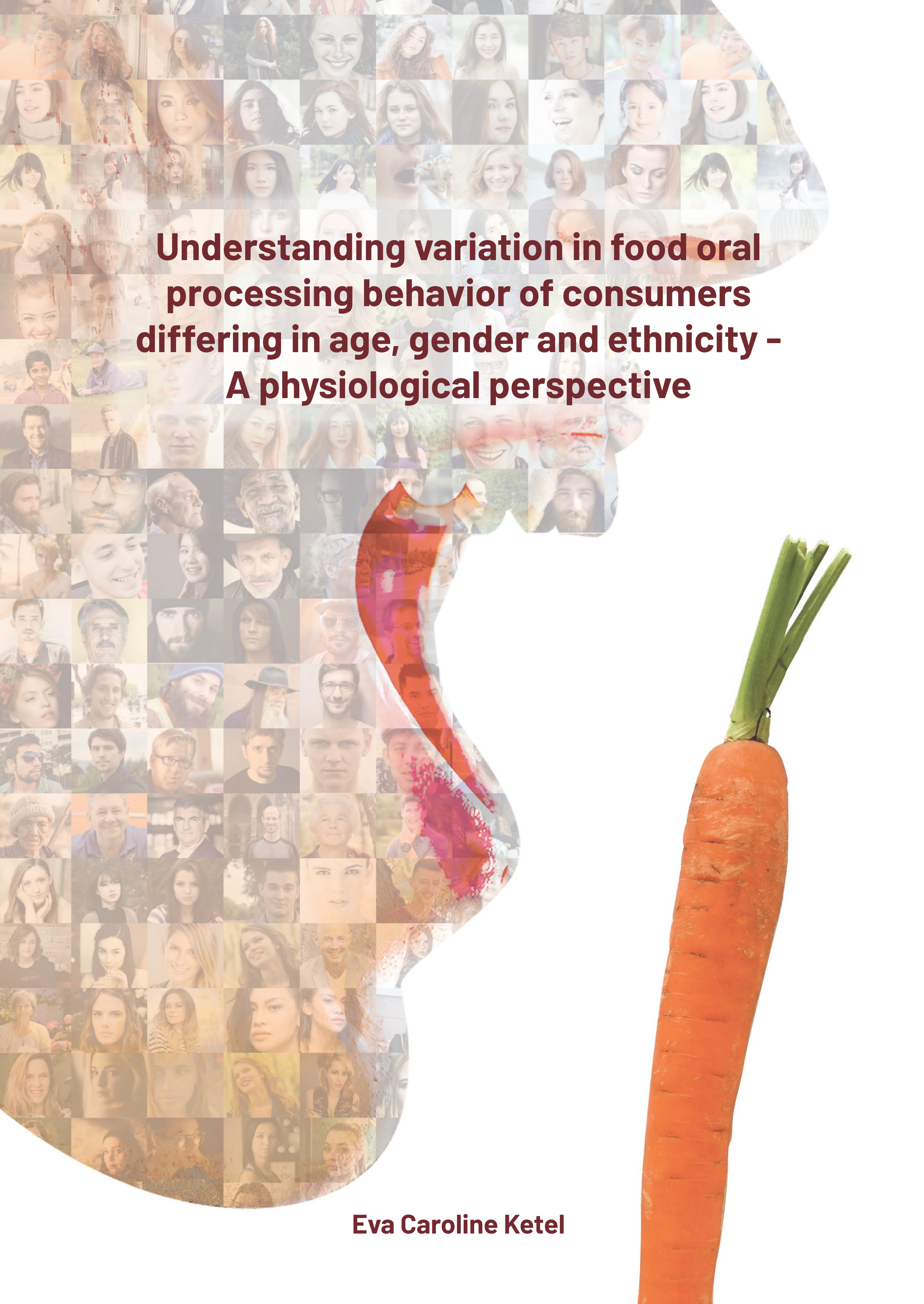

Understanding variation in food oral processing behavior of consumers differing in age, gender and ethnicity – A physiological perspective

Eva Caroline Ketel

Propositions

1. Chinese consume foods with lower eating rate than Dutch. (*this thesis*)

2. Oral physiology and anatomy are hardly related to food oral processing behavior. (*this thesis*)

3. Gender equality should be dealt with at the start of careers and not the end by setting quotas in boards (Bertrand et al. (2018), The Review of Economic Studies, 86(1), 191-239).

4. Universities should coach PhD candidates to balance dedication and commitment with mental health to reduce burn-out risk.

5. Obtaining ethical approval for human studies results in an unethical amount of stress.

6. While online work meetings are efficient, online social meetings are inefficient.

Propositions belonging to the PhD thesis, entitled:

"Understanding variation in food oral processing behavior of consumers differing in age, gender and ethnicity – A physiological perspective."

Eva Ketel

Wageningen, 16 October 2020

Understanding variation in food oral processing behavior of consumers differing in age, gender and ethnicity – A physiological perspective

Eva Ketel

Thesis committee

Promotors

Prof. Dr Markus Stieger
Personal chair, Sensory Science and Eating Behaviour
Wageningen University & Research

Prof. Dr Kees de Graaf
Professor of Sensory Science and Eating Behaviour
Wageningen University & Research

Co-promotor

Dr René de Wijk
Senior Scientist, Food and Biobased Research
Wageningen University & Research

Other members

Prof. Dr Lisette C.P.G.M. de Groot, Wageningen University & Research
Prof. Dr Wender Bredie, University of Copenhagen, Denmark
Prof. Dr Jeffrey Brunstorm, University of Bristol, UK
Prof Dr Christopher Vinyard, North East Medical University, Rootstown, Ohio, USA

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

Understanding variation in food oral processing behavior of consumers differing in age, gender and ethnicity – A physiological perspective

Eva Ketel

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 Friday 16 October 2020
at 4.00 p.m. in the Aula.

Eva Ketel

Understanding variation in food oral processing behavior of consumers differing in age, gender and ethnicity – A physiological perspective
184 pages.

PhD thesis, Wageningen University, Wageningen, The Netherlands (2020)
With references, with summary in English and Dutch

ISBN: 978-94-6395-495-2
DOI: https://doi.org/10.18174/528910

Table of contents

CHAPTER 1

1

General Introduction

Imagine eating a very crunchy and juicy apple. You take a few bites and only need a couple of minutes to consume the whole apple. Now imagine your grandmother eating the same apple. She needs more bites and more time to consume the whole apple. Your grandmother has a very different consumption style compared to you. The process of breaking down foods into smaller particles by mastication until we can safely swallow the bolus is called food oral processing behavior. A longer consumption time and smaller bite size result in a low eating rate (g/s) and consequently lower energy intake rate (kcal/min). As this example shows, oral processing behavior differs between consumers. Secondly, oral processing behavior depends on the food consumed (Chen, 2009), i.e. it takes much longer to eat a 100g apple compared to drinking 100g apple juice. Food properties could therefore be modified to change eating rate, energy intake rate and food intake. It is therefore important to understand the properties of foods and the characteristics of consumers which determine oral processing behavior.

1.1 Food oral processing behavior

Oral processing behavior is the first stage of food digestion during which food is broken down into smaller particles (Pereira, 2012) (Figure 1.1). First, the food is broken down into smaller particles with the incisors and moved to the molars to be further grinded into even smaller particles. Different physiological properties work together to facilitate this first stage of oral processing including dental status, mastication performance, ability to place bolus particles between teeth using the tongue, muscle activity of masseter and temporalis and bite force (Pereira et al., 2006). The second step of food oral processing is the formation of a smooth bolus that can be safely swallowed. Foods are lubricated by the release of fluids from the food itself and by incorporation of saliva from the salivary glands into the bolus. Lubrication of the bolus ensures safe swallowing without the hazard of choking (Chen, 2012). Salivary enzymes, especially salivary amylase, are secreted by saliva glands and start food digestion in the oral cavity during oral processing. Tongue movements, pressure and dimensions are relevant for bolus formation and bolus transportation from the anterior part of the oral cavity towards the pharynx. In addition to oral physiology, anatomical parameters have been suggested to be relevant for oral processing behavior. For example, the volume of oral cavity and anatomy of the body and head have been suggested to be related to food oral processing behavior.

Food oral processing behavior has been related to food intake. Consuming foods with higher eating rate caused either by shorter consumption time and/or larger bites, is known to result in higher energy intake and contributes to increased BMI (Ohkuma et al., 2015). Adaptation of eating rate of food can be used to change food intake in different ways. For vulnerable populations, such as the elderly, increasing eating rate to increase food intake might lower the risk of under- and malnutrition. For overweight consumers, decreasing eating rate to decrease food intake might promote weight loss and healthier lifestyle.

Food oral processing behavior also impacts sensory perception. Increased mastication time of model gels can enhance sweetness perception (Mosca et al., 2015). With increasing mastication time, the bolus of solid foods is broken down into more and smaller fragments so that the total surface area of all bolus fragments increases. Consequently, the release of tastants such as sucrose through the newly generated surface area increases, which enhances taste intensity (Koliandris et al., 2008; Mosca et al., 2015; Sala & Stieger, 2013). Mastication time is also known to impact texture perception of foods. Consumers differing in mastication time perceived the texture of foods differently (Devezeaux de Lavergne et al., 2015). Differences in consumption time caused differences in bolus properties which explained differences in texture perception between consumers. These studies demonstrate that oral processing behavior has a large impact on food intake and sensory perception. Understanding the variation in oral processing behavior can assist in the design of more palatable and healthier foods targeted for specific consumer groups (Kim et al., 2015).

1.2 Determinants of food oral processing behavior

1.2.1 Food properties

Physical-chemical, rheological and mechanical properties of foods determine oral processing behavior (Abhyankar et al., 2011; Chanasattru et al., 2002; Chen & Stokes, 2012; Hiiemae, 2004). The model of Hutchings and Lillford proposes that every food has their own breakdown pathway, depending on the change in structure and lubrication that are needed until the bolus can be swallowed (Hutchings & Lillford, 1988). Solid foods need more oral processing than liquid foods due to more structural breakdown that is needed before swallowing (Witt & Stokes, 2015). While several chewing cycles are needed to break down solid foods, semi-solid and liquid foods need less structural breakdown until swallowing and are not chewed. Liquid foods are orally processed by compressing the food between tongue and palate and often require only transportation from the front of the oral cavity to the pharynx (Chen, 2012; Pereira, 2012). This results in large differences in oral processing behavior between liquid, semi-solid and solid foods. Most of the energy in our diets comes from solid foods, with 30-40% of daily energy intake comes from hot meals (Forde et al., 2013a). Solid foods are known to show a large variation in number of bites, chews per bite and eating rate (Forde et al., 2017; Forde et al., 2013a; Forde et al., 2013b). Instrumental texture properties of a broad range of solid foods strongly correlated with eating rate and oral processing behavior (Wee et al., 2018). Springiness, chewiness and resilience are positively related to number of chews and consumption time in commercially available foods. Hardness of model foods was positively correlated with number of chews, muscle activity and jaw opening (Koç et al., 2014). Differences in food preparation, resulting in changes in food texture, were related to oral processing behavior (Forde et al., 2017). Foods that are pureed, mashed, cooked or shredded were consumed with higher eating rate compared to their unprocessed, raw versions. These studies demonstrate that physical-chemical, rheological and mechanical properties of solid foods determine oral processing behavior.

While numerous studies investigated oral processing behavior of solid foods, little is known about the relationships between rheological properties of liquid and semi-solid foods and oral processing behavior. Viscosity has been positively related to consumption time for a range of liquid foods (Chen & Lolivret, 2011). Sip size did not differ between various liquid foods differing in consistency (Steele & Van Lieshout, 2004) whereas number of swallows decreased with increasing consistency. Bite size of semi-solid foods was smaller compared to sip size of liquids (de Wijket al., 2008).

1.2.2 Product liking

Product liking has been positively related to consumption time, food intake, eating rate and negatively related to chewing time and number of chews (Bellisle & Le Magnen, 1980; Forde et al., 2017; Yeomans, 1996; Yeomans et al., 1997). Only few studies provide information about the effect size of liking on oral processing. As one might expect, higher food intake was observed for highly palatable pasta sauces (approximately 15-20%) compared to less palatable pasta sauces (Yeomans et al., 1997). Similar results were found for at home measurements with a 44% increase in meal intake for highly liked meals compared to less liked meals (de Castro et al., 2000a; de Castro et al., 2000b). Yeomans and colleagues even suggested that product liking stimulates appetite and eating rate (Yeomans et al., 1997). A negative correlation was found between chews per bite and liking of a large set of Asian foods (Forde et al., 2017). Bellisle and Le Magnen indicated that highly palatable foods were masticated 4.5s longer (26.2%) than foods of low palatability (Bellisle & Le Magnen, 1980). However, palatability was not quantified in this study. In contrast, several other studies did not find an effect of liking on oral processing behavior (Ferriday et al., 2016; Forde et al., 2013a; Michon et al., 2010). The foods we eat are generally well liked. Many studies included well-liked foods and thereby the differences in liking between foods were limited. Those studies tend to find no effect of liking on oral behavior. The studies that do tend to find an effect of liking on oral behavior are the ones that compared foods with very large differences in liking. To summarize, while studies are contra dictionary, it seems that food liking has little to no effect on oral behavior unless foods differing considerably in liking are masticated.

Frequent consumption of foods is also known to enhance product liking (Mahar & Duizer, 2007; Michon et al., 2010), probably due to increased familiarity of the food (Birch &

Lawley, 2014; Kim et al., 2015). Familiarity and liking were found to be highly correlated, with both a higher liking of familiar foods and lower liking of unfamiliar foods (Kim et al., 2015).

1.2.3 Consumer characteristics

In addition to the influence of food properties on oral processing behavior, consumer characteristics such as age, gender and ethnicity influence food oral processing behavior. A previous study clustered consumers based on individual chewing strategies of cheeses (Yven et al., 2012). Consumer clusters differed in how number of chewing cycles, consumption time and muscle activity were adopted in response to cheese properties. The ability to orally process foods can affect food intake and food choices especially among vulnerable populations, including older adults and consumers with decreased eating capability (N'Gom & Woda, 2002; Walls & Steele, 2004). It is therefore important to understand how consumer characteristics such as age influence oral processing behavior.

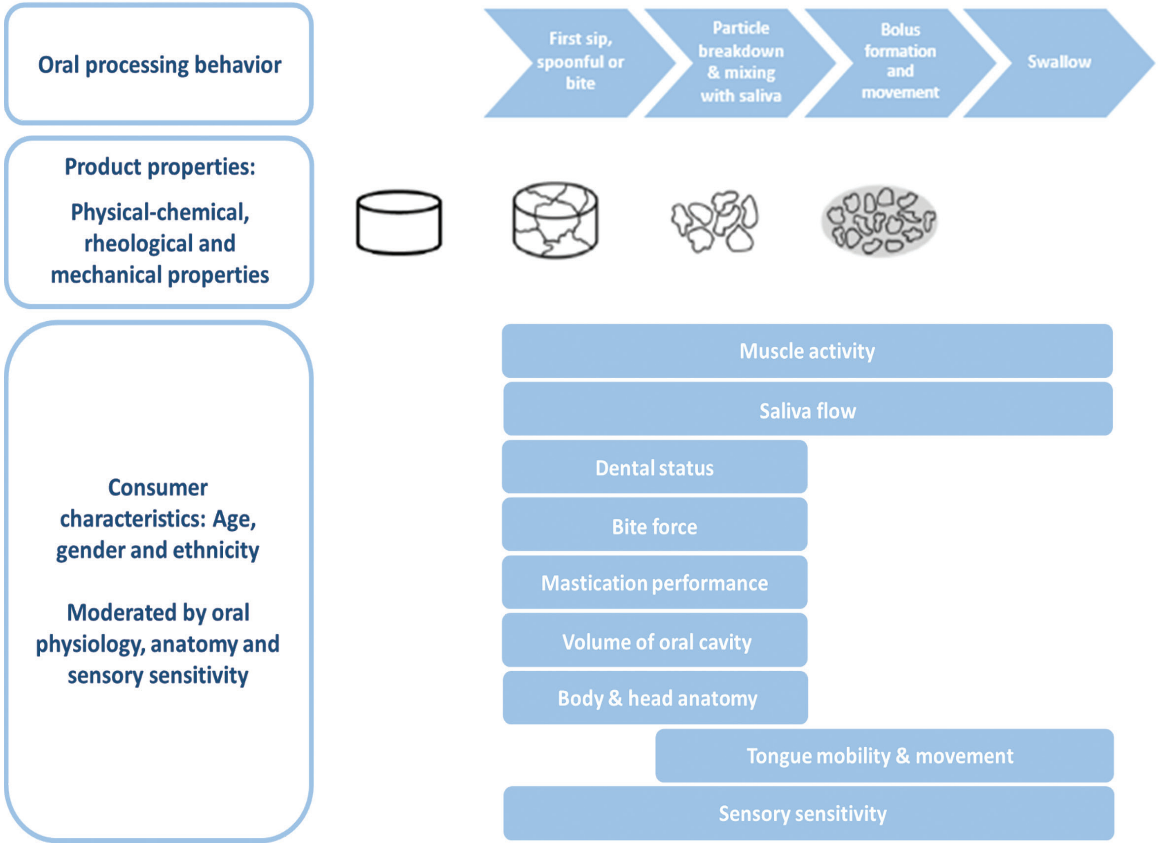

Figure 1.1: Schematic representation of different stages of food oral processing behavior, including (1) the effect of product properties including physical-chemical, rheological and mechanical properties on food breakdown and bolus formation during oral processing and (2) the effect of consumer characteristics moderated by oral physiology, anatomy and sensory sensitivity on oral processing behavior. Figure is adopted from Stieger and van de Velde (Stieger & van de Velde, 2013).

During ageing muscle mass and dental status decrease, which influences oral processing behavior (Mioche et al., 2004a). As mentioned before, efficient oral processing requires multiple factors working together. Several studies found that with ageing dental status, jaw muscle activity, bite force, tongue pressure, oral volume, saliva flow rate, maximum tongue pressure and tongue thickness decline (Affoo et al., 2015; Alsanei & Chen, 2014; Laguna et al., 2015a; Laguna et al., 2015b; Percival et al., 1994; Tamura et al., 2012; Vandenberghe-Descamps et al., 2016; Yeh et al., 1998; Youmans et al., 2009). Older adults have smaller volume of oral cavity, lower body weight, lower body height and a narrow face compared to young adults (Alsanei & Chen, 2014; Sorkin et al., 1999; Steen, 1988; Zhuang et al., 2010). Loss of teeth in older adults decreases the ease of chewing and oral health-related quality of life (Gerritsen et al., 2010; Walls & Steele, 2004). These changes in oral physiology and anatomy during ageing lead to an adaptation of oral processing behavior. Older adults consume foods with longer consumption time, need a higher number of chews and have a lower mastication efficiency and muscle activity per chew compared to younger adults (Kohyama et al., 2002; Mioche et al., 2004b; Peyron et al., 2004). The lower mastication efficiency results in older adults being less able to break down foods in smaller particles, therefore they increase consumption time and number of chews. While the effect of age on oral processing behavior in solid foods has been studied extensively, little is known about the effect of ageing on oral processing behavior of liquid and semi-solid foods. Oral processing behavior of liquid and semi-solid foods has not been compared between different age groups yet.

Gender affects oral processing behavior. Oral physiological differences between females and males seem to affect oral processing behavior. Males have higher maximum bite force, saliva flow rate, lip and cheek strength and chew foods with higher muscle activity than females (Clark & Solomon, 2012; Inoue et al., 2006; Julien et al., 1996; Nagasawa et al., 1997; Palinkas et al., 2010; Park & Shin, 2015; Percival et al., 1994). These oral physiological differences are expected to affect oral processing behavior. Males tend to be taller, weigh more and have an increased face size (Sorkin et al., 1999; Zhuang et al., 2010) than females. Males are known to have a higher masticatory frequency and therefore have a shorter chewing cycle duration than females (Nagasawa et al., 1997; Woda et al., 2006). Males consumed solid foods with shorter consumption time, less number of chews, larger bite size and higher eating rate compared to females (Hill & McCutcheon, 1984; Park & Shin, 2015). The effect of gender on oral processing behavior has been studied so far only in solid foods. Therefore, investigating the effect of gender on oral processing behavior of liquid and semi-solid foods will give new insights.

There has been an increasing interest in understanding product perception and oral processing behavior of consumers across the globe. Food companies want to know whether their products are orally processed and perceived equally by consumers living in different countries and belonging to different ethnic groups. Since sensory perception can be influenced by oral processing behavior (section 1.3), it is relevant to explore how country of living or ethnicity influence oral processing behavior of foods. The Asian population is considered an expanding market for European food producers due to the rapidly growing population (Chen, 2016; McKay, 2007; Seo et al., 2015). Differences in oral physiology and anatomy between Asian and European consumers could cause differences in food oral processing behavior. Ethnicity affected volume of oral cavity (Xue & Hao, 2006). Chinese consumers had a larger volume of oral cavity compared to Caucasian consumers from America and African Americans. Tongue dimensions differed between Europeans and Africans (Beghini et al., 2017). Asian adults had lower body height, lower body weight and wider faces compared to Caucasian adults (Collaboration N.R.F., 2016; Zhuang et al., 2010). Other physiological parameters such as saliva flow rate, dental status, mastication performance, muscle activity and bite force, which might be relevant for food oral processing behavior, have not been compared between consumers living in different countries or belonging to different ethnicities. Therefore, the effect of ethnicity on food oral processing behavior is not known.

Clearly, consumers characteristics are linked to oral physiology and anatomy. However, it remains unclear whether the consumers characteristics themselves or the physiology and anatomy parameters explain differences between individual consumers. Several studies have suggested oral physiology and anatomy are related to oral processing behavior, however these relationships have not been investigated systematically. Subjects with poor dental status masticated foods longer (Assad-Bustillos et al., 2019). Bite size has been positively related to lower dental arch size and BMI (Shiozawa et al., 2019). These studies suggest oral physiology and anatomy are related to oral processing behavior. However, these studies only investigated few physiological parameters in relation to oral processing behavior. Understanding of relationships between a wide range of oral physiology and anatomy parameters with oral processing behavior will give more insights in the underlying mechanisms of oral processing behavior.

1.3 How consumer phenotype affects sensory sensitivity

Sensory sensitivity has been suggested to be linked to sensory perception and consequently could affect oral processing behavior (Nachtsheim & Schlich, 2013). Changes in sensory sensitivity, for instance during ageing, can affect dietary behavior (Schiffman, 1993). Impaired taste and smell perception is known to decrease appetite (de Jong et al., 1999) and to increase consumption of sodium and sugar (Rolls, 1999). Taste acuity has been suggested to be affected by age, gender and ethnicity (Simpson et al., 2012).

During ageing, texture and taste sensitivity decline (Cowart et al., 1994; Kremer et al., 2007; Methven et al., 2012; Mojet et al., 2001; Stevens et al., 1998; Wiriyawattana et al., 2018). Gender impacts taste sensitivity, with females being more sensitive than males (Ahne et al., 2000; Gudziol & Hummel, 2007; Hyde & Feller, 1981; Landis et al., 2009; Michon et al., 2009; Pingel et al., 2010). Ethnicity is known to influence sensory perception and therefore could affect taste and texture sensitivity (Pedrotti et al., 2019). However, the effect of ethnicity on taste and texture sensitivity has not been studied yet.

1.3.1 Consumer's phenotype

Taste and texture sensitivity has been suggested to be influenced by physiological parameters and consumer phenotype, including saliva flow rate, Fungiform Papillae Density (FPD), lingual tactile thresholds and 6-n-propylthiouracil (PROP) taster status. Consumer phenotype can be defined as physical characteristics of the consumer that are genetically determined.

Saliva is essential during food consumption and perception by diluting food particles, digestion by salivary enzymes, transportation of flavor to taste buds and forming a smooth bolus for safe swallowing (Carpenter, 2012; Engelen et al., 2003; van Ruth et al., 1996). All these processes indicate that saliva has a large influence on sensory perception. Increased saliva flow rate has been related to increased fat perception of milks (Nachtsheim & Schlich, 2013). A positive relationship has been found between saliva flow and time to reach maximum sweetness of cherry-flavored gums, indicating that saliva flow affects flavor release (Guinard et al., 1997). Gender seems to impact saliva flow rate with females having lower saliva flow rate than males (Inoue et al., 2006; Percival et al., 1994). Ethnicity does not seem to influence saliva flow rate (Pedrotti et al., 2019; Santagiuliana et al., 2019). To summarize, saliva is essential during oral processing and might therefore play a role in sensory perception differences between consumers.

Texture perception and sensitivity has been suggested to depend on fungiform papillae density (FPD). Fungiform papillae are peripheral structures on the tongue including taste buds specialized in taste detection. Fungiform papillae density is known to be a good indicator of individual taste sensitivity (Miller Jr & Reedy Jr, 1990a). Sweetness, creaminess and saltiness perception has been found to be related to FPD (Hayes & Duffy, 2007; Miller Jr & Reedy Jr, 1990b). Multiple studies have found differences in FPD between genders and ethnicity (Bartoshuk et al., 1994; Fischer et al., 2013; Hayes et al., 2008; Miller Jr, 1986; Pedrotti et al., 2019; Prutkin et al., 2000; Santagiuliana et al., 2019), while other studies found no differences in FPD between genders and ethnicity (Cattaneo et al., 2020; Hayes & Duffy, 2007; Masi et al., 2015; Shen et al., 2016). Therefore, it remains unclear what the role of FPD is in sensory sensitivity and how consumers differ with regard to FPD.

During the formation of the bolus, the tongue and palate detect the texture of the food. Mechanoreceptor nerve fibers located on the tongue and palate surface detect tactile sensations (Hiiemae & Palmer, 2003). Texture sensitivity has been suggested to be related to tactile thresholds, however these relationships have not been confirmed yet (Aktar et al., 2015a, 2015b). Tactile sensations have been suggested to differ between consumers, however, lingual tactile sensitivity of the tongue did not differ between gender (Komiyama & De Laat, 2005) and ethnicity (Komiyama et al., 2007; Santagiuliana et al., 2019).

Individual bitter sensitivity has a large effect on food preferences and perception. The sensitivity to taste bitter compounds has often been investigated using 6-n-propylthiouracil (PROP) (Bakke & Vickers, 2008; Masi et al., 2015). Consumers can be classified into three segments based on their sensitivity to PROP, non-tasters do not perceive PROP as bitter; medium tasters perceive PROP as moderately bitter; supertasters perceive PROP as extremely bitter. PROP taster status is linked to sweet and bitter sensitivity (Chang et al., 2006). PROP taster status differs between genders, with females being more often a supertaster than males (Bartoshuk et al., 1994). The distribution of PROP taster status in a population has been suggested to depend on ethnicity (Cattaneo et al., 2020; Tepper, 2008). However, this has not been confirmed by other studies (Genick et al., 2011; Santagiuliana et al., 2019).

Understanding taste and texture sensitivity in relation to consumer's phenotype will give more insights in product perception differences between consumers. Differences in sensitivity and phenotype could be potentially linked to oral processing behavior.

1.4 Thesis aim and outline

The aim of this thesis was to better understand food oral processing behavior of consumers varying in age, gender and ethnicity based on oral physiology, anatomy and sensory sensitivity. This thesis (Figure 1.2) provides new insights into inter-individual variation in oral processing behavior. Secondly, this thesis systematically investigates the relationship of oral processing behavior with oral physiology and anatomy.

Chapter 2 aimed to understand the influence of rheological and mechanical properties of foods on oral processing behavior of liquids, semi-solid and solid foods. Secondly, the influence of product liking, frequency of consumption and familiarity on oral processing behavior was quantified in 18 foods using video recordings.

The aim of **chapter 3** was to investigate the influence of age, gender, ethnicity and eating capability on oral processing behavior of liquid, semi-solid and solid foods. Participants varying in age (young vs old), gender (female vs male), ethnicity (Dutch vs Chinese) and eating capability (good vs poor) consumed 18 liquid, semi-solid and solid foods and oral processing behavior was quantified using video recordings.

Chapters 4 and 5 explored the contribution of oral physiology and anatomy to oral processing behavior in consumer groups differing in age and ethnicity. For Dutch adults and older adults (**chapter 4**) and Chinese adults and older adults (**chapter 4 & 5**) the same set of oral physiological and anatomical parameters was assessed, including saliva flow rate, mastication performance, volume of oral cavity, dental status and head anatomy. Oral processing behavior of three solid foods was quantified using video recordings.

Chapter 6 investigated texture and taste sensitivity and consumer's phenotype. Thickness, firmness and sweetness sensitivity were assessed in model foods and consumer's phenotype quantified in terms of saliva flow rate, FPD, lingual tactile threshold and PROP taster status in consumers varying in gender and ethnicity.

In **chapter 7**, the overall results and their implications are discussed and suggestions for future research are given.

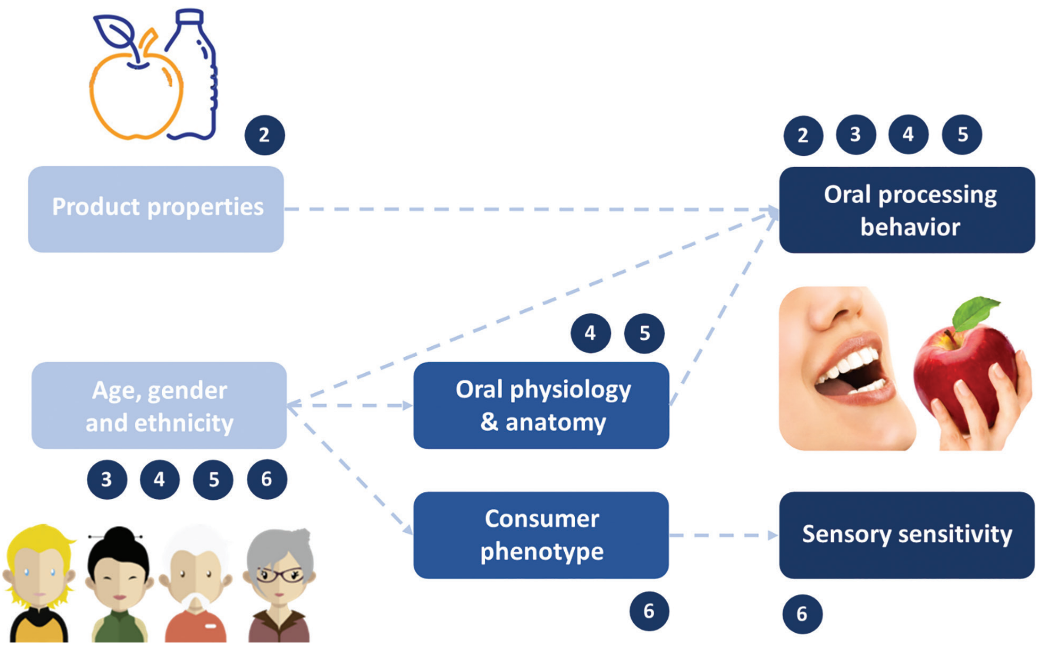

Figure 1.2: Schematic overview of this thesis. Numbers indicate chapters in this thesis.

CHAPTER 2

2

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

Monica G. Aguayo-Mendoza*
Eva C. Ketel*
Erik van der Linden
Ciarán G. Forde
Betina Piqueras-Fiszman
Markus Stieger

* Authors contributed equally to the work

Published in Food Quality and Preference (2019) 71, 87-95.

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.

2.1 Introduction

Oral processing is the manipulation and break down of food inside the mouth up to the moment of swallowing (Chen, 2009; Foegeding, 2007; Stieger & van de Velde, 2013). 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 (Chen, 2009; Hutchings & Lillford, 1988).

Foods are processed differently in the mouth depending on their physical-chemical, rheological and mechanical properties (Abhyankar et al., 2011; Chanasattru et al., 2002; Chen & Stokes, 2012; Hiiemae, 2004). 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 (van Aken et al., 2007; van Vliet et al., 2009). 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 (Hiiemae et al., 1996).

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 (Ferriday et al., 2016; Forde et al., 2017; Forde et al., 2013a; Hiiemae et al., 1996; Koç et al., 2014). These studies showed that the number of chews and bite size vary depending on the food item consumed (Hiiemae et al., 1996). Hardness of soft-solid model food gels was positively correlated with number of chews, muscle activity, and jaw opening amplitude (Koç et al., 2014). 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 (Forde et al., 2013a). Eating rate represents the amount of food eaten per unit of time and has been associated with caloric intake (van den Boer et al., 2017). Forde et al. (2017) found that the way the food is prepared significantly influenced eating rate. 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 (Chen & Lolivret, 2011; de Wijk et al., 2008; Steele & Van Lieshout, 2004). Chen & Lolivret (Chen & Lolivret, 2011) found that apparent shear viscosity was positively correlated with perceived difficulty to swallow and longer residence time in mouth of liquid foods. de Wijk et al. (de Wijk et al., 2008) 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 liquids. Steele and Lieshout (Steele & Van Lieshout, 2004) found that when comparing bite size within one food category, liquid foods, bite/sip size was not affected by product consistency. 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 (Campbell et al., 2017; Woda et al., 2006). However, only a few studies account for food liking and/or familiarity when assessing oral processing behavior (Bellisle & Le Magnen, 1980; Ferriday et al., 2016; Forde et al., 2017; Forde et al., 2013a). Forde et al. (Forde et al., 2017) and Bellisle and Le Magnen (Bellisle & Le Magnen, 1980) showed that for solids, liking was negatively correlated with chews per bite and chewing time. However, other studies (Ferriday et al., 2016; Forde et al., 2013a) showed no relationship between liking and oral processing behavior. Yet, the relationship between liking and familiarity for liquid and semisolid 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.

2.2 Material and methods

2.2.1 Test foods

Eighteen commercially available foods were used and classified into three categories: liquid/drinkable, semi-solid/spoonable, and solid/chewable foods (Table 2.1). 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.

Table 2.1: 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	

2.2.2 Instrumental analyses

2.2.2.1 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 2.1). Though the food temperature may vary during oral processing, it was assumed that the temperature of liquid and semisolid 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}($\eta_{1s^{-1}}$), 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 (Wagner & Kretzschmar, 2007), and used for water and tea. Viscosity of sparkling water was assumed to be the same as viscosity of still water.

2.2.2.2 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. Processed cheese (Kiri) was used in its original shape, a block of 37×37×14 mm. 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 1 mm/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 (σ15%) were calculated by averaging over the replicate measurements.

2.2.3 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 (Fontijn-Tekamp et al., 2004; Sánchez-Ayala et al., 2014) and only subjects considered with good mastication efficiency, defined as subjects with a median particle size<3.5 mm, were included. Eating Assessment Tool 10 (Belafsky et al., 2008), 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).

2.2.4 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 two hours before the sessions. Sessions were held between 13:00 – 17:00 h and lasted 30 min. Participants consumed a total of 18 test foods divided over three sessions. In each session, participants consumed six test foods. 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 (section 2.5). 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 100 g portions in a plastic cup and subjects were instructed to drink the liquid products directly from the cup. Spoonable products were served in 100 g portions in a bowl and subjects had to use a table spoon to consume them. Finally, chewable foods were served in 50 g 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.

2.2.5. 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 2.2 shows the parameters describing oral processing behavior obtained for each product category.

Table 2.2: Parameters describing oral processing behavior of 18 foods belonging to three categories.

Variables	**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)			●

2.2.6 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.

2.2.7 Statistical data analysis

All data analyses were done with SPSS (IBM SPSS statistics, version 24). Data is presented as mean ± 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 (ηp 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.

2.3 Results

2.3.1 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 2.3. 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.

Table 2.3: 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.

The Young's modulus and stress needed to compress to 15% strain (σ15%) for solid, chewable foods are shown in Table 2.4. Young's modulus ranged from 0.28 kPa for tofu to 50.31 kPa for carrot. σ15% ranged from 4.42 kPa for tofu to 661.25 kPa for chocolate.

Table 2.4: 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

2.3.2 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 2.5. 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 10.6 g whereas chewable foods had an average bite size 4.8 g.

Table 2.5: 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 ($p < .05$).

		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
Drinkable	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
Spoonable	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	$6.0 \pm 1.1c$	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

2

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).

2.3.3 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 2.5. 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.

2.3.4 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 2.6).

Table 2.6: 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**
			Liquid and semi-solid foods				
Consistency K^a	-.880**	.750*	.853**	-.915**	-	-	-
Flow behavior index n	.891**	-.762*	-.848**	.921**	-	-	-
			Solid foods				
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 < .05 level and **correlation is significant at p < .001 level. [a] Variables were transformed into logarithmic scale.

Bite size of liquid and semi-solid foods was negatively correlated with product consistency K ($r = -.880$, $n = 10$, $p < .001$) (Fig. 2.1a and Table 2.6) 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 ($r = -.899$, $n = 7$, $p = .006$) (Fig. 2.2a and Table 2.6).

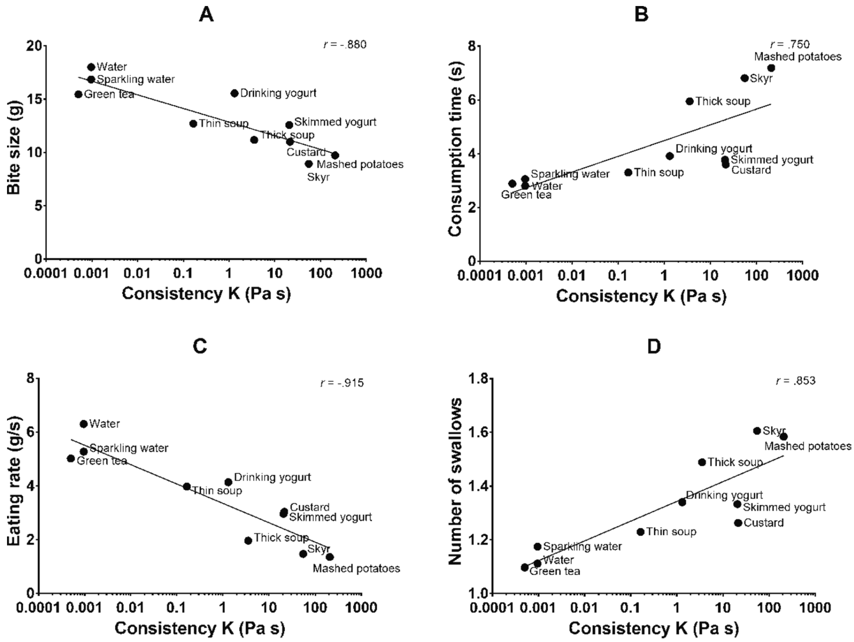

Figure 2.1: Correlations between consistency K and (A) bite size, (B) consumption time, (C) eating rate and (D) number of swallows of liquid and semi-solid foods.

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) (Fig. 2.1b and Table 2.6). Fig. 2b shows that for chewable foods, with increasing σ15% 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) (Fig. 2.2d). Likewise, a trend was observed with regards to number of chews and σ15%. With increasing σ15%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.

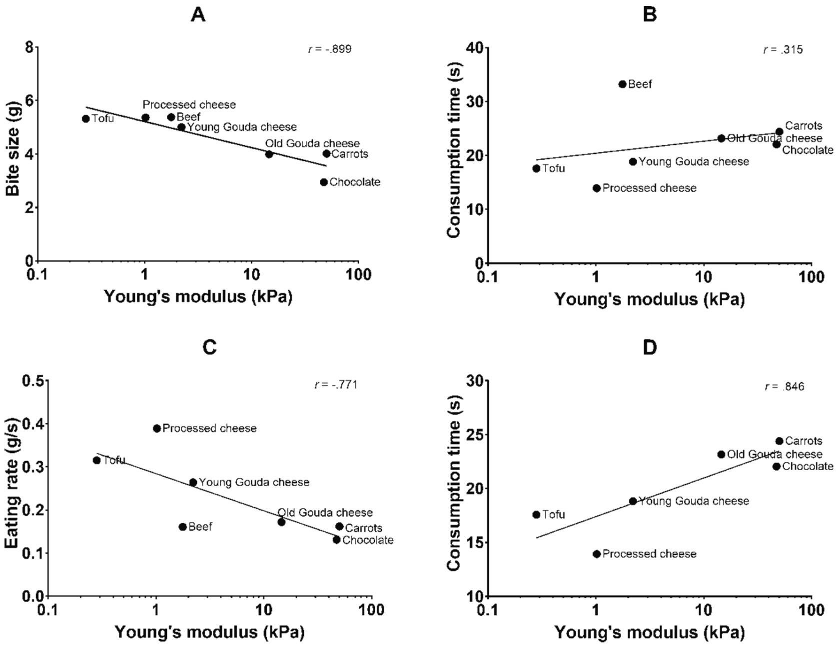

Figure 2.2: Correlations between Young's modulus and (A) bite size, (B) consumption time of all products, (C) eating rate and (D) consumption time excluding beef meat.

Eating rate was negatively correlated with product consistency for liquid and semi-solid foods and σ15% 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 (Figs. 2.1c and 2.2c and Table 2.6). 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.

2.4 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 (σ15%) for chewable foods. In line with our results are the results of de Wijk et al. (de Wijk et al., 2008) who investigated the effect of viscosity on bite size of one liquid (milk) and one semisolid food (custard). de Wijk et al. (de Wijk et al., 2008) 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 drank 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 (σ15%) although bite size decreases. Engelen, Fontijn-Tekamp, and van der Bilt (Engelen et al., 2005) investigated oral processing behavior of solid foods. 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 σ15% 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 (Mioche et al., 2002b). 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, Bourdiol, and Monier (Mioche et al., 2003). 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 (Koç et al., 2014) indicating that people unconsciously adapt the number of chews to the mechanical properties of food.

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 (Forde et al., 2017; Forde et al., 2013a; van den Boer et al., 2017; Viskaal-van Dongen et al., 2011) 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. 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 (Bolhuis et al., 2014; McCrickerd et al., 2017). 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 σ15% 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 0.7 s and 1.4 chews/s, respectively. These values are in line with previously reported results (Bellisle et al., 2000; Farooq & Sazonov, 2016). 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 (Jean, 2001). However, probably as consequence of the sensory feedback provided by the food bolus (Agrawal et al., 2000), 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 (Hiiemae, 2004; Okada et al., 2007). 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 (Chen & Lolivret, 2011). In the case of chewable foods, multiple swallows occurred since some parts of the bolus may be ready to swallow earlier than others (Hiiemae, 2004).

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 et al. (Ferriday et al., 2016), who showed that liking of solid foods had a small effect on bite size and eating rate. 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.

2.5 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.

Acknowledgments

The authors have declared that no competing interests exist. The research forms part of a project that is organised by TiFN, a publicprivate partnership on precompetitive research in food and nutrition and executed under its auspices. The public partners are responsible for the study design, data collection and analysis, decision to publish, and preparation of the manuscript. The private partners FrieslandCampina, Fromageries Bel and Unilever have contributed to the project through regular discussions. Co-funding for the project was obtained from the Top-Consortium for Knowledge and Innovation Agri&Food and the Netherlands Organisation for Scientific Research.

The authors thank Alvaro Garcia-Fuentes for his assistance during the development of the video recording analysis. We also thank Claudia Briseno-Ozumbilla and Philipp Fuhrmann for their assistance during the data collection.

CHAPTER 3

3

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

Eva C. Ketel*
Monica G. Aguayo-Mendoza*
René A. de Wijk
Cees de Graaf
Betina Piqueras-Fiszman
Markus Stieger

*Authors contributed equally to the work

Published in Food Research International (2019) 119, 143-151.

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, ranging from liquids, semisolids to solids, 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). Participants were video recorded during food consumption and six oral processing parameters extracted. 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 demonstrates 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.

3.1 Introduction

Oral processing behavior is the first stage of food digestion, which is affected by food properties and consumer characteristics (Chen, 2009). Physical-chemical, rheological and mechanical properties of foods strongly determine oral processing behavior (Chen & Stokes, 2012; Hiiemae, 2004). Forde et al. found large variations in number of bites, chews per bite and eating rate (g/s) for different solid, savoury meal components of European (Forde et al., 2013a, 2013b) and Asian foods (Forde et al., 2017). Faster eating rates (g/s) have been related to higher ad-libitum energy intakes and higher body mass index (Ohkuma et al., 2015). Eating rates (g/s) and food intake have been demonstrated to depend on food texture (Bolhuis et al., 2014; Forde et al., 2013a, 2013b; McCrickerd et al., 2017; Zijlstra et al., 2009). The ability to orally process foods can affect food intake and food choices among vulnerable populations, including elderly and consumers with decreased eating capability (N'Gom & Woda, 2002; Walls & Steele, 2004). 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 (Fogel et al., 2017b; Leong et al., 2011; McCrickerd & Forde, 2017; Robinson et al., 2014). 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 (Aguayo-Mendoza et al., 2019). 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 (Wee et al., 2018). 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 (Yven et al., 2012). 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

3

to differences in texture perception (Devezeaux de Lavergne et al., 2015). 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 (Mioche et al., 2004a). Essential oral functionalities, such as dental status, jaw muscle activity, bite force, tongue pressure and oral volume, decrease with age and affect oral processing (Alsanei & Chen, 2014; Laguna et al., 2015a, 2015b; Percival et al., 1994; Yeh et al., 1998; Youmans et al., 2009). 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 (Mioche et al., 2004b). 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 (Kohyama et al., 2002; Peyron et al., 2004). Elderly tend to have fewer teeth, influencing both the ease and comfort of chewing and the oral health-related quality of life (Gerritsen et al., 2010; Walls & Steele, 2004). Few studies investigated oral processing behavior of liquid foods either in young adults (Derks et al., 2016) or elderly (Jacobsson et al., 2000). 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 (Clark & Solomon, 2012; Julien et al., 1996; Palinkas et al., 2010; Percival et al., 1994), which can facilitate oral processing behavior. Males displayed higher muscle activities and masticatory frequency when chewing solid foods than females (Nagasawa et al., 1997; Park & Shin, 2015; Woda et al., 2006). Males showed shorter chewing cycle durations (Nagasawa et al., 1997; Youssef et al., 1997), shorter meal durations, lower number of chews, larger bite sizes (g) and higher eating rates (g/s) (Hill & McCutcheon, 1984; Park & Shin, 2015) than females for a variety of solid foods. 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 (Xue & Hao, 2006). Chinese 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 (Laguna & Chen, 2016). 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 (Laguna & Chen, 2016; Laguna et al., 2016; Laguna et al., 2015a). 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 (Belafsky et al., 2008). 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 (Humbert & Robbins, 2008). Dysphagia patients are considered to display unhealthy swallowing behavior (Humbert & Robbins, 2008), 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 (Aguayo-Mendoza et al., 2019).

3.2 Materials & method

3.2.1 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 (Fontijn-Tekamp et al., 2000). Participants chewed 14 cubes of Optosil (5×5×5 mm; 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 ||) 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<3.5 mm. Swallowing problems were self-assessed by the EAT-10, a questionnaire with 10 statements on swallowing problems (Belafsky et al., 2008). 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).

3.2.2 Foods

Participants consumed 18 commercially available foods covering a wide range of physical properties, classified as liquid (drinkable), semisolid (spoonable) or solid (chewable) (Table 3.1). 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. Fifty grams 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 50 g 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. 50 g 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. 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 (Aguayo-Mendoza et al., 2019).

3.2.3 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.

Table 3.1: 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	100 g 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	100 g 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	50 g 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.

3.2.4 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 (Aguayo-Mendoza et al., 2019; van Eck et al., 2019). 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 zerocrossing 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 be to significant (Table 3.2), including consumption time and chews per bite with a Pearson correlation of 0.943 ($p < .001$). Interrelationships between oral processing parameters were previously described (Fogel et al., 2017a).

3.2.5 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, 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<3.5 mm, n=103) and a group with low mastication efficiency (=< 50% of masticated particles had an average size of<3.5 mm, 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.

3.3 Results

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

Table 3.3 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 7.0 s longer for consumption of chewable foods (Cohen's d = 3.4), 1.3 s longer for consumption of drinkