bell pepper gel piece fracture stress and concentration (Mean $\pm$ SE). Sample codes are explained in Table 7.1.

Processed cheese	Consumption time (s)	Number of chews (-)	Number of swallows (-)	Eating rate (g/min)
Sa (-)	10.9 $\pm$ 0.4	13.3 $\pm$ 0.8	2.2 $\pm$ 0.2	30.1 $\pm$ 1.3
SaSo ₁₅	13.0 $\pm$ 0.5	17.3 $\pm$ 1.0	2.0 $\pm$ 0.1	25.7 $\pm$ 1.0
SaSo ₃₀	13.0 $\pm$ 0.8	18.8 $\pm$ 1.4	2.0 $\pm$ 0.2	26.9 $\pm$ 1.9
SaHa ₁₅	13.1 $\pm$ 0.5	19.3 $\pm$ 1.0	1.8 $\pm$ 0.1	25.4 $\pm$ 1.3
SaHa ₃₀	13.5 $\pm$ 0.7	20.0 $\pm$ 1.4	1.8 $\pm$ 0.1	25.0 $\pm$ 1.5
Hn (-)	11.2 $\pm$ 0.5	14.1 $\pm$ 0.1	1.9 $\pm$ 0.1	30.3 $\pm$ 1.5
HnSo ₁₅	11.9 $\pm$ 0.5	16.7 $\pm$ 1.0	1.9 $\pm$ 0.1	28.6 $\pm$ 1.4
HnSo ₃₀	12.0 $\pm$ 0.5	17.7 $\pm$ 1.1	1.8 $\pm$ 0.1	28.9 $\pm$ 1.6
HnHa ₁₅	12.9 $\pm$ 0.6	18.9 $\pm$ 1.0	1.9 $\pm$ 0.1	27.2 $\pm$ 1.6
HnHa ₃₀	13.4 $\pm$ 0.7	19.3 $\pm$ 1.3	1.9 $\pm$ 0.1	25.6 $\pm$ 1.7

Table 7.4. Descriptive data of bolus properties at the moment of swallowing of heterogeneous cheeses varying in cheese texture, bell pepper gel pieces fracture stress and concentration on bolus properties (Mean $\pm$ SE). Sample codes are explained in Table 7.1.

Processed cheese	Number of particles (-)	d ₅₀ (μ m)	Saliva incorporation (mg of saliva/g of food)	Bolus hardness (N)	Bolus adhesiveness (N·s)
Sa	-	-	182 $\pm$ 26	2.9 $\pm$ 0.2	14.7 $\pm$ 1.0
SaSo ₁₅	266 $\pm$ 18	2533 $\pm$ 50	303 $\pm$ 27	3.9 $\pm$ 0.2	9.7 $\pm$ 1.0
SaSo ₃₀	478 $\pm$ 18	2538 $\pm$ 41	263 $\pm$ 23	4.9 $\pm$ 0.7	5.9 $\pm$ 1.0
SaHa ₁₅	272 $\pm$ 19	2477 $\pm$ 36	274 $\pm$ 27	4.9 $\pm$ 0.6	10.3 $\pm$ 1.0
SaHa ₃₀	488 $\pm$ 18	2540 $\pm$ 46	302 $\pm$ 25	9.8 $\pm$ 1.0	6.7 $\pm$ 1.0
Hn	-	-	202 $\pm$ 27	2.0 $\pm$ 0.2	13.7 $\pm$ 1.0
HnSo ₁₅	192 $\pm$ 15	2878 $\pm$ 68	185 $\pm$ 25	2.9 $\pm$ 0.2	9.2 $\pm$ 1.0
HnSo ₃₀	320 $\pm$ 27	2994 $\pm$ 77	231 $\pm$ 23	2.9 $\pm$ 0.3	6.9 $\pm$ 1.0
HnHa ₁₅	203 $\pm$ 16	2977 $\pm$ 91	245 $\pm$ 30	3.9 $\pm$ 0.4	8.8 $\pm$ 1.0
HnHa ₃₀	336 $\pm$ 29	3139 $\pm$ 109	249 $\pm$ 23	6.9 $\pm$ 1.0	6.0 $\pm$ 0.5

7.3.3. Temporal Dominance of Sensations (TDS)

Normalized TDS curves of all cheeses are shown in Figure 7.1. The dominant sensation of the homogeneous, soft/adhesive cheese was sticky for the first half of consumption time. Simultaneously present dominant sensations after 20% of consumption time were creamy and smooth. Dairy flavor and melting sensation became dominant in the second half of consumption time and remained dominant sensations until swallowing. The homogeneous, hard/non-adhesive cheese was perceived as firm during the first 25% of consumption time. Then the dominant sensation became dairy flavor and around 50% of consumption time melting and smooth sensations became dominant together with dairy flavor. Close to swallowing sticky became dominant but at low dominance rate.

For heterogeneous cheeses, the number of attributes reaching significance decreased with increasing fracture stress and concentration of gel pieces. Processed cream cheeses with soft/adhesive matrices showed higher dominance rates and longer dominance durations for creaminess, dairy flavor, smoothness and melting compared with processed cream cheeses with hard/non-adhesive matrices. Increasing fracture stress of bell pepper gel pieces decreased dominance rate and duration of creaminess and bell pepper flavor while dominance rate and duration of graininess increased. Incorporation of gel pieces at high concentration (30% w/w) reduced dominance rate and duration of creaminess, melting and dairy flavor while dominance rate and duration of graininess and bell pepper flavor increased and remained dominant during the entire consumption time.

7.3.4. Relationships between oral behavior, bolus properties and dynamic sensory perception

Figure 7.2 displays the first three dimensions of the MFA which together explain 86.2% of the variance in the data. Figure 7.2.A shows the position of the eight cream cheeses with gel pieces relative to each other in the first two dimensions. Figure 7.2.B shows the correlations between the variables. The first dimension shows that number of chews and total consumption time were positively correlated, and both were negatively correlated with eating rate.

Figure 7.1. Temporal Dominance of Sensations (TDS) curves (n=34, duplicate) of processed cheeses without and with bell pepper gel pieces. Sample codes are explained in Table 7.1.

Figure 7.2. A) MFA sample space depicting dimension one and two. B) Correlation circle displaying relationships between variables describing oral behavior (gray), bolus properties (blue) and sensory perception (yellow) of dimension one and two. C) MFA sample space depicting dimension one and three. D) Correlation circle displaying relationships between the variables describing oral behavior (gray), bolus properties (blue), and sensory perception (yellow) of dimension one and three.

Consumption time and number of chews were correlated with bolus properties such as saliva content, number of bolus particles and bolus hardness as well as with sensory perception of firmness, chewiness and graininess. Cheeses that were masticated for longer time and with more chews incorporated more saliva and were broken down into more fragments which corresponds to cheeses that contain gel pieces with high fracture stress at

high concentration. In the second dimension, the sensory attributes creaminess, smoothness, stickiness, melting and dairy flavor were positively correlated with each other and with adhesiveness of bolus. These variables described cheeses with soft/adhesive matrices and gel pieces at low concentration ($--_{15}$) with soft and hard gel pieces. Besides, bolus particles size was positively correlated with sensory attributes powdery and bell pepper flavor and negatively correlated with creaminess, smoothness, stickiness, melting and dairy flavor. The later attributes were also negatively correlated with grainy and chewy attributes in the first dimension.

The third dimension (Figure 7.2.C and D) shows a positive correlation between total number of bolus particles, bell pepper flavor and number of swallows; variables that describe a cheese with soft/adhesive matrix, soft gel particles at high concentration (SaSo₃₀). Similar to dimension two, dimension three shows that bolus adhesiveness, and dairy flavor were positively correlated. Lastly, adding the third dimension shows that there was a positive correlation between eating rate and melting, creamy and smoothness in the first dimension that describes cheeses with embedded soft gel pieces.

7.4. Discussion

7.4.1. Effect of addition of bell pepper gel pieces into homogeneous processed cream cheeses on oral behavior, bolus properties and sensory perception

We hypothesized that the extent to which oral behavior is affected by the addition of particles to foods depends on the magnitude of the difference in mechanical properties between particles and matrix. Our results showed that, independently of the gel characteristics, the mere addition of particles into cream cheeses, showed a similar influence on oral behavior than the one previously observed in another study of yogurts where addition of peach gel particles increased number of chews and consumption time and consequently reduced eating rate ²²². However, the impact of addition of bell pepper gel pieces to processed cream cheeses on oral behavior was smaller than the impact previously reported for addition of peach gel pieces to yogurt, since mechanical contrast between food matrix and embedded particles was smaller. Thus, the mere addition of solid

particles is a favorable strategy to steer oral behavior not only when incorporated into liquid foods but also when added to semi-solid foods. This strategy can be especially relevant since subtle food texture modifications are more easily sustained, implemented and accepted by consumers and can be used to potentially moderate food intake ²⁰⁷. Nevertheless, the magnitude by which oral processing behavior was modified depended on the texture of the cheese matrix. In soft/adhesive cheese matrices the effect of addition of particles on oral processing behavior was almost twice as large than in hard/non-adhesive cheese matrices. When gel pieces were incorporated into soft/adhesive cheese matrices, eating rate decreased from 30.1 g/min for the homogeneous cheese to an average of 25.7 g/min (-14.5%) for the heterogeneous soft/adhesive cheeses, while for homogeneous hard/non-adhesive cheese matrices eating rate decreased from 30.3 g/min to 27.6 g/min (-8.9%). Therefore, when designing heterogeneous food structures with the desire to influence oral behavior, the characteristics of the matrix and the mechanical contrast between particles and matrix need to be considered.

The properties of the bolus at the swallowing point were also affected by the incorporation of gel pieces. Upon addition of gel pieces to the cheeses, the amount of saliva incorporated in the bolus and bolus hardness increased whereas bolus adhesiveness decreased. Surprisingly, hardness and adhesiveness showed very similar increments in both cheese matrices. Whereas the increment in saliva was greater when the cheese matrix was soft/adhesive than hard/non-adhesive (increment of 56.8 and 12.62% respectively); this discrepancy in the increment of saliva between the matrices could be connected to the relative changes in consumption time and number of chews.

With regards to dynamic sensory perception, as expected the addition of particles reduced the dominance rate and duration of attributes that mainly describe the cheese matrices (creaminess, smoothness, melting and dairy flavor) while dominance rate and duration of attributes describing the bell pepper gel pieces (graininess and bell pepper flavor) increased.

7.4.2. Influence of cheese matrix and gel pieces characteristics on oral behavior of heterogeneous cheeses

Cheeses with soft/adhesive matrix were consumed slightly longer than cheeses with hard/non-adhesive matrix (difference of 0.6 sec). It would be expected that cheeses with hard matrices would be processed orally for longer time. Slight elongation on consumption time of the soft/adhesive cheese matrices might be attributed to its higher adhesiveness rather than its lower hardness most likely because of additional mouth clearance. The number of chews was not affected by cheese matrix type but by fracture stress of embedded bell pepper gel pieces which also prolonged consumption time. We conclude that not only food hardness but also other texture characteristics such as adhesiveness contribute to consumption time ²²³.

7.4.3. Influence of cheese matrix and gel pieces characteristics on bolus properties of heterogeneous cheeses

Bolus properties at the swallowing point were influenced by the properties of the cheese matrix and the bell pepper gel piece characteristics. Number of bolus particles was higher when concentration of bell pepper gels pieces was high (30% w/w) in soft/adhesive cheese matrices. We speculate that oral detection of gel piece fragments might be more evident when fragments are embedded in a soft matrix than when they are embedded in a hard matrix. Gel fragments in soft/adhesive matrices may be selectively moved towards the molars to be comminuted, which might also explain why bolus particles from soft/adhesive matrices were in smaller (2522 μm) than particles from hard/non-adhesive matrices (2997 μm). Another interesting fact is that the bolus particle size of the gels in these heterogeneous cheeses is larger than the size previously reported for homogeneous foods. A previous study suggested that homogeneous foods such as peanuts, mushrooms, carrots or ham should reach a particle size smaller than 2000 μm before being swallowed unless particles are soft enough to avoid injury of the upper digestive mucosa ⁹. In our study, gel pieces were embedded in a cheese matrix which upon chewing could serve as coating layer decreasing the friction between the bolus particles and the oral mucosa facilitating swallowing.

Saliva incorporation in the bolus increased in cheeses with hard/non-adhesive matrices and low concentration of particles (15% w/w/) when fracture stress of the bell pepper gel pieces was increased from 100 to 300kPa. This increase in saliva incorporation might be caused by higher mechanical stimulation subsequent to the increment in the hardness of the gel pieces, which in turn increases the salivary flow ²²⁴.

Bolus hardness and adhesiveness were predominantly influenced by the characteristics of the gel pieces. During compression, the presence of particles influenced the force necessary to deform the bolus so that an increase in gel fracture stress or gel pieces concentration increased bolus hardness. On the contrary, increasing the concentration of gel pieces decreased bolus adhesiveness by limiting the contact surface of the cheese structure.

7.4.4. Influence of cheese matrix and gel pieces characteristics on dynamic sensory perception of heterogeneous cheeses

The dynamic sensory perception of heterogeneous cheeses was influenced by the cheese matrix texture and bell pepper gel pieces properties. Cheese matrices with hard/non-adhesive texture displayed lower dominance durations and dominance rates for creaminess, smoothness and melting sensations than cheese matrices with soft/adhesive texture. The differences in sensory properties between the cheeses may be explained by the presence of k-carrageenan in the hard/non-adhesive cheese matrices. Previous studies have shown that the addition of k-carrageenan increased cheese hardness producing a negative effect on meltability ^{225–227}. Melting perception might therefore have been reduced contributing to a decline in smoothness and creaminess ^{45,228}.

With increasing concentration of gel pieces, dominance rate and duration of bell pepper flavor increased. Increasing the concentration of particles expands the contact area between the gel pieces and the tongue which might have contributed to a higher dominance of bell pepper flavor. Higher concentrations of gel pieces led to a lower dominance rate and duration of creaminess, melting and dairy flavor while graininess increased and remained significantly dominant during the entire consumption time. Graininess perception has been related to the detectability of particles in the mouth, so adding particles or increasing their concentration is expected to rise graininess perception.

When in addition to the concentration of gel pieces, these were of low fracture stress, then bell pepper flavor showed higher dominance rate. Taste and aroma perception are influenced by fracture stress of foods. Increasing fracture stress leads to decreasing taste and aroma perception^{229,230}.

An unexpected result was that several attributes were dominant for long periods resulting in little temporal dynamics among the attributes for several cheeses. Only firmness and melting showed some dynamics over the consumption time. Firmness was only perceived at the beginning of consumption time, but this sensation was only dominant in the homogeneous hard/non-adhesive cheese. Whereas melting was a sensation always perceived after some degree of oral manipulation, which may be needed to bring the food to mouth temperature before the meltiness is perceived. On the other hand, attributes that show the lowest dynamics were graininess and bell pepper flavor, both attributes are dependent on the presence of bell pepper gel pieces. Upon mastication, bell pepper pieces become more numerous but with smaller size, so the perception of graininess and bell pepper flavor remains. Thus, there seem to be attributes that need certain transformation of the food structure during oral processing in order to be perceived whereas other attributes may be more stable over time with changes just in their intensity.

7.4.5. Relationships between oral processing, bolus properties and sensory perception

Oral behavior (consumption time and number of chews) was positively correlated with several bolus properties (saliva incorporation, number of bolus particles and bolus hardness) and with perception of several sensory attributes (firmness, graininess, chewiness). These relationships were found in heterogeneous cheeses with bell pepper gel pieces of high fracture stress and high concentration independent of the cheese matrix. The addition of bell pepper gel pieces with high fracture stress prolonged consumption time compared to the softer counterpart. This is in agreement with several other studies that demonstrated that mastication time increases when hardness or stiffness of foods increase properties^{39,46,47,49,50,69,167,218,220}. Furthermore, increments in consumption time caused by presence of bell pepper gel pieces with high fracture stress on both cheese matrices gave rise to more saliva incorporation into the bolus. It is known that increments in mastication

time will in turn increase salivation, so the increase in saliva incorporation in the bolus might be caused by the prolonged consumption time. Moreover, the increased number of chews increment the number of bolus particles which clearly relates with attributes such as graininess. Graininess perception has been linked to the presence of food particles and their oral selection for further bolus degradation in order to reduce particle size ¹⁸¹. Firmness and chewiness of foods have been correlated with expected satiation ⁵². Therefore, we suggest that incorporating particles to foods that increase perceived firmness and chewiness without increasing energy content could aid in regulating energy intake. This approach should be considered carefully though, since the presence of chewiness and/or graininess in foods where these sensations are not expected, can reduce acceptability, however when these perceptions are congruent with the product palatability can be maintained ²⁰⁰.

Consumption time and number of chews were negatively correlated with faster eating rate. Faster eating rate was positively correlated with smoothness, creaminess and meltiness sensations. This was specially observed in heterogeneous cheeses that contained soft particles independently of the matrix characteristics (Figure 7.2.D). Smoothness, creaminess and meltiness are sensations that are commonly found after some degree of oral processing and are related to the absence of large particles in the bolus ^{66,181}, thus it is probable that faster eating rates are connected to attributes that resemble a more bolus like structure.

Overall, the magnitude of the effect by which oral behavior is affected, may depend on the food combination used and on whether a texture contrast is perceived or not. Therefore, further studies should make a systematic variation on the combination of food items across different food categories to observe how the different combinations behave and to define how big should be the texture contrast in order to impact oral behavior.

7.5. Conclusions

The present research studied the effect of heterogeneous food components, processed cheese matrix and embedded bell pepper gel pieces, on oral processing, bolus properties and dynamic sensory perception. Both matrix and gel pieces characteristics effected consumption time, eating rate, number of chews, bolus particle size distribution, saliva

incorporation, bolus hardness and adhesiveness, as well as perception of sensory attributes. The magnitude of the effect depended on the specific combination of the mechanical properties of both food items (i.e. matrix and gel pieces). Therefore, we conclude that when two homogeneous foods are combined, the physicochemical properties of the foods may elicit a sensory contrast that lead to a different oral behavior, bolus breakdown and sensory perception that would not be anticipated on the basis of the separate homogeneous components. We suggest that the modification of food properties by manipulation of one of the food components can be a convenient strategy to steer oral behavior which could potentially influence on food intake.

8

General discussion

8.1. Aim and summary of the main findings

The aim of this thesis was to determine the effect of food properties and consumer characteristics on oral processing behavior, bolus properties and sensory perception of foods. Different groups of consumers and different foods varying in physical properties were used across the six studies of this thesis as shown in Figure 8.1. Table 8.1 summarizes the main findings and the rest of this chapter discusses them and provides practical implications and outlook for future research.

Table 8.1. Overview of main findings presented in this thesis.

Chapter	Aim(s)	Approach	Main findings
2	To compare self-reported and video recording methodologies to characterize oral behavior during consumption of ice cream.	Classification of oral behaviors (n=103) based on questionnaire and video recordings	<ul style="list-style-type: none">• Different types of oral behavior were detected.• Often self-reported behavior did not agree with the categorization of oral behavior captured by video recordings.
	To understand how oral processing behavior dynamic influences sensory perception of ice creams.	TDS (n=22) evaluations while applying specific oral processing protocols	<ul style="list-style-type: none">• Oral processing behavior influence dominance rate and duration of aroma and taste attributes (chewing protocol ↑fruity aroma and coldness; melting protocol ↑sweetness, firmness and smoothness).• Increasing hardness influenced dominance rate and duration of fruity aroma (↓), coldness (↑) and sweetness (↓).• Texture attributes were perceived as dominant sensations at the beginning of consumption whereas taste and aroma attributes were dominant towards the end of consumption.
3	To determine the influence of rheological and mechanical properties of foods on oral processing behavior of liquid, semi-solid and solid foods.	Characterization of oral behavior (n=61) of 18 foods varying in physical properties	<ul style="list-style-type: none">• Consumers strongly adapt oral processing behavior with respect to bite size, consumption time, and eating rate to rheological and mechanical properties of liquid, semi-solid and solid foods.
		Mechanical and rheological properties quantification of test foods by either uniaxial compression tests or flow curves.	<ul style="list-style-type: none">• Consistency is negatively related to bite size and eating rate and positively to consumption time for liquid and semi-solid foods.• Stress at 15% strain and Young's modulus are negatively related with bite size and eating rate for solid foods.
4	To investigate the influence of age, gender, ethnicity and eating capability on oral processing behavior of liquid, semi-solid and solid foods.	Characterization oral behavior of consumers	<ul style="list-style-type: none">• Age, gender and ethnicity impact oral processing behavior differently. Effects are consistent for all three food groups.
		Young Dutch-Caucasian n=32 Elderly Dutch-Caucasian n=29 Young Chinese-Asian n=35 Decrease eating capability n=39	<ul style="list-style-type: none">• Consumption time increases and eating rate decreases with age.• Males consume solid foods with larger bite size and higher eating rate than females.• Chinese-Asian consume liquid, semi-solid and solid foods with smaller bite size and lower eating rate than Dutch-Caucasian.

5	To determine the effect of age, gender and ethnicity on consumption time, bolus properties and dynamic sensory perception of sausages.	Quantification of consumption time of a hotdog sausage bite (7g)	<ul style="list-style-type: none"> Elderly have longer consumption times than young consumers. Elderly produced more broken down boli than young consumers.
		Young Dutch-Caucasian n=21	<ul style="list-style-type: none"> Effect of gender interact with Ethnicity and Age, where Chinese males have shorter consumption time than Chinese females. Elderly females produced more adhesive and less cohesive boli than elderly males.
		Elderly Dutch-Caucasian n=21	<ul style="list-style-type: none"> Chinese females have longer consumption time than Dutch females. Chinese consumers produced more broken down boli than Dutch.
		Young Chinese-Asian n=22	<ul style="list-style-type: none"> Effect of age, gender and ethnicity on bolus properties was mediated by consumption time.
		Characterization of bolus properties TDS evaluations	<ul style="list-style-type: none"> Differences in dynamic texture perception between consumer groups were only observed during the middle stages of oral processing.
6	To investigate the effect of the addition of peach gel particles varying in size, fracture stress and concentration to yogurt on oral processing behavior, sensory perception and liking of consumers differing in age.	Characterization of oral behavior of consumers	<ul style="list-style-type: none"> Addition of particles to yogurt increased consumption time and decreased eating rate up to 60%.
		Young Dutch-Caucasian n=62	<ul style="list-style-type: none"> Increasing particle fracture stress or particle concentration prolongs consumption time by 40 and 30%, respectively.
		Elderly Dutch-Caucasian n=62 Liking and Sensory profile analysis	<ul style="list-style-type: none"> Aging had a marginal effect on sensory perception.
7	To determine the influence of physical-chemical properties of processed cream cheeses with bell pepper gel pieces on oral processing behavior, bolus properties and dynamic sensory perception.	Characterization of oral behavior	<ul style="list-style-type: none"> Oral processing behavior can be steered by modifications of either food matrix or embedded particle properties (fracture stress, concentration).
		Characterization of bolus properties TDS evaluation	<ul style="list-style-type: none"> Addition of particles to soft/adhesive or hard/non adhesive cheese decreased eating rate by 14.5% and 9% respectively, regardless of particle characteristics. However, the size of the effect depends on the characteristics of the matrix.
			<ul style="list-style-type: none"> Among heterogeneous cheeses increasing particle fracture stress by 3 folds decreased eating rate 5.3%. Sensory perception is dominated by the hardest component of the heterogeneous food.

Figure 8.1. Schematic overview of the different methodological approaches taken across the different studies in this thesis.

8.2. Influence of consumer characteristics on oral processing behavior, bolus properties and sensory perception

Chapter 2 showed that changes in oral behavior during ice cream consumption influences dynamic sensory perception (attribute selection, dominance rate, and dominance duration). Besides, the majority of consumers combined more than one “eating style” during consumption of ice cream, demonstrating that the suggestion of having one preferred mouth behavior while eating does not hold. It is known that oral processing behavior differs considerably between consumers ^{74,142}, and that inter-individual differences in oral processing behavior are often related to differences in oral physiology ^{13,20,36} and possibly to differences in cultural factors. Therefore, a practical approach to understand the variability across consumers on oral behavior is to group them based on specific characteristics such as age, gender and ethnicity. The research presented in this thesis focuses on understanding key factors contributing to differences in oral processing behavior, bolus properties and sensory perception of consumer groups differing in age, gender and ethnicity (**chapters 4-6**).

8.2.1. Effect of aging

Chapters 4-6 show that, among healthy older adults, the ability to produce a bolus, that is broken down enough and sufficiently lubricated so that it can be swallowed safely, is still achieved. This was observed in old healthy adults (70±5 years) with good dental status. The findings of this thesis showed that the underlying mechanism that explains the differences in bolus properties between young healthy adults (21±2 years) and older healthy adults was the prolongation of consumption time by the healthy older adults while keeping a fixed bite size (Figure 8.2).

This age-related prolongation of consumption time might be an adaptative mechanism to compensate age-related physiological changes, such as less efficient digestion, and to avoid choking ¹⁷⁸. However, it is important to note that ageing is often accompanied by deterioration in dental status, reduction of oral muscle mass and force and decreased salivary flow ^{179,180,231}. These factors are likely to induce changes in oral behavior; consequently, with deterioration in health status, the achievement of a safe to swallow

bolus may be compromised. Mishellany-Dutour showed that among elderly, denture wearers needed more chewing time than fully dentate but produced bolus with more and larger particles³³. This may indicate that declined oral health impede the accomplishment of a safe to swallow bolus. Nevertheless, in **chapter 4**, we showed that, within a relatively healthy population of older adults with full denture, mild mastication or swallowing problems do not yield significant differences in oral behavior of liquids, semi-solids or solid foods. Despite, changes in the bolus properties that deviate from those found among the bolus of healthy older population should be a sign of concern; this may indicate the starting point of impaired oral processing which could in turn produce further deterioration of the older individual health^{135,232,233}.

On the other hand, although healthy aging affected oral processing behavior and bolus properties, sensory perception seems to be affected to a limited extent since only few differences were observed between healthy young and older consumers in perceived intensity and attribute dominance rate (**chapters 5-6**) of yogurts with peach particles and sausage. We observed that taste intensity perception decreased with age whereas differences in texture perception were more attribute specific (lubrication and particle size related) rather than consistent decrements across all studied texture attributes. This seems to be contradictory to other studies that report losses of acuity in sensory perception as age progresses^{234,235}. However, not all sensory modalities are impacted to the same degree²³⁶. Smell and taste perception sharply decrease with age^{237,238} whereas tactile sensitivity also deteriorates but it may be at slower rate^{239,240}. A possible explanation for the limited differences between age groups is that the participants selected in this thesis studies were generally healthy and with full denture. Nevertheless, it is worth mentioning that elderly consumers are a very heterogeneous group since they are known to vary significantly in health status and sensory acuity^{143,241}. Consequently, the small variations observed in perception may be enhanced later in life, in the presence of denture loss, medication or disease^{242,243}.

Similar to texture perception, in **chapter 6**, liking followed comparable trends between age groups with small differences in the factors that contributed to determine liking of yogurts with particles. In contrast to young consumers, elderly found the hardness of the peach

particle important to determine liking. A possible explanation is that elderly prefer soft particles in order to reduce muscle effort during mastication²⁴⁴. Another explanation is that their preference for softer particles served as a compensatory mechanism to a decreased taste intensity perception since taste-texture interactions shows that taste intensity increases with decreasing food fracture stress²⁴⁵.

8.2.2. Effect of ethnicity

Understanding how Westerns and Asians differ in terms of oral processing behavior, and how this impact sensory perception could be a competitive advantage for European food companies that aim to grow in Asian markets. To date, very little is known about the effect of ethnicity on oral processing behavior. This thesis, in **chapters 4-5**, is one of the first to show differences in oral behavior between Dutch-Caucasian and Chinese-Asian and that these differences are consistent between food categories. Overall, Chinese-Asian consumed foods with longer consumption time and smaller bite size than Dutch-Caucasian. The variations in oral behavior between these two ethnicities may partly be explained by physiological differences and cultural factors.

There have been studies that reported physiological differences between Dutch-Caucasian and Chinese-Asian consumers, mainly in oral volume, salivary flow, protein concentration in saliva, mastication performance and facial anthropometry^{40,182,187,246}. However, a recent study showed that differences in oral physiology between Dutch-Caucasian and Chinese-Asian explained differences in oral behavior only to a very limited extent¹⁸². Therefore, it is not possible to fully explain the differences in oral processing behavior found in **chapters 4-5** based only on differences in oral physiology between different ethnic groups. Cultural habits may also contribute to the observed differences in oral behavior. For instance, the observed differences in consumption time between females belonging to different ethnicities may be associated to learnt customs of certain traditional cultures that encourage slowing eating pace in order to enhance femininity^{37,185,247,248}. On top of that, a recent study showed that Chinese consumers enjoy eating soft foods that can be manipulated between tongue and palate and held in the mouth for a long period compared to Danish consumers that enjoy to use their teeth to rapidly breakdown foods²⁴⁹. The latter

behavior may be similar in Dutch consumers. Thus, physiological variations combined with cultural differences might contribute to adaptation of oral processing behavior.

The previous mentioned differences in consumption time mediated bolus properties of consumers varying in ethnicity (Figure 8.2), giving as a result significantly different bolus properties between them at the swallowing point (**chapter 5**). Overall, Chinese-Asian produced more broken down boli than Dutch consumers. Despite this, there were no differences in dynamic texture perception at the beginning or final stages of mastication, but only during the middle stages of consumption time, where Dutch-Caucasian consumers perceived the test product (sausage) as fatty whereas Chinese-Asian perceived it as dry. Although this stage represents only a third of the consumption time, it may have an impact on the direction that oral behavior may take and the final bolus that it is being produced, e.g. consumers perceiving the product as dry will continue chewing it, prolonging consumption time to increase lubrication through saliva addition and possibly having a more degraded bolus (Figure 1.1). Moreover, the differences in fatty/dry sensations may relate to saliva differences as Chinese-Asian have lower salivary flow and higher protein concentration in saliva than Dutch-Caucasian ^{187,246}, the latter have showed negative correlations with slippery lip-tooth feel and fatty mouth feeling ²⁵⁰. Furthermore, cultural expectations related to the food may direct the attention of both consumers groups towards different attributes where for consumers that are used to high fat sausages, as the Chinese-Asian, may perceive a product as being dry whereas consumers that are used to lower fat contents in sausages may perceive it as fatty ¹⁸⁸.

As far as we know, these are some of the first studies investigating the differences between ethnicities on oral processing, bolus properties and texture perception. Therefore, in order to corroborate and broaden the understanding on the effect of ethnicity in oral behavior, bolus properties and sensory perception, further studies should investigate more ethnicities, include larger sample sizes and also investigate foods with distinct texture characteristics than the ones observed in sausages.

8.2.3. Effect of gender

Chapters 4-5 demonstrated that gender influenced some parameters of oral processing behavior. **Chapter 4** showed that males exhibited larger bite sizes, lower number of chews and higher eating rates than females. Similar results have been reported in previous studies for solid foods ^{37,38,152,153}. New insights were gathered in **chapter 4** for lesser explored foods, i.e. semi-solid and liquids foods, for which only bite size was influenced by gender. Together, bite size and consumption time, contribute to modulate eating rate. **Chapter 4** confirmed previous studies that eating rate is higher for males than females ³⁸. Although eating rate showed similar trends for liquid and semi-solid foods, males and females exhibited significant differences in eating rate only in solid foods. The observed variation in oral behavior between genders could be explained by physiological, metabolic and social differences. Physiologically, males have higher muscle strength in lips and cheeks as well as a more powerful bite force and higher salivary flow than females ^{25,29,34}, these factors can contribute to facilitate bolus formation and consequently increase eating rate. Furthermore, males have higher basal metabolic rate than females which have been associated with higher eating rate ¹⁵⁹. Lastly, gender stereotypes regarding mealtime etiquette, where females are taught to take smaller bites and chew thoroughly, may also contribute to the variations in oral behavior ^{37,185,247,248}.

In **chapter 5**, the effect of gender on oral processing is explored further and bolus properties are quantified. Interestingly, in this study, it was not found a direct effect of gender on oral processing or bolus properties; the effects of gender were significant only when it interacted with other consumer factors like age and ethnicity (Figure 8.2). The results showed that when the bite size was fixed, Chinese males have a shorter consumption time compared to Chinese females. As stated before, differences in oral behavior between genders may be more pronounced in some cultures than in others, thus gender differences observed in one ethnicity may not occur in another. Bolus properties, on the other hand, were also affected only when gender interacted with age, where elderly females produced more adhesive and less cohesive boli than elderly males. Dynamic texture perception did not differ considerably between these groups, a result that is in line with previous studies that report no influence of gender on tactile acuity ^{251,252}.

Figure 8.2. Integration of the effects of age, gender and ethnicity on oral behavior, bolus properties and sensory perception.

8.3. Influence of product properties on oral processing behavior, bolus properties and sensory perception

Apart from consumer characteristics, another element that influences oral processing behavior and that is important to consider are food properties. There are well known differences in oral behavior between liquid, semi-solid and solid foods ^{7,110}. Within each food category the rheological properties of foods cause large differences in oral behavior. Several studies investigating solid model foods have shown that changes in rheological properties affect oral behavior ^{45,223}. However, model foods may not fully reflect the variety of oral behaviors displayed during consumption of real foods from all different categories that are part of our diet. Yet apart from solid foods, limited knowledge on the effect of food

rheology on oral behavior is available for commercially available semi-solids and liquid foods; and even less information is available about the behavior of heterogeneous foods (i.e. two different food components combined). The combined results from **chapters 2, 3, 6 and 7** present new knowledge in these aspects and the integration of the effects of food properties on oral processing, bolus properties and sensory perception can be seen in Figure 8.3.

First, homogeneous foods were explored in **chapters 2 and 3**. The results confirmed that there are large differences in oral behavior within each food category. Even when the oral behavior of liquids is mainly transportation of the bolus to the back of the oral cavity and the pharynx, changes in the consistency of the liquids can have a significant effect on oral behavior parameters such as bite (sip) size, consumption time and eating rate. Among solid foods, a similar effect was seen when changes in hardness in the food product affected consumption time. Conversely, chewing rate or cycle duration remained relatively stable independently of the products characteristics.

Overall, in **chapter 3**, we found that physical properties such as consistency (K which corresponds to viscosity at shear rate of $1s^{-1}$) for liquid and semi-solid foods, and the stress needed to compress to 15% strain and Young's modulus for solids have a positive relationship with consumption time and a negative relationship with bite size. These findings helped to obtain logarithmic equations (see Figure 8.3) that estimate the eating rate of a specific food based on the values for consistency or Young's modulus according to the type of product. Together, these variables influence eating rate, a behavioral parameter that gained relevance in recent years as an adjustable risk parameter for obesity and association with food and energy intake^{93,253}. Besides, it was shown that when consumers are presented with a large food portion, they adapt their bite size, consumption time and eating rate to the rheological properties of the food (**chapter 3**). Thus collectively, these studies highlight the fact that oral behavior can be steered by modifications of rheological and mechanical food properties. It is, however, still debatable whether the mechanical properties previously mentioned are the best ones to predict oral behavior. It is important to mention that Young's modulus represents a mechanical property determined under small deformation which can be considered relatively small compared to the deformations

occurring during oral processing. Besides, during mastication solid foods are fractured repetitively, something that neither the measurement of stress needed to compress to 15% strain nor the Young's modulus can represent. Further measurements could help to refine these equations to increase their accuracy. Nevertheless, it should be pointed out that in the case of solid foods, not all food products may follow the same trends as was the case of meat, probably due to its anisotropic structure. Therefore, future studies should explore how other physical properties such as adhesiveness affect oral behavior.

In addition to changes in oral behavior, **chapter 2** showed that variations in ice cream hardness can also influence sensory perception. Hardness of ice cream defined the perception of mainly texture attributes as dominant during the consumption time. Fruitiness was the only aroma attribute that was dominant in soft ice creams and only at the end of consumption time in hard ice creams. This suggests again that aroma compounds are only perceived after being released from the food matrix and that food hardness limits aroma release ⁶.

Despite the effects seen among homogeneous foods, it is known that foods consumed in daily life are often heterogeneous, i.e. combination of two food components that differ considerably in texture or mechanical properties. Nevertheless, there is still little information about how heterogeneous foods are orally processed and how the bolus transformation of heterogeneous foods affects sensory perception. The contrast in texture found in heterogeneous foods has been suggested to increase food palatability ²²¹. Therefore, **chapters 6 and 7** contribute to understanding of oral processing of heterogeneous foods.

Figure 8.3. Integration of the effects of food product properties on oral processing, bolus properties and sensory perception.

Both **chapters 6 and 7**, demonstrated that oral processing behavior can be steered by modification in either food matrix or the embedded particle. The results showed that the mere addition of particles to food matrices can slow down eating rate. Moreover, not only the mere addition of particles but also the physical properties of the embedded particle influence oral behavior. However, the degree that oral behavior will be affected depends also on the characteristics of the matrix. Changes in eating rate were more pronounced when particles were added to yogurt than when added to soft cheese. This may be due to the fact that heterogeneity is more easily perceived in liquid foods than in semi-solids ²⁵⁴. These results suggest that the bigger the perception of texture contrast between the matrix and the added particles is, the greater the impact on oral processing behavior.

In addition, **chapter 7** showed that inclusion of particles into a matrix also influenced bolus properties at the swallowing point. It was observed that between the heterogenous cheeses, the particles had a strong influence on the bolus formation probably because it

requires a higher degree of structural breakdown and because the presence of particles may increase the perception of eating difficulty as suggested by Laguna and Sarkar ²⁵⁵. Moreover, the incorporation of particles into the cheese had a negative impact on the dominance perception and duration of the cheese related attributes, smoothness and meltiness, whereas the dominance rate and duration of attributes related to the particles' graininess increased. Thus, it seems that sensory perception is dominated by the hardest component in the heterogeneous food. Comparable tendencies were observed when combining granola with yogurt, bread with mayonnaise and carrots with mayonnaise, where the perception of the solid component overruled the sensations related to the softest component ^{256,257}. Thus, when designing heterogeneous foods, special attention should be given to the hardest component since it will likely dominate perception of the product and might overrule the influence of the softest component on perception.

8.4. Temporal order of sensory attributes during oral processing

Once in the mouth, the physical properties of the food continuously change, and at each stage of oral processing, those structural changes might give rise to changes in sensory perception. Consequently, sensory perception shows dynamic changes throughout mastication ^{21,66}. **Chapter 2** showed that in a homogeneous food such as ice cream, textural attributes (coldness and firmness and smoothness) were perceived as dominant sensations in the early stages of oral processing whereas taste and aroma attributes (sweetness and fruitiness) dominated more towards the swallowing point. **Chapter 5** showed also a chronological order between textural attributes in sausages, where firmness was the sensation that dominated the perception during the early stages of mastication. In the middle stage of mastication, the dominant attributes were related to (lack of) lubrication (fattiness, dryness, juiciness). Finally, towards the swallowing point, graininess dominated the perception. These results support the idea that bulk texture attributes can be assessed as soon as the food is in contact with oral surfaces and/or subjected to stress; whereas other texture, aroma and taste attributes require more oral processing time, addition of saliva and complex moments before they become dominant ^{21,61,181}. Nevertheless, in heterogeneous foods, the chronological order of attributes may not be as evident as in

homogeneous foods. For instance, in **chapter 7**, the perception of heterogeneous cheeses showed an unexpected low attribute dynamicity since several attributes remain dominant for long periods. Firmness and meltiness were the exception, both attributes showed a clear chronology where firmness was always perceived at the beginning of mastication and then cease; whereas, meltiness sensation became dominant from the middle stage of mastication and towards the swallowing point. In summary, these results prove that the chronological order of attribute perception may be dependent of the food properties. Furthermore, within the chronological appearance of attributes, variations in oral behavior may impact the selection or duration of sensory attributes at any stage of oral processing as shown in **chapter 2 and 5**.

8.5. Practical implications

This thesis demonstrated that food oral processing can be regulated through modifications of food structure. One behavioral parameter of special interest is eating rate as it impacts energy intake ^{43,139,253}. Contributors to modulate food intake are relevant since obesity in the general population and undernutrition in the growing elderly population are big public health challenges. Creating textural differences through controlling food hardness and consistency (Figure 8.3) can help to either slow down or increase eating rate according to the need of the target population. Providing foods with texture contrast by adding particles can also be used to change oral behavior in order to slow down eating rate and consequently impact food intake within a meal. Upon addition of particles that do not increase food energy density (e.g. made from food components such as fiber) and that have a higher fracture stress than the food matrix, it is possible to reduce eating rate.

On the other hand, addition of particles with high energy density can be used as a strategy to combat undernutrition among vulnerable populations such as elderly consumers. This consumer group shows low eating rates which can contribute to lower food intake and might in turn negatively affect their nutrient intake. Besides, elderly often report missing texture diversity which can impact enjoyment of food ²⁵⁸. Pleasantness of food is an important determinant of food choice and food intake ²¹⁶. Thus, the addition of high energy dense particles that initially provide texture contrast, but that are relatively soft, and that

upon oral processing melt in the mouth providing extra lubrication, can contribute to increase liking of foods in elderly consumers. This strategy could be especially useful in soft solids since the addition of particles seems to affect eating rate to a lower extent than in fluid foods. In Chinese consumers, a similar strategy could be used to increase pleasantness of foods by creating products that can be held in the mouth for longer times but that at the same time may be manipulated with tongue and palate.

Additionally, consideration of bolus properties variation between consumers segments can be useful for new product development. Consumer groups that need to form a more broken-down bolus before swallowing is initiated, such as elderly and people from specific background like Chinese-Asian consumers, can be product-specific targeted. Through this, food products (texture and nutrient content) can be tailored according to the consumers oral behavior and typical bolus formation. Therefore, new product development of foods that are not only rich in nutrients but also that reduce their chewing effort and follow a breakdown path that generates rapidly a soft and moist bolus that leaves low residue after swallowing can boost eating rate.

Along with the previous recommendations, it is suggested that when designing sensory evaluations, the scientist should reflect upon the oral behavior protocol used during sensory evaluations, for example whether it is natural or an imposed oral behavior protocol. Because when participants apply different oral behaviors in the same food product, dynamic sensory perception might be considerably affected.

8.6. Outlook of future research

Likewise, the knowledge generated in this thesis provides some practical recommendations for further research. When aiming to cluster consumer groups, we warn that simple classifications of consumers into mouth behavior groups (crunchers, suckers, smooshers etc.) can be erroneous. Consumers typically display combinations of different oral processing behaviors, not only across foods but also within one food. We suggest that a more objective classification can be based on measured oral processing parameters such as consumption time or eating rate and they might be more useful to cluster consumers and to compare results across studies. For this, video recordings of people during food

consumption is an inexpensive and precise method that can effectively help in the characterization oral behavior. The main parameters that can be obtained are number of bites, consumption time, number of chews and number of swallows, as well as derived measurements such as eating rate (g/min), chewing rate (chews/min) and bite size (initial food amount/number of bites). However, in order to make advances in this area, additional studies should dedicate time to develop a common methodology, based on open access software such as Kinovea, that uses standard protocol, coding scheme and software. This could benefit the field by allowing a better comparison across studies.

Finally, the studies presented in this thesis showed that consumption time is one of the main oral behavior characteristics reflecting differences in oral processing. We demonstrated that consumption time determines to a large extent bolus properties. It has been demonstrated that fast eaters swallow bolus that contain fewer and larger particles than slow eaters ⁷⁵. These physical differences in bolus properties may lead to variations in digestive properties and disintegration rates of macronutrients, absorption and feelings of satiation ²⁵⁹. Therefore, oral behavior is an important factor in understanding food digestibility ²⁶⁰. Up to date a large body of literature studied the effect of food structure and mechanical properties on oral processing behavior and digestion of carbohydrates ^{261–266}. These studies demonstrated that in vitro digestion of starch depends on the breakdown of foods during oral processing. Furthermore, these studies show mounting evidence that variations in oral behavior lead to differences in digestion rates of carbohydrates which cause differences in postprandial metabolic responses. In comparison to carbohydrates, little is known about the impact of oral processing behavior on digestion of other macronutrients such proteins and lipids. Thus, in order to get a better understanding on the impact that oral processing has on digestion and nutrient uptake, further research should investigate the impact of oral behavior and bolus properties on protein and lipid digestion.

8.7. Conclusion

The series of studies presented in this thesis aimed to investigate the effect of food and consumer characteristics on oral processing behavior, bolus properties and dynamic sensory perception. Food properties and consumer characteristics contribute to the

variability observed in food oral processing behavior between consumer groups differing in age gender and ethnicity. Variations in oral processing behavior affect bolus properties and in consequence dynamic sensory perception. Therefore, through modification of the food structure, oral behavior might be tuned guiding the breakdown path and perception. Tailoring food products targeted towards specific consumers should consider the differences observed between consumer segments in the bolus properties at the swallowing point in order to facilitate oral processing of vulnerable consumer groups.

R

References

1. Chen, J. Food oral processing—A review. *Food Hydrocoll.* **23**, 1–25 (2009).
2. Foegeding, E. A., Vinyard, C. J., Essick, G., Guest, S. & Campbell, C. Transforming Structural Breakdown into Sensory Perception of Texture. *J. Texture Stud.* **46**, 152–170 (2015).
3. Hutchings, J. B. & Lillford, P. J. The Perception of Food Texture - the Philosophy of the Breakdown Path. *J. Texture Stud.* **19**, 103–115 (1988).
4. Foster, K. D. *et al.* The Role of Oral Processing in Dynamic Sensory Perception. *J. Food Sci.* **76**, R49–R61 (2011).
5. Koç, Vinyard, C. J., Essick, G. K. & Foegeding, E. A. Food Oral Processing: Conversion of Food Structure to Textural Perception. *Annu. Rev. Food Sci. Technol.* **4**, 237–266 (2013).
6. Stieger, M. & van de Velde, F. Microstructure, texture and oral processing: New ways to reduce sugar and salt in foods. *Curr. Opin. Colloid Interface Sci.* **18**, 334–348 (2013).
7. Hiiemae, K. Mechanisms of Food Reduction, Transport and Deglutition: How the Texture of Food Affects Feeding Behavior. *J. Texture Stud.* **35**, 171–200 (2004).
8. Appelqvist, I. A. M. 9 - In-mouth measurement of food quality. in *Instrumental Assessment of Food Sensory Quality* (ed. Kilcast, D.) 255–283 (Woodhead Publishing, 2013).
9. Jalabert-Malbos, M.-L., Mishellany-Dutour, A., Woda, A. & Peyron, M.-A. Particle size distribution in the food bolus after mastication of natural foods. *Food Qual. Prefer.* **18**, 803–812 (2007).
10. Loret, C. *et al.* Physical and related sensory properties of a swallowable bolus. *Physiol. Behav.* **104**, 855–864 (2011).
11. Peyron, M.-A., Mishellany, A. & Woda, A. Particle Size Distribution of Food Boluses after Mastication of Six Natural Foods. *J. Dent. Res.* **83**, 578–582 (2004).
12. Devezeaux de Lavergne, M., van de Velde, F., van Boekel, M. A. J. S. & Stieger, M. 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 Hydrocoll.* **49**, 61–72 (2015).
13. Jourden, S. *et al.* Breakdown pathways during oral processing of different breads: impact of crumb and crust structures. *Food Funct* **7**, 1446–1457 (2016).

14. Lavergne, M. D. de, Srijbosch, V. M. G., Broek, A. W. M. V. den, Velde, F. V. de & Stieger, M. Uncoupling the Impact of Fracture Properties and Composition on Sensory Perception of Emulsion-Filled Gels. *J. Texture Stud.* **47**, 92–111 (2016).
15. Lenfant, F. *et al.* Impact of the shape on sensory properties of individual dark chocolate pieces. *LWT - Food Sci. Technol.* **51**, 545–552 (2013).
16. Pascua, Y., Koç, H. & Foegeding, E. A. Food structure: Roles of mechanical properties and oral processing in determining sensory texture of soft materials. *Curr. Opin. Colloid Interface Sci.* **18**, 324–333 (2013).
17. Rizo, A. *et al.* Impact of texture TDS and flavour TDS tasks and of chocolate-chip biscuit characteristics on oral processing features. *Food Qual. Prefer.* **76**, 109–117 (2019).
18. Neyraud, E., Peyron, M. A., Vieira, C. & Dransfield, E. Influence of Bitter Taste on Mastication Pattern. *J. Dent. Res.* **84**, 250–254 (2005).
19. Rosenthal, A. J. & Share, C. Temporal Dominance of Sensations of peanuts and peanut products in relation to Hutchings and Lillford's "breakdown path". *Food Qual. Prefer.* **32, Part C**, 311–316 (2014).
20. Brown, W. E. & Braxton, D. Dynamics of food breakdown during eating in relation to perceptions of texture and preference: a study on biscuits1. *Food Qual. Prefer.* **11**, 259–267 (2000).
21. Rosenthal, A. Relation between instrumental and sensory measures of food texture. **29** (1999).
22. Tournier, C. *et al.* Investigation of oral gels breakdown using image analysis. *Food Hydrocoll.* **63**, 67–76 (2017).
23. Devezeaux de Lavergne, M., Velde, F. van de & Stieger, M. Bolus matters: the influence of food oral breakdown on dynamic texture perception. *Food Funct.* **8**, 464–480 (2017).
24. Alsanei, W. A. & Chen, J. Studies of the Oral Capabilities in Relation to Bolus Manipulations and the Ease of Initiating Bolus Flow. *J. Texture Stud.* **45**, 1–12 (2014).
25. Bakke, M., Holm, B., Jensen, B. L., Michler, L. & Möller, E. Unilateral, isometric bite force in 8-68-year-old women and men related to occlusal factors. *Scand. J. Dent. Res.* **98**, 149–158 (1990).
26. Hatch, J. P., Shinkai, R. S. A., Sakai, S., Rugh, J. D. & Paunovich, E. D. Determinants of masticatory performance in dentate adults. *Arch. Oral Biol.* **46**, 641–648 (2001).

27. Kohyama, K., Mioche, L. & Martin, J.-F. Chewing Patterns of Various Texture Foods Studied by Electromyography in Young and Elderly Populations. *J. Texture Stud.* **33**, 269–283 (2002).
28. Koshino, H., Hirai, T., Ishijima, T. & Ikeda, Y. Tongue motor skills and masticatory performance in adult dentates, elderly dentates, and complete denture wearers. *J. Prosthet. Dent.* **77**, 147–152 (1997).
29. Palinkas, M. *et al.* Age and gender influence on maximal bite force and masticatory muscles thickness. *Arch. Oral Biol.* **55**, 797–802 (2010).
30. Mioche, L. Mastication and Food Texture Perception: Variation with Age. *J. Texture Stud.* **35**, 145–158 (2004).
31. Peyron, M.-A., Blanc, O., Lund, J. P. & Woda, A. Influence of Age on Adaptability of Human Mastication. *J. Neurophysiol.* **92**, 773–779 (2004).
32. Mioche, L., Bourdiol, P., Monier, S., Martin, J.-F. & Cormier, D. Changes in jaw muscles activity with age: effects on food bolus properties. *Physiol. Behav.* **82**, 621–627 (2004).
33. Mishellany-Dutour, A., Renaud, J., Peyron, M.-A., Rimek, F. & Woda, A. Is the goal of mastication reached in young dentates, aged dentates and aged denture wearers? *Br. J. Nutr.* **99**, 121–128 (2008).
34. Clark, H. M. & Solomon, N. P. Age and Sex Differences in Orofacial Strength. *Dysphagia* **27**, 2–9 (2012).
35. Julien, K. C., Buschang, P. H., Throckmorton, G. S. & Dechow, P. C. Normal masticatory performance in young adults and children. *Arch. Oral Biol.* **41**, 69–75 (1996).
36. Kim, S. & Vickers, Z. Liking of food textures and its relationship with oral physiological parameters and mouth-behavior groups. *J. Texture Stud.* **51**, 412–425 (2020).
37. Hill, S. W. & McCutcheon, N. B. Contributions of obesity, gender, hunger, food preference, and body size to bite size, bite speed, and rate of eating. *Appetite* **5**, 73–83 (1984).
38. Park, S. & Shin, W.-S. Differences in eating behaviors and masticatory performances by gender and obesity status. *Physiol. Behav.* **138**, 69–74 (2015).
39. Mioche, L., Bourdiol, P. & Monier, S. Chewing behaviour and bolus formation during mastication of meat with different textures. *Arch. Oral Biol.* **48**, 193–200 (2003).

40. Zhuang, Z., Landsittel, D., Benson, S., Roberge, R. & Shaffer, R. Facial anthropometric differences among gender, ethnicity, and age groups. *Ann. Occup. Hyg.* **54**, 391–402 (2010).
41. Xue, S. A. & Hao, J. G. Normative standards for vocal tract dimensions by race as measured by acoustic pharyngometry. *J. Voice Off. J. Voice Found.* **20**, 391–400 (2006).
42. Bourne, M. C. Chapter 2 - Body-Texture Interactions. in *Food Texture and Viscosity (Second Edition)* 33–57 (Academic Press, 2002).
43. Campbell, C. L., Wagoner, T. B. & Foegeding, E. A. Designing foods for satiety: The roles of food structure and oral processing in satiation and satiety. *Food Struct.* **13**, 1–12 (2017).
44. Barrangou, L. M., Drake, M. A., Daubert, C. R. & Foegeding, E. A. Sensory Texture Related to Large-Strain Rheological Properties of Agar/Glycerol Gels as a Model Food. *J. Texture Stud.* **37**, 241–262 (2006).
45. Çakir, E. *et al.* Evaluation of Texture Changes Due to Compositional Differences Using Oral Processing. *J. Texture Stud.* **43**, 257–267 (2012).
46. Foster, K. D., Woda, A. & Peyron, M. A. Effect of Texture of Plastic and Elastic Model Foods on the Parameters of Mastication. *J. Neurophysiol.* **95**, 3469–3479 (2006).
47. Koç *et al.* Adaptation of Oral Processing to the Fracture Properties of Soft Solids. *J. Texture Stud.* **45**, 47–61 (2014).
48. Kohyama, K., Ohtsubo, K., Toyoshima, H. & Shiozawa, K. Electromyographic Study on Cooked Rice with Different Amylose Contents. *J. Texture Stud.* **29**, 101–113 (1998).
49. Peyron, M., Lassauzay, C. & Woda, A. Effects of increased hardness on jaw movement and muscle activity during chewing of visco-elastic model foods. *Exp. Brain Res.* **142**, 41–51 (2002).
50. Engelen, L., Fontijn-Tekamp, A. & Bilt, A. van der. The influence of product and oral characteristics on swallowing. *Arch. Oral Biol.* **50**, 739–746 (2005).
51. Forde, C. G., van Kuijk, N., Thaler, T., de Graaf, C. & Martin, N. Oral processing characteristics of solid savoury meal components, and relationship with food composition, sensory attributes and expected satiation. *Appetite* **60**, 208–219 (2013).
52. Forde, C. G., Leong, C., Chia-Ming, E. & McCrickerd, K. Fast or slow-foods? Describing natural variations in oral processing characteristics across a wide range of Asian foods. *Food Funct.* (2016) doi:10.1039/c6fo01286h.

53. Viskaal-van Dongen, M., Kok, F. J. & de Graaf, C. Eating rate of commonly consumed foods promotes food and energy intake. *Appetite* **56**, 25–31 (2011).
54. Chen, J. & Lolivret, L. The determining role of bolus rheology in triggering a swallowing. *Food Hydrocoll.* **25**, 325–332 (2011).
55. Hutchings, S. C. *et al.* Mastication of heterogeneous foods: Peanuts inside two different food matrices. *Food Qual. Prefer.* **22**, 332–339 (2011).
56. Chen, J., Khandelwal, N., Liu, Z. & Funami, T. Influences of food hardness on the particle size distribution of food boluses. *Arch. Oral Biol.* **58**, 293–298 (2013).
57. Drago, S. R. *et al.* Relationships between saliva and food bolus properties from model dairy products. *Food Hydrocoll.* **25**, 659–667 (2011).
58. Mioche, L., Bourdiol, P., Monier, S. & Martin, J.-F. The relationship between chewing activity and food bolus properties obtained from different meat textures. *Food Qual. Prefer.* **13**, 583–588 (2002).
59. Saint-Eve, A., Panouillé, M., Capitaine, C., Délérès, I. & Souchon, I. Dynamic aspects of texture perception during cheese consumption and relationship with bolus properties. *Food Hydrocoll.* **46**, 144–152 (2015).
60. Peyron, M.-A. *et al.* Role of physical bolus properties as sensory inputs in the trigger of swallowing. *PloS One* **6**, e21167 (2011).
61. de Wijk, R. A., Engelen, L. & Prinz, J. F. The role of intra-oral manipulation in the perception of sensory attributes. *Appetite* **40**, 1–7 (2003).
62. Engelen, L. & de Wijk, R. A. Oral Processing and Texture Perception. in *Food Oral Processing* (eds. Chen, J. & Engelen, L.) 157–176 (Wiley-Blackwell, 2012).
63. Schwartz, C., Vandenberghe-Descamps, M., Sulmont-Rossé, C., Tournier, C. & Feron, G. Behavioral and physiological determinants of food choice and consumption at sensitive periods of the life span, a focus on infants and elderly. *Innov. Food Sci. Emerg. Technol.* **46**, 91–106 (2018).
64. Engelen, L. Chapter 16 - Oral Processing: Implications for Consumer Choice and Preferences. in *Methods in Consumer Research, Volume 1* (eds. Ares, G. & Varela, P.) 401–421 (Woodhead Publishing, 2018). doi:10.1016/B978-0-08-102089-0.00016-9.
65. Laguna, L. & Chen, J. The eating capability: Constituents and assessments. *Food Qual. Prefer.* **48, Part B**, 345–358 (2016).
66. de Wijk, R. A., Janssen, A. M. & Prinz, J. F. Oral movements and the perception of semi-solid foods. *Physiol. Behav.* **104**, 423–428 (2011).

67. Gonzalez Espinosa, Y. & Chen, J. Applications of Electromyography (EMG) Technique for Eating Studies. in *Food Oral Processing* (eds. Chen, J. & Engelen, L.) 289–317 (Wiley-Blackwell, 2012).
68. Ketel, E. C. *et al.* Age, gender, ethnicity and eating capability influence oral processing behaviour of liquid, semi-solid and solid foods differently. *Food Res. Int.* **119**, 143–151 (2019).
69. Aguayo-Mendoza, M. G. *et al.* Oral processing behavior of drinkable, spoonable and chewable foods is primarily determined by rheological and mechanical food properties. *Food Qual. Prefer.* **71**, 87–95 (2019).
70. Laguna, L., Barrowclough, R. A., Chen, J. & Sarkar, A. New approach to food difficulty perception: Food structure, food oral processing and individual's physical strength. *J. Texture Stud.* n/a-n/a (2016) doi:10.1111/jtxs.12190.
71. Jeltema, M., Beckley, J. H. & Vahalik, J. Importance of understanding mouth behavior when optimizing product texture now and in the future. in *Food Texture Design and Optimization* (eds. Dar, Y. L. & Light, J. M.) 423–442 (John Wiley & Sons, Ltd, 2014).
72. Jeltema, M., Beckley, J. & Vahalik, J. Food texture assessment and preference based on Mouth Behavior. *Food Qual. Prefer.* **52**, 160–171 (2016).
73. Engelen, L. & van Doorn, J. *Eating custard*. (2000).
74. Carvalho-da-Silva, A. M., Van Damme, I., Wolf, B. & Hort, J. Characterisation of chocolate eating behaviour. *Physiol. Behav.* **104**, 929–933 (2011).
75. Devezeaux de Lavergne, M., Derks, J. A. M., Ketel, E. C., de Wijk, R. A. & Stieger, M. Eating behaviour explains differences between individuals in dynamic texture perception of sausages. *Food Qual. Prefer.* **41**, 189–200 (2015).
76. Bartoshuk, L. M., Rennert, K., Rodin, J. & Stevens, J. C. Effects of temperature on the perceived sweetness of sucrose. *Physiol. Behav.* **28**, 905–910 (1982).
77. Calviño, A. M. Perception of sweetness: The effects of concentration and temperature. *Physiol. Behav.* **36**, 1021–1028 (1986).
78. Cruz, A. & Green, B. G. Thermal stimulation of taste. *Nature* **403**, 889–892 (2000).
79. Green, B. G. & Frankmann, S. P. The effect of cooling on the perception of carbohydrate and intensive sweeteners. *Physiol. Behav.* **43**, 515–519 (1988).
80. Green, B. G. & Nachtigal, D. Temperature Affects Human Sweet Taste via At Least Two Mechanisms. *Chem. Senses* **40**, 391–399 (2015).

81. Mony, P. *et al.* Temperature of served water can modulate sensory perception and acceptance of food. *Food Qual. Prefer.* **28**, 449–455 (2013).
82. Roberts, D. D. & Acree, T. E. Simulation of retronasal aroma using a modified headspace technique: investigating the effects of saliva, temperature, shearing, and oil on flavor release. *J. Agric. Food Chem.* **43**, 2179–2186 (1995).
83. Aime, D. B., Arntfield, S. D., Malcolmson, L. J. & Ryland, D. Textural analysis of fat reduced vanilla ice cream products. *Food Res. Int.* **34**, 237–246 (2001).
84. Guinard, J.-X. *et al.* Sugar and fat effects on sensory properties of ice cream. *J. Food Sci.* **62**, 1087–1094 (1997).
85. King, B. M. Sensory Profiling of Vanilla Ice Cream: Flavour and Base Interactions. *LWT - Food Sci. Technol.* **27**, 450–456 (1994).
86. Varela, P., Pintor, A. & Fiszman, S. How hydrocolloids affect the temporal oral perception of ice cream. *Food Hydrocoll.* **36**, 220–228 (2014).
87. Warren, M. M. & Hartel, R. W. Structural, Compositional, and Sensorial Properties of United States Commercial Ice Cream Products. *J. Food Sci.* **79**, E2005–E2013 (2014).
88. Pineau, N. *et al.* Temporal Dominance of Sensations: Construction of the TDS curves and comparison with time–intensity. *Food Qual. Prefer.* **20**, 450–455 (2009).
89. Lenfant, F., Loret, C., Pineau, N., Hartmann, C. & Martin, N. Perception of oral food breakdown. The concept of sensory trajectory. *Appetite* **52**, 659–667 (2009).
90. Wilson, A., Luck, P., Woods, C., Foegeding, E. A. & Morgenstern, M. Comparison of jaw tracking by single video camera with 3D electromagnetic system. *J. Food Eng.* **190**, 22–33 (2016).
91. Cohen, D. A. & Farley, T. A. Eating as an Automatic Behavior. *Prev. Chronic. Dis.* (2008).
92. Pesch, M. H. & Lumeng, J. C. Methodological considerations for observational coding of eating and feeding behaviors in children and their families. *Int. J. Behav. Nutr. Phys. Act.* **14**, 170 (2017).
93. Fogel, A. *et al.* Faster eating rates are associated with higher energy intakes during an Ad libitum meal, higher BMI and greater adiposity among 4.5 year old children – Results from the GUSTO cohort. *Br. J. Nutr.* **117**, 1042–1051 (2017).
94. Albert, A., Salvador, A., Schlich, P. & Fiszman, S. Comparison between temporal dominance of sensations (TDS) and key-attribute sensory profiling for evaluating solid food with contrasting textural layers: Fish sticks. *Food Qual. Prefer.* **24**, 111–118 (2012).

95. Nguyen, Q. C., Næs, T. & Varela, P. When the choice of the temporal method does make a difference: TCATA, TDS and TDS by modality for characterizing semi-solid foods. *Food Qual. Prefer.* **66**, 95–106 (2018).
96. Kantono, K. *et al.* Listening to music can influence hedonic and sensory perceptions of gelati. (2015).
97. Repoux, M. *et al.* Combined effect of cheese characteristics and food oral processing on *in vivo* aroma release: *In vivo* aroma release during cheeses oral processing. *Flavour Fragr. J.* **27**, 414–423 (2012).
98. Chen, J. Food oral processing: Mechanisms and implications of food oral destruction. *Trends Food Sci. Technol.* **45**, 222–228 (2015).
99. Doyennette, M. *et al.* Main individual and product characteristics influencing in-mouth flavour release during eating masticated food products with different textures: Mechanistic modelling and experimental validation. *J. Theor. Biol.* **340**, 209–221 (2014).
100. Burdach, K. J. & Doty, R. L. The effects of mouth movements, swallowing, and spitting on retronasal odor perception. *Physiol. Behav.* **41**, 353–356 (1987).
101. Devezeaux de Lavergne, M., van Delft, M., van de Velde, F., van Boekel, M. A. J. S. & Stieger, M. Dynamic texture perception and oral processing of semi-solid food gels: Part 1: Comparison between QDA, progressive profiling and TDS. *Food Hydrocoll.* **43**, 207–217 (2015).
102. van der Bilt, A., Engelen, L., Pereira, L. J., van der Glas, H. W. & Abbink, J. H. Oral physiology and mastication. *Physiol. Behav.* **89**, 22–27 (2006).
103. de Wijk, R. A., Prinz, J. F. & Janssen, A. M. Explaining perceived oral texture of starch-based custard desserts from standard and novel instrumental tests. *Food Hydrocoll.* **20**, 24–34 (2006).
104. Baek, I., Linforth, R. S. T., Blake, A. & Taylor, A. J. Sensory Perception is Related to the Rate of Change of Volatile Concentration In-nose during Eating of Model Gels. *Chem. Senses* **24**, 155–160 (1999).
105. Mestres, M., Moran, N., Jordan, A. & Buettner, A. Aroma Release and Retronasal Perception during and after Consumption of Flavored Whey Protein Gels with Different Textures. 1. *In Vivo* Release Analysis. *J. Agric. Food Chem.* **53**, 403–409 (2005).
106. Weel, K. G. C. *et al.* Effect of Emulsion Properties on Release of Esters under Static Headspace, *in Vivo*, and Artificial Throat Conditions in Relation to Sensory Intensity. *J. Agric. Food Chem.* **52**, 6572–6577 (2004).

107. Foegeding, E. A. Rheology and sensory texture of biopolymer gels. *Curr. Opin. Colloid Interface Sci.* **12**, 242–250 (2007).
108. Chanasattru, W., Corradini, M. G. & Peleg, M. Determination of Practically Significant Differences in the Sensorily Perceived Consistency of Semiliquid Foods1. *J. Texture Stud.* **33**, 445–460 (2002).
109. Abhyankar, A. R., Mulvihill, D. M. & Auty, M. A. E. Combined microscopic and dynamic rheological methods for studying the structural breakdown properties of whey protein gels and emulsion filled gels. *Food Hydrocoll.* **25**, 275–282 (2011).
110. Chen, J. & Stokes, J. R. Rheology and tribology: Two distinctive regimes of food texture sensation. *Trends Food Sci. Technol.* **25**, 4–12 (2012).
111. van Aken, G. A., Vingerhoeds, M. H. & de Hoog, E. H. A. Food colloids under oral conditions. *Curr. Opin. Colloid Interface Sci.* **12**, 251–262 (2007).
112. van Vliet, T., van Aken, G. A., de Jongh, H. H. J. & Hamer, R. J. Colloidal aspects of texture perception. *Adv. Colloid Interface Sci.* **150**, 27–40 (2009).
113. Hiiemae, K. *et al.* Natural bites, food consistency and feeding behaviour in man. *Arch. Oral Biol.* **41**, 175–189 (1996).
114. Ferriday, D. *et al.* Variation in the Oral Processing of Everyday Meals Is Associated with Fullness and Meal Size; A Potential Nudge to Reduce Energy Intake? *Nutrients* **8**, 315 (2016).
115. van den Boer, J. H. W. *et al.* Self-reported eating rate is associated with weight status in a Dutch population: a validation study and a cross-sectional study. *Int. J. Behav. Nutr. Phys. Act.* **14**, 121 (2017).
116. de Wijk, R. A., Zijlstra, N., Mars, M., de Graaf, C. & Prinz, J. F. The effects of food viscosity on bite size, bite effort and food intake. *Physiol. Behav.* **95**, 527–532 (2008).
117. Steele, C. M. & Lieshout, P. H. H. M. V. Influence of Bolus Consistency on Lingual Behaviors in Sequential Swallowing. *Dysphagia* **19**, 192–206 (2004).
118. Campbell, C. L., Wagoner, T. B. & Foegeding, E. A. Designing foods for satiety: The roles of food structure and oral processing in satiation and satiety. *Food Struct.* doi:10.1016/j.foostr.2016.08.002.
119. Woda, A., Foster, K., Mishellany, A. & Peyron, M. A. Adaptation of healthy mastication to factors pertaining to the individual or to the food. *Physiol. Behav.* **89**, 28–35 (2006).
120. Bellisle, F. & Le Magnen, J. The analysis of human feeding patterns: the edogram. *Appetite* **1**, 141–150 (1980).

121. Wagner, Wolfgang & Kretzschmar, Hans-Joachim. *International Steam Tables: Properties of Water and Steam Based on the Industrial Formulation IAPWS-IF97*. (Springer Berlin Heidelberg, 2008).
122. Fontijn-Tekamp, F. A., van der Bilt, A., Abbink, J. H. & Bosman, F. Swallowing threshold and masticatory performance in dentate adults. *Physiol. Behav.* **83**, 431–436 (2004).
123. Sánchez-Ayala, A., Vilanova, L. S. R., Costa, M. A. & Farias-Neto, A. Reproducibility of a silicone-based test food to masticatory performance evaluation by different sieve methods. *Braz. Oral Res.* **28**, 1–8 (2014).
124. Belafsky, P. C. *et al.* Validity and Reliability of the Eating Assessment Tool (EAT-10). *Ann. Otol. Rhinol. Laryngol.* **117**, 919–924 (2008).
125. Bolhuis, D. P. *et al.* Slow Food: Sustained Impact of Harder Foods on the Reduction in Energy Intake over the Course of the Day. *PLOS ONE* **9**, e93370 (2014).
126. McCrickerd, K., Lim, C. M., Leong, C., Chia, E. M. & Forde, C. G. Texture-Based Differences in Eating Rate Reduce the Impact of Increased Energy Density and Large Portions on Meal Size in Adults—3. *J. Nutr.* **147**, 1208–1217 (2017).
127. Farooq, M. & Sazonov, E. Automatic Measurement of Chew Count and Chewing Rate during Food Intake. *Electronics* **5**, 62 (2016).
128. Bellisle, F., Guy-Grand, B. & Le Magnen, J. Chewing and swallowing as indices of the stimulation to eat during meals in humans: effects revealed by the edogram method and video recordings. *Neurosci. Biobehav. Rev.* **24**, 223–228 (2000).
129. Jean, A. Brain Stem Control of Swallowing: Neuronal Network and Cellular Mechanisms. *Physiol. Rev.* **81**, 929–969 (2001).
130. Agrawal, K. R., Lucas, P. W. & Bruce, I. C. The effects of food fragmentation index on mandibular closing angle in human mastication. *Arch. Oral Biol.* **45**, 577–584 (2000).
131. Okada, A., Honma, M., Nomura, S. & Yamada, Y. Oral behavior from food intake until terminal swallow. *Physiol. Behav.* **90**, 172–179 (2007).
132. Forde, C., van Kuijk, N., Thaler, T., de Graaf, C. & Martin, N. Texture and savoury taste influences on food intake in a realistic hot lunch time meal. *Appetite* **60**, 180–186 (2013).
133. Ohkuma, T. *et al.* Association between eating rate and obesity: a systematic review and meta-analysis. *Int. J. Obes.* **39**, 1589–1596 (2015).

134. Zijlstra, N., de Wijk, R. A., Mars, M., Stafleu, A. & de Graaf, C. Effect of bite size and oral processing time of a semisolid food on satiation. *Am. J. Clin. Nutr.* **90**, 269–275 (2009).
135. N’Gom, P. I. & Woda, A. Influence of impaired mastication on nutrition. *J. Prosthet. Dent.* **87**, 667–673 (2002).
136. Walls, A. W. G. & Steele, J. G. The relationship between oral health and nutrition in older people. *Mech. Ageing Dev.* **125**, 853–857 (2004).
137. Fogel, A. *et al.* A description of an ‘obesogenic’ eating style that promotes higher energy intake and is associated with greater adiposity in 4.5-year-old children: Results from the GUSTO cohort. *Physiol. Behav.* **176**, 107–116 (2017).
138. Leong, S. L., Madden, C., Gray, A., Waters, D. & Horwath, C. Faster self-reported speed of eating is related to higher body mass index in a nationwide survey of middle-aged women. *J. Am. Diet. Assoc.* **111**, 1192–1197 (2011).
139. Robinson, E. *et al.* A systematic review and meta-analysis examining the effect of eating rate on energy intake and hunger. *Am. J. Clin. Nutr.* **100**, 123–151 (2014).
140. McCrickerd, K. & Forde, C. G. Consistency of Eating Rate, Oral Processing Behaviours and Energy Intake across Meals. *Nutrients* **9**, (2017).
141. Wee, M. S. M., Goh, A. T., Stieger, M. & Forde, C. G. Correlation of instrumental texture properties from textural profile analysis (TPA) with eating behaviours and macronutrient composition for a wide range of solid foods. *Food Funct.* **9**, 5301–5312 (2018).
142. Yven, C. *et al.* Consequences of Individual Chewing Strategies on Bolus Rheological Properties at the Swallowing Threshold. *J. Texture Stud.* **43**, 309–318 (2012).
143. Laguna, L., Sarkar, A., Artigas, G. & Chen, J. A quantitative assessment of the eating capability in the elderly individuals. *Physiol. Behav.* **147**, 274–281 (2015).
144. Laguna, L., Sarkar, A. & Chen, J. Assessment of eating capability of elderly subjects in UK: a quantitative evaluation. *Proc. Nutr. Soc.* **74**, E167 (1 pages) (2015).
145. Percival, R. S., Challacombe, S. J. & Marsh, P. D. Flow rates of resting whole and stimulated parotid saliva in relation to age and gender. *J. Dent. Res.* **73**, 1416–1420 (1994).
146. Yeh, C. K., Johnson, D. A. & Dodds, M. W. Impact of aging on human salivary gland function: a community-based study. *Aging Milan Italy* **10**, 421–428 (1998).

147. Youmans, S. R., Youmans, G. L. & Stierwalt, J. A. G. Differences in tongue strength across age and gender: is there a diminished strength reserve? *Dysphagia* **24**, 57–65 (2009).
148. Mioche, L., Bourdiol, P. & Peyron, M.-A. Influence of age on mastication: effects on eating behaviour. *Nutr. Res. Rev.* **17**, 43–54 (2004).
149. Gerritsen, A. E., Allen, P. F., Witter, D. J., Bronkhorst, E. M. & Creugers, N. H. J. Tooth loss and oral health-related quality of life: a systematic review and meta-analysis. *Health Qual. Life Outcomes* **8**, 126 (2010).
150. Derks, J. a. m., De Wijk, R. a., De Graaf, C. & Stieger, M. Influence of Stimulus Properties and Sensory Task Instructions on Oral Processing Behavior of Liquid Stimuli. *J. Texture Stud.* **47**, 49–57 (2016).
151. Jacobsson, C., Axelsson, K., Osterlind, P. O. & Norberg, A. How people with stroke and healthy older people experience the eating process. *J. Clin. Nurs.* **9**, 255–264 (2000).
152. Nagasawa, T., Yanbin, X., Tsuga, K. & Abe, Y. Sex difference of electromyogram of masticatory muscles and mandibular movement during chewing of food. *J. Oral Rehabil.* **24**, 605–609 (1997).
153. Youssef, R. E., Throckmorton, G. S., Ellis, E. & Sinn, D. P. Comparison of habitual masticatory patterns in men and women using a custom computer program. *J. Prosthet. Dent.* **78**, 179–186 (1997).
154. Laguna, L., Hetherington, M. M., Chen, J., Artigas, G. & Sarkar, A. Measuring eating capability, liking and difficulty perception of older adults: A textural consideration. *Food Qual. Prefer.* **53**, 47–56 (2016).
155. Humbert, I. A. & Robbins, J. Dysphagia in the elderly. *Phys. Med. Rehabil. Clin. N. Am.* **19**, 853–866, ix–x (2008).
156. Fontijn-Tekamp, F. A. *et al.* Biting and chewing in overdentures, full dentures, and natural dentitions. *J. Dent. Res.* **79**, 1519–1524 (2000).
157. van Eck, A. *et al.* Oral processing behavior and dynamic sensory perception of composite foods: Toppings assist saliva in bolus formation. *Food Qual. Prefer.* (2018) doi:10.1016/j.foodqual.2018.05.009.
158. Kamegai, T. *et al.* A determination of bite force in northern Japanese children. *Eur. J. Orthod.* **27**, 53–57 (2005).
159. Henry, C. J., Ponnalagu, S., Bi, X. & Forde, C. Does basal metabolic rate drive eating rate? *Physiol. Behav.* **189**, 74–77 (2018).

160. Herman, C. P., Roth, D. A. & Polivy, J. Effects of the presence of others on food intake: a normative interpretation. *Psychol. Bull.* **129**, 873–886 (2003).
161. Triandis, H. C. The self and social behavior in differing cultural contexts. *Psychol. Rev.* **96**, 506–520 (1989).
162. Sun, L., Ranawana, D. V., Tan, W. J. K., Quek, Y. C. R. & Henry, C. J. The impact of eating methods on eating rate and glycemic response in healthy adults. *Physiol. Behav.* **139**, 505–510 (2015).
163. Aguayo-Mendoza, M. *et al.* How addition of peach gel particles to yogurt affects oral behavior, sensory perception and liking of consumers differing in age. *Food Res. Int.* **134**, 109213 (2020).
164. Pereira, L. J. & van der Bilt, A. The influence of oral processing, food perception and social aspects on food consumption: a review. *J. Oral Rehabil.* n/a-n/a (2016) doi:10.1111/joor.12395.
165. Peyron, M.-A., Santé-Lhoutellier, V., François, O. & Hennequin, M. Oral declines and mastication deficiencies cause alteration of food bolus properties. *Food Funct.* **9**, 1112–1122 (2018).
166. Prinz, J. F. & Lucas, P. W. Swallow thresholds in human mastication. *Arch. Oral Biol.* **40**, 401–403 (1995).
167. Doyennette, M., Aguayo-Mendoza, M. G., Williamson, A.-M., Martins, S. I. F. S. & Stieger, M. Capturing the impact of oral processing behaviour on consumption time and dynamic sensory perception of ice creams differing in hardness. *Food Qual. Prefer.* 103721 (2019) doi:10.1016/j.foodqual.2019.103721.
168. Braghieri, A. *et al.* Effect of preservative addition on sensory and dynamic profile of Lucanian dry-sausages as assessed by quantitative descriptive analysis and temporal dominance of sensations. *Meat Sci.* **122**, 68–75 (2016).
169. Farouk, M. M., Hall, W. K., Harrison, M. & Swan, J. E. Instrumental and Sensory Measurement of Beef Patty and Sausage Texture. *J. Muscle Foods* **10**, 17–28 (1999).
170. Fonseca, S., Gómez, M., Domínguez, R. & Lorenzo, J. M. Physicochemical and sensory properties of Celta dry-ripened “salchichón” as affected by fat content. *Grasas Aceites* **66**, 059 (2015).
171. Jones, R. C., Dransfield, E., Crosland, A. R. & Francombe, M. A. Sensory characteristics of british sausages: Relationships with composition and mechanical properties. *J. Sci. Food Agric.* **48**, 63–85 (1989).

172. Laranjo, M. *et al.* Characterisation of “Catalão” and “Salsichão” Portuguese traditional sausages with salt reduction. *Meat Sci.* **116**, 34–42 (2016).
173. Laranjo, M. *et al.* Impact of salt reduction on biogenic amines, fatty acids, microbiota, texture and sensory profile in traditional blood dry-cured sausages. *Food Chem.* **218**, 129–136 (2017).
174. Paulos, K. *et al.* Sensory Characterization and Consumer Preference Mapping of Fresh Sausages Manufactured with Goat and Sheep Meat. *J. Food Sci.* **80**, S1568–S1573 (2015).
175. Solheim, R. Consumer liking for sausages affected by sensory quality and information on fat content. *Appetite* **19**, 285–292 (1992).
176. Cheong, J. N. *et al.* The Application of Temporal Dominance of Sensations (TDS) for Oral Processing Studies: An Initial Investigation. *J. Texture Stud.* **45**, 409–419 (2014).
177. Newton, J. P., Abel, E. W., Robertson, E. M. & Yemm, R. Changes in human masseter and medial pterygoid muscles with age: a study by computed tomography. *Gerodontology* **3**, 151–154 (1987).
178. Rémond, D. *et al.* Understanding the gastrointestinal tract of the elderly to develop dietary solutions that prevent malnutrition. *Oncotarget* **6**, 13858–13898 (2015).
179. Navazesh, M., Mulligan, R. A., Kipnis, V., Denny, P. A. & Denny, P. C. Comparison of Whole Saliva Flow Rates and Mucin Concentrations in Healthy Caucasian Young and Aged Adults. *J. Dent. Res.* **71**, 1275–1278 (1992).
180. Vandenberghe-Descamps, M. *et al.* Salivary Flow Decreases in Healthy Elderly People Independently of Dental Status and Drug Intake. *J. Texture Stud.* **47**, 353–360 (2016).
181. Fiszman, S. & Tarrega, A. The dynamics of texture perception of hard solid food: A review of the contribution of the temporal dominance of sensations technique. *J. Texture Stud.* **49**, 202–212 (2018).
182. Ketel, E. C., de Wijk, R. A., de Graaf, C. & Stieger, M. Relating oral physiology and anatomy of consumers varying in age, gender and ethnicity to food oral processing behavior. *Physiol. Behav.* **215**, 112766 (2020).
183. Shiga, H., Kobayashi, Y., Katsuyama, H., Yokoyama, M. & Arakawa, I. Gender difference in masticatory performance in dentate adults. *J. Prosthodont. Res.* **56**, 166–169 (2012).

184. Kiliaridis, S., Karlsson, S. & Kjellberg, H. Characteristics of masticatory mandibular movements and velocity in growing individuals and young adults. *J. Dent. Res.* **70**, 1367–1370 (1991).
185. Fogel, A. *et al.* Prospective associations between parental feeding practices and children's oral processing behaviours. *Matern. Child. Nutr.* **15**, e12635 (2019).
186. Sook Wah, C. Gender differences in eating behaviour. *Int. J. Account. Bus. Manag.* (2016).
187. Ketel, E. C. *et al.* Comparison of and relationships between oral physiology, anatomy and food oral processing behavior of Chinese-Asian and Dutch-Caucasian consumers differing in age. (Submitted).
188. Ang, C. Y. W., Liu, K. & Huang, Y.-W. *Asian Foods: Science and Technology*. (CRC Press, 1999).
189. Di Monaco, R., Cavella, S. & Masi, P. Predicting Sensory Cohesiveness, Hardness and Springiness of Solid Foods from Instrumental Measurements. *J. Texture Stud.* **39**, 129–149 (2008).
190. Meullenet, J.-F., Lyon, B. G., Carpenter, J. A. & Lyon, C. E. RELATIONSHIP BETWEEN SENSORY AND INSTRUMENTAL TEXTURE PROFILE ATTRIBUTES. *J. Sens. Stud.* **13**, 77–93 (1998).
191. Santagiuliana, M., Bhaskaran, V., Scholten, E., Piqueras-Fiszman, B. & Stieger, M. Don't judge new foods by their appearance! How visual and oral sensory cues affect sensory perception and liking of novel, heterogeneous foods. *Food Qual. Prefer.* **77**, 64–77 (2019).
192. Fuhrmann, P. L., Aguayo-Mendoza, M., Jansen, B., Stieger, M. & Scholten, E. Characterisation of friction behaviour of intact soft solid foods and food boli. *Food Hydrocoll.* **100**, 105441 (2020).
193. Pedersen, A. M., Bardow, A., Jensen, S. B. & Nauntofte, B. Saliva and gastrointestinal functions of taste, mastication, swallowing and digestion. *Oral Dis.* **8**, 117–129 (2002).
194. Foegeding, E. A., Stieger, M. & van de Velde, F. Moving from molecules, to structure, to texture perception. *Food Hydrocoll.* **68**, 31–42 (2017).
195. Lasschuijt, M. *et al.* Comparison of oro-sensory exposure duration and intensity manipulations on satiation. *Physiol. Behav.* doi:10.1016/j.physbeh.2017.02.003.

196. Nishinari, K., Fang, Y. & Rosenthal, A. Human oral processing and texture profile analysis parameters: Bridging the gap between the sensory evaluation and the instrumental measurements. *J. Texture Stud.* **50**, 369–380 (2019).
197. Szczesniak, A. S. & Kahn, E. L. Texture Contrasts and Combinations - a Valued Consumer Attribute. *J. Texture Stud.* **15**, 285–301 (1984).
198. Lévy, C. M., MacRae, A. & Koster, E. P. Perceived stimulus complexity and food preference development. *Acta Psychol. (Amst.)* **123**, 394–413 (2006).
199. Santagiuliana, M., Christaki, M., Piqueras-Fiszman, B., Scholten, E. & Stieger, M. Effect of mechanical contrast on sensory perception of heterogeneous liquid and semi-solid foods. *Food Hydrocoll.* **83**, 202–212 (2018).
200. Santagiuliana, M., Hoek, I. A. F. van den, Stieger, M., Scholten, E. & Piqueras-Fiszman, B. As good as expected? How consumer expectations and addition of vegetable pieces to soups influence sensory perception and liking. *Food Funct.* **10**, 665–680 (2019).
201. Forde, C. G. & Delahunty, C. M. Understanding the role cross-modal sensory interactions play in food acceptability in younger and older consumers. *Food Qual. Prefer.* **15**, 715–727 (2004).
202. Forde, C. G., Cantau, B., Delahunty, C. M. & Elsner, R. J. F. Interactions between texture and trigeminal stimulus in a liquid food system: Effects on elderly consumers preferences. *J. Nutr. Health Aging* **6**, 130–133 (2002).
203. Forde, C. G. & Delahunty, C. M. Examination of chemical irritation and textural influence on food preferences in two age cohorts using complex food systems. *Food Qual. Prefer.* **13**, 571–581 (2002).
204. Tarrega, A., Marcano, J. & Fiszman, S. Yogurt viscosity and fruit pieces affect satiating capacity expectations. *Food Res. Int.* **89**, 574–581 (2016).
205. Larsen, D. S., Tang, J., Ferguson, L. R. & James, B. J. Increased textural complexity in food enhances satiation. *Appetite* **105**, 189–194 (2016).
206. Tang, J., Larsen, D. S., Ferguson, L. R. & James, B. J. The effect of textural complexity of solid foods on satiation. *Physiol. Behav.* **163**, 17–24 (2016).
207. Mosca, A. C. *et al.* Small food texture modifications can be used to change oral processing behaviour and to control ad libitum food intake. *Appetite* **142**, 104375 (2019).
208. Zijlstra, N., Mars, M., Stafleu, A. & de Graaf, C. The effect of texture differences on satiation in 3 pairs of solid foods. *Appetite* **55**, 490–497 (2010).

209. Field, K. & Duizer, L. M. Food Sensory Properties and the Older Adult. *J. Texture Stud.* **47**, 266–276 (2016).
210. Kohyama, K., Mioche, L. & Bourdio, P. Influence of age and dental status on chewing behaviour studied by EMG recordings during consumption of various food samples. *Gerodontology* **20**, 15–23 (2003).
211. Shaker, R. *et al.* Effect of aging, position, and temperature on the threshold volume triggering pharyngeal swallows. *Gastroenterology* **107**, 396–402 (1994).
212. Morquette, P. *et al.* Generation of the masticatory central pattern and its modulation by sensory feedback. *Prog. Neurobiol.* **96**, 340–355 (2012).
213. Anderson, K., Throckmorton, G. S., Buschang, P. H. & Hayasaki, H. The effects of bolus hardness on masticatory kinematics. *J. Oral Rehabil.* **29**, 689–696 (2002).
214. Brunstrom, J. M. & Rogers, P. J. How Many Calories Are on Our Plate? Expected Fullness, Not Liking, Determines Meal-size Selection. *Obesity* **17**, 1884–1890 (2009).
215. Richardson-Harman, N. J. *et al.* Mapping consumer perceptions of creaminess and liking for liquid dairy products. *Food Qual. Prefer.* **11**, 239–246 (2000).
216. Hetherington, M. M. Taste and appetite regulation in the elderly. *Proc. Nutr. Soc.* **57**, 625–631 (1998).
217. Witt, T. & Stokes, J. R. Physics of food structure breakdown and bolus formation during oral processing of hard and soft solids. *Curr. Opin. Food Sci.* **3**, 110–117 (2015).
218. Agrawal, K. R., Lucas, P. W., Bruce, I. C. & Prinz, J. F. Food Properties that Influence Neuromuscular Activity During Human Mastication. *J. Dent. Res.* **77**, 1931–1938 (1998).
219. Koç, H. *et al.* Emulsion filled polysaccharide gels: Filler particle effects on material properties, oral processing, and sensory texture. *Food Hydrocoll.* **94**, 311–325 (2019).
220. Kohyama, K., Gao, Z., Ishihara, S., Funami, T. & Nishinari, K. Electromyography analysis of natural mastication behavior using varying mouthful quantities of two types of gels. *Physiol. Behav.* **161**, 174–182 (2016).
221. Hyde, R. J. & Witherly, S. A. Dynamic Contrast: A Sensory Contribution to Palatability. *Appetite* **21**, 1–16 (1993).
222. Aguayo-Mendoza, M. *et al.* How addition of peach gel particles to yogurt affects oral behavior, sensory perception and liking of consumers differing in age. *Food Res. Int.* 109213 (2020) doi:10.1016/j.foodres.2020.109213.

223. Wagoner, T. B., Luck, P. J. & Foegeding, E. A. Caramel as a Model System for Evaluating the Roles of Mechanical Properties and Oral Processing on Sensory Perception of Texture. *J. Food Sci.* **81**, S736–S744 (2016).
224. Anderson, D. J. & Hector, M. P. Periodontal mechanoreceptors and parotid secretion in animals and man. *J. Dent. Res.* **66**, 518–523 (1987).
225. Ahmad, S., Butt, M. S., Pasha, I. & Sameen, A. Quality of Processed Cheddar Cheese as a Function of Emulsifying Salt Replaced by κ -Carrageenan. *Int. J. Food Prop.* **19**, 1874–1883 (2016).
226. Błaszak, B., Gozdecka, G. & Shyichuk, A. Carrageenan as a Functional Additive in the Production of Cheese and Cheese-Like Products. *Acta Sci. Pol. Technol. Aliment.* **17**, 107–116 (2018).
227. Černíková, M. *et al.* Replacement of traditional emulsifying salts by selected hydrocolloids in processed cheese production. *Int. Dairy J.* **20**, 336–343 (2010).
228. Kokini, J. L. The physical basis of liquid food texture and texture-taste interactions. *J. Food Eng.* **6**, 51–81 (1987).
229. Mosca, A. C., van de Velde, F., Bult, J. H. F., van Boekel, M. A. J. S. & Stieger, M. Taste enhancement in food gels: Effect of fracture properties on oral breakdown, bolus formation and sweetness intensity. *Food Hydrocoll.* **43**, 794–802 (2015).
230. Tournier, C., Sulmont-Rossé, C. & Guichard, E. Flavour Perception: Aroma, Taste and Texture Interactions. **12** (2007).
231. Deurenberg, P. & Deurenberg-Yap, M. 9 - Ageing and changes in body composition: the importance of valid measurements. in *Food for the Ageing Population* (eds. Raats, M., de Groot, L. & van Staveren, W.) 169–183 (Woodhead Publishing, 2009). doi:10.1533/9781845695484.2.169.
232. Hutton, B., Feine, J. & Morais, J. Is There an Association Between Edentulism and Nutritional State? **68**, 6 (2002).
233. Sheiham, A. *et al.* The Relationship among Dental Status, Nutrient Intake, and Nutritional Status in Older People. *J. Dent. Res.* **80**, 408–413 (2001).
234. Graaf, C. de, Polet, P. & van Staveren, W. A. Sensory Perception and Pleasantness of Food Flavors in Elderly Subjects. *J. Gerontol.* **49**, P93–P99 (1994).
235. Mojet, J., Christ-Hazelhof, E. & Heidema, J. Taste Perception with Age: Generic or Specific Losses in Threshold Sensitivity to the Five Basic Tastes? *Chem. Senses* **26**, 845–860 (2001).

236. Kremer, S. & Mojet, J. *Interaction and Compensation Mechanisms between the Senses*. 12 (2004).
237. Cain, W. S., Reid, F. & Stevens, J. C. Missing Ingredients. *J. Nutr. Elder.* **9**, 3–15 (1990).
238. Stevens, J. C. & Cain, W. S. Changes in taste and flavor in aging. *Crit. Rev. Food Sci. Nutr.* **33**, 27–37 (1993).
239. Calhoun, K. H., Gibson, B., Hartley, L., Minton, J. & Hokanson, J. A. Age-related changes in oral sensation. *The Laryngoscope* **102**, 109–116 (1992).
240. Kremer, S., Mojet, J. & Kroeze, J. H. A. Perception of Texture and Flavor in Soups by Elderly and Young Subjects. *J. Texture Stud.* **36**, 255–272 (2005).
241. Kremer, S., Bult, J. H. F., Mojet, J. & Kroeze, J. H. A. Food Perception with Age and Its Relationship to Pleasantness. *Chem. Senses* **32**, 591–602 (2007).
242. Laguna, L., Aktar, T., Ettelaie, R., Holmes, M. & Chen, J. A Comparison Between Young and Elderly Adults Investigating the Manual and Oral Capabilities During the Eating Process. *J. Texture Stud.* **47**, 361–372 (2016).
243. Wendin, K. *et al.* Appetite for life : reflections on how to increase food intake in the elderly. *MENU J. Food Hosp. Res.* **6**, 25–33 (2017).
244. Roininen, K., Fillion, L., Kilcast, D. & Lähteenmäki, L. Perceived Eating Difficulties and Preferences for Various Textures of Raw and Cooked Carrots in Young and Elderly Subjects. *J. Sens. Stud.* **18**, 437–451 (2003).
245. Brossard, C. D., Lethuaut, L., Boelrijk, A. E. M., Mariette, F. & Genot, C. Sweetness and aroma perceptions in model dairy desserts: an overview. *Flavour Fragr. J.* **21**, 48–52 (2006).
246. Mosca, A. C. *et al.* How are macronutrient intake, BMI, ethnicity, age, and gender related to the composition of unstimulated saliva? A case study. *J. Texture Stud.* **50**, 53–61 (2019).
247. Bock, B. C. & Kanarek, R. B. Women and men are what they eat: The effects of gender and reported meal size on perceived characteristics. *Sex Roles* **33**, 109–119 (1995).
248. Campos, L., Bernardes, S. & Godinho, C. Food as a way to convey masculinities: How conformity to hegemonic masculinity norms influences men's and women's food consumption. *J. Health Psychol.* 1359105318772643 (2018) doi:10.1177/1359105318772643.
249. Cattaneo, C., Liu, J., Bech, A. C., Pagliarini, E. & Bredie, W. L. P. Cross-cultural differences in lingual tactile acuity, taste sensitivity phenotypical markers, and preferred oral processing behaviors. *Food Qual. Prefer.* **80**, 103803 (2020).

250. Engelen, L. *et al.* The effect of saliva composition on texture perception of semi-solids. *Arch. Oral Biol.* **52**, 518–525 (2007).
251. Essick, G. K., Chen, C. C. & Kelly, D. G. A letter-recognition task to assess lingual tactile acuity. *J. Oral Maxillofac. Surg.* **57**, 1324–1330 (1999).
252. Jacobs, R., Serhal, C. B. & van Steenberghe, D. Oral stereognosis: a review of the literature. *Clin. Oral Investig.* **2**, 3–10 (1998).
253. de Graaf, C. & Kok, F. J. Slow food, fast food and the control of food intake. *Nat. Rev. Endocrinol.* (2010) doi:10.1038/nrendo.2010.41.
254. Liu, K., Stieger, M., van der Linden, E. & van de Velde, F. Effect of microparticulated whey protein on sensory properties of liquid and semi-solid model foods. *Food Hydrocoll.* **60**, 186–198 (2016).
255. Laguna, L. & Sarkar, A. Influence of mixed gel structuring with different degrees of matrix inhomogeneity on oral residence time. *Food Hydrocoll.* **61**, 286–299 (2016).
256. van Bommel, R., Stieger, M., Boelee, N., Schlich, P. & Jager, G. From first to last bite: Temporal dynamics of sensory and hedonic perceptions using a multiple-intake approach. *Food Qual. Prefer.* **78**, 103748 (2019).
257. van Eck, A., Fogliano, V., Galindo-Cuspinera, V., Scholten, E. & Stieger, M. Adding condiments to foods: How does static and dynamic sensory perception change when bread and carrots are consumed with mayonnaise? *Food Qual. Prefer.* **73**, 154–170 (2019).
258. Cichero, J. a. Y. Adjustment of Food Textural Properties for Elderly Patients. *J. Texture Stud.* **47**, 277–283 (2016).
259. Bornhorst, G. M. & Singh, R. P. Bolus Formation and Disintegration during Digestion of Food Carbohydrates. *Compr. Rev. Food Sci. Food Saf.* **11**, 101–118 (2012).
260. Freitas, D. & Le Feunteun, S. Oro-gastro-intestinal digestion of starch in white bread, wheat-based and gluten-free pasta: Unveiling the contribution of human salivary α -amylase. *Food Chem.* **274**, 566–573 (2019).
261. Foschia, M., Peressini, D., Sensidoni, A., Brennan, M. A. & Brennan, C. S. Mastication or masceration: Does the preparation of sample affect the predictive in vitro glycemic response of pasta? *Starch - Stärke* **66**, 1096–1102 (2014).
262. Hoebler, C., Devaux, M. F., Karinthi, A., Belleville, C. & Barry, J. L. Particle size of solid food after human mastication and in vitro simulation of oral breakdown. *Int. J. Food Sci. Nutr.* **51**, 353–366 (2000).

263. Ranawana, V. Degree of particle size breakdown during mastication may be a possible cause of interindividual glycemic variability. *Nutr. Res.* **30**, 246–254 (2010).
264. Ranawana, V., Clegg, M. E., Shafat, A. & Henry, C. J. Postmastication digestion factors influence glycemic variability in humans. *Nutr. Res.* **31**, 452–459 (2011).
265. Ranawana, V., Leow, M. K.-S. & Henry, C. J. K. Mastication effects on the glycaemic index: impact on variability and practical implications. *Eur. J. Clin. Nutr.* **68**, 137–139 (2014).
266. Tamura, M., Okazaki, Y., Kumagai, C. & Ogawa, Y. The importance of an oral digestion step in evaluating simulated in vitro digestibility of starch from cooked rice grain. *Food Res. Int.* **94**, 6–12 (2017).

S

Summary

Food oral processing refers to the oral manipulations of food upon ingestion (i.e. oral behavior), the production of a bolus safe to swallow and simultaneously the sensory responses evoked from the structural transformation of the bolus. Deeper understanding of the factors involved in oral processing can facilitate the creations of food products that are goal-specific (e.g. controlling eating rate) and population-specific (e.g. elderly consumers) besides being nutritive and palatable. The main factors determining oral processing are the consumer and food being eaten. Therefore, in this thesis both factors were explored and their contribution to oral behavior, bolus properties and sensory perception determined.

Chapter 2 explored whether or not consumers exhibit different oral behaviors for a specific food product and how these differences in behavior might impact sensory perception. The results confirmed that consumers used different oral behaviors which differed in consumption time. Vigorous protocols (chewing and natural style) required shorter consumption time than passive protocols (melting). Furthermore, changes in oral behavior also influence dynamic sensory perception. For instance, changing oral behavior influenced significantly aroma and taste attributes, where upon applying an active oral behavior aroma attributes were detected earlier and for longer time than when a passive protocol was applied. On the other hand, if a passive protocol was applied, taste perception was perceived earlier and for longer time whereas aroma perception was delayed. Additionally, this chapter highlighted the existence of attribute chronology during oral processing and that consumers adopt an oral processing behavior that is optimized in terms of oral efficiency and sensory perception.

Chapter 3 explored a broad range of commercial foods and the effect of their rheological and mechanical properties on oral behavior parameters. The results showed that consumers adapted their bite size, consumption time and eating rate to food properties and that this adaptation was consistent within each food category. Overall, consistency (K) of liquids and semi-solids and stress at 15% strain of solid foods have a negative relationship with bite size, and positive relationship with consumption time. Together, these variables contribute to modulate eating rate. Thus, this chapter highlighted that oral behavior can be steered by modifications on food properties.

Chapters 4 demonstrated that not only food properties but also consumers characteristics can influence oral behavior. For instance, elderly exhibited longer consumption times and lower eating rates than their younger counterparts. Amongst genders, females took smaller bite sizes, and had lower eating rates than males. Finally, between ethnicities, Dutch-Caucasian exhibited larger bite sizes and faster eating rates than Asian-Chinese. Generally, the observed differences between consumer groups was relatively constant across food categories.

Chapter 5 investigated how the changes in oral behavior between consumer groups affected bolus properties and dynamic sensory perception. The results showed that consumers differing in age, gender or ethnicity adjust their consumption time in a way that allows them to form a bolus with optimized textural properties that guarantee them a safe and comfortable swallow. Also, these results show that the swallowing threshold is not universal but that it differs between consumers. Possibly due to the inherent physiological and cultural differences. Additionally, this chapter showed that dynamic sensory perception varied only in middle stages of oral processing maybe providing input to determine if further bolus degradation or saliva incorporation was needed.

Finally, **chapters 6 and 7**, demonstrated that when eating heterogeneous foods, oral processing behavior can be steered by modification in either food matrix or the embedded particle and that these results may be applicable to different consumer groups. The results of **chapter 6** showed that the mere addition of peach particles to yogurts slowed down eating rate up to 60%, regardless of the particles' characteristics (size, fracture stress or concentration). Similarly, in **chapter 7** the addition of bell pepper pieces to cream cheeses also showed an impact on oral processing behavior although this was to a lower extent. Hence, we suggest that the bigger is the perception of contrast, between the disperse matrix and the added particle, the greater the impact on oral processing behavior. Moreover, not only the mere addition of particles but also the fracture stress of the embedded particle can influence oral behavior. For instance, embedding particles of high fracture stress, leads to longer consumption times and lower eating rates than when the particles have low fracture stress. Furthermore, it was observed that the perception of the solid component overruled the sensations arouse from the softest component. Thus, when designing

heterogeneous foods, attention should be given to the hardest component since it will likely overrule the influence of the softest component.

In conclusion, consumer and food characteristics shape oral behavior which in turn affects bolus properties and consequently sensory perception. Therefore, new product development aiming for a more tailored sensory experience should take not only food characteristics into account but also the fact that consumer groups differ in oral processing behavior.

A

Acknowledgements

I would like to start by thanking my promotor and supervisor **Markus Stieger** who trusted me since I was his master student. **Markus** your guidance and patience was fundamental through each stage of this project and for that I am extremely grateful. My gratitude also goes to my promotor and co-promotor **Erik van der Linden** and **Betina Piqueras** for their thoughtful comments and recommendations during these four years.

Besides my supervisors, I want to express my gratitude to **Laura Laguna**, **Andrew Rosenthal**, **Nicoleta Pellegrini** and **Edith Feskens** who said yes and became my thesis committee members. Thank you for taking the time to read, review and approve my thesis.

I want to recognize all the experts involved in the smooth bite for all team from Friesland Campina, **Marcel Paques**, **Yves Nicolas**, **Martijn Veltkamp**; from Unilever **Veronica Galindo**, **Michel Mellema**; from Bel group **Benoit Goldschmidt**, **Julie Poette**, **Cecile Renault**; and from Wageningen University **Elke Scholten**, **Rene de Wijk**, **Gerry Jager** and **Guido Sala**. Thanks for your continuous feedback, collaboration and insights before, during and after the experiments. I would like to acknowledge my co-authors **Ciaran Forde** and **Marion Doyennette** who even when outside the project or Wageningen University their input significantly contributed to my thesis.

Also special thanks to my PhD colleagues involved in the project **Eva Ketel**, **Philipp Fuhrmann**, **Roelien van Bommel**, **Arianne van Eck**, **Marco Santagiuliana**, and to all my PhD colleagues from the constantly growing group of Food Physics. Likewise, thanks to the group staff, specially to **Elke Scholten** who was always nice, funny, supportive and willing to help and listen even when she was not my supervisor. Also, thanks to **Mehdi Habibi** for trusting me with one project. Thanks to **Harry Baptist**, **Miranda de Beus**, **Roy** and **Els Jansen** for their guidance and technical assistance

I am really grateful to my students that worked alongside with me sometimes weekends, holydays or sometimes before and after working hours. Thanks **Jessica Wiech**, **Montse Briseño**, **Esmee ten Brundel**, **Annemiek van der Zanden**, **Suzanne Poppe**, **Xian Ong**, **Bas Jansen**, **Eduardo Martinez**, **Georgia Chatonidi**, **Jirapat Wisitwong**, **Michael Camilleri** and **Phoebe Nikolaou**. Also, I wish to thank all the participants whose help was a milestone in the completion of this thesis.

Gracias a mis mejores amigos quienes han permanecido constantes a través de los años. Gracias por ser y estar siempre para planear como conquistar el mundo, compartir sueños, ilusiones, tristezas y miles de alegrías **Edgar Mendivil, Alberto Buenrostro, Juane Jimenez.**

Gracias a mi familia. A mis papas **José Luis Aguayo y Martha Mendoza** por su apoyo y por no detenerme nunca en mis locuras y sueños. Gracias por todo lo que me han enseñado durante toda mi vida. Gracias, aunque la vida no me alcance para regresarles todo lo que me han dado. También gracias a mis hermanos **Miguel, Ariadna, Luis y Jessica Aguayo Mendoza** por tantos momentos compartidos a lo largo de los años. A **Tarcicio Garcia, Lupita Fuentes, Samuel, Miguel y Angel Garcia Fuentes** quienes me han acogido y brindado apoyo como si fuera un miembro más su familia.

Finalmente, gracias **Alvaro Garcia Fuentes** las palabras no me alcanza para agradecerte todo lo que has hecho por mi en ya más de una década. Gracias por ser mi pareja, apoyo incondicional, mi luz en la oscuridad y también por regalarme dos hijos maravillosos (**Andy y Dulce**) quienes junto contigo se han convertido en el motor de mi vida.

A

About the author

Monica Aguayo was born on September 3rd 1987 in Mexico.

She studied at the University of Guadalajara and obtained a BSc in Human Nutrition. After her graduation, she worked in the food industry as food quality assurance inspector at “Verde Valle”. Afterwards she worked in parallel at the University of Guadalajara as research assistant and at “Kurago Biotek” as medical representative. During that period Monica co-founded

the company “Conciencia Alimentos” dedicated to provide nutritional advice and to commercialize healthy, locally produced food products.

In 2013 Monica married Alvaro Garcia and moved to The Netherlands. The same year she enrolled at Wageningen University to study a master’s in human nutrition with specialization in Sensory Science and Eating Behavior. As part of the master, she moved to Denmark to study for 6 months at the University of Copenhagen.

After completing her master, she worked as a teaching assistant at Wageningen University. In 2016 she started her PhD at Wageningen University in the department of Physical Chemistry of Foods in the TiFN project “Smooth Bite for all”.

During her PhD she supervised more than 10 master and bachelor theses and attended several international courses and conferences in the area of sensory science, oral processing and statistics. In addition to that, she taught in the courses Advance Molecular Gastronomy and Food Properties and Function.

On November 22nd 2018 at 06:34 hrs she became the proud mother of Andres “Andy” Rafael, and later on September 21st 2020 at 00:00 hrs she had her second baby, Dulce Maria. The rest of her story is to be continued.

Monica can be contacted through the following channels:

LinkedIn: <https://www.linkedin.com/in/monicaaguayophd/>

Email: monica.aguayo@sciencewithsense.com

Overview of completed training activities

Discipline specific activities: conferences courses and workshops		
4 th International Conference on Food Oral Processing ¹	Lausanne, Switzerland	2016
5 th International Conference on Food Oral Processing ^{1,2}	Nottingham, United Kingdom	2018
8 th European Conference on Sensory and Consumer Research “Eurosense” ¹	Verona, Italy	2018
33 rd EFFoST International Conference ²	Rotterdam, The Netherlands	2019
Sensory Perception and Food Preference	Wageningen, The Netherlands	2016
Smooth Bite for All: results to success workshop ¹	Hilvarenbeek, The Netherlands	2019
Dynamic <i>In-vitro</i> digestion training	Venlo, The Netherlands	2019
General courses and workshops		
PhD workshop carousel	Wageningen, The Netherlands	2016
VLAG PhD week	Baarlo, The Netherlands	2016
Multivariate analysis for food data/sciences	Wageningen, The Netherlands	2016
Introduction to R	Wageningen, The Netherlands	2017
Teaching and supervising thesis students	Wageningen, The Netherlands	2017
Reviewing a scientific paper	Wageningen, The Netherlands	2017
Scientific writing	Wageningen, The Netherlands	2017
R for statistics	Wageningen, The Netherlands	2018
Brain friendly working and writing	Wageningen, The Netherlands	2019
Career perspectives	Wageningen, The Netherlands	2019
Optional courses and activities		
Preparation of research proposal	Wageningen, The Netherlands	2016
PhD trip ^{1,2}	Indonesia and Singapore	2018
Project partner visit to Friesland Campina	Wageningen, The Netherlands	2016
Project partner visit to Bel group	Sureness, France	2017
Project meetings TIFN	Wageningen, The Netherlands	2016-2020
¹ Poster presentation, ² Oral presentation		

List of publications

- Aguayo-Mendoza, M. G. *, Ketel, E. C. *, van der Linden, E., Forde, C. G., Piqueras-Fiszman, B., & Stieger, M. (2019). Oral processing behavior of drinkable, spoonable and chewable foods is primarily determined by rheological and mechanical food properties. *Food Quality and Preference*, 71, 87–95.
- Doyennette, M. *, Aguayo-Mendoza, M. G. *, Williamson, A.-M., Martins, S. I. F. S., & Stieger, M. (2019). Capturing the impact of oral processing behavior on consumption time and dynamic sensory perception of ice creams differing in hardness. *Food Quality and Preference*, 103721.
- Ketel, E. C. *, Aguayo-Mendoza, M. G. *, de Wijk, R. A., de Graaf, C., Piqueras-Fiszman, B., & Stieger, M. (2019). Age, gender, ethnicity and eating capability influence oral processing behavior of liquid, semi-solid and solid foods differently. *Food Research International*, 119, 143–151.
- Aguayo-Mendoza, M. *, Santagiuliana, M. *, Ong, X., Piqueras-Fiszman, B., Scholten, E., & Stieger, M. (2020). How addition of peach gel particles to yogurt affects oral behavior, sensory perception and liking of consumers differing in age. *Food Research International*, 134, 109213.
- Fuhrmann, P. L., Aguayo-Mendoza, M., Jansen, B., Stieger, M., & Scholten, E. (2020). Characterisation of friction behavior of intact soft solid foods and food boli. *Food Hydrocolloids*, 100, 105441.
- Aguayo-Mendoza, M., Martinez-Almaguer, E., Piqueras-Fiszman, B., & Stieger, M. Differences in oral processing behavior of consumers varying in age, gender and ethnicity lead to changes in bolus properties but only to small differences in dynamic texture perception of sausages. *Submitted*.
- Aguayo-Mendoza, M., Chatonidi, G., Piqueras-Fiszman, B., & Stieger, M. (2020). Linking oral processing behavior to bolus properties and dynamic sensory perception of processed cheeses with bell pepper pieces. *Food Quality and Preference*, 104084.

*Both authors contributed equally to the work

Colophon

The research described in this thesis was performed within the framework of TiFN.

Financial support from Wageningen University and TiFN for this research and for printing this thesis is gratefully acknowledged.

Copyright © Monica Gabriela Aguayo Mendoza, 2020.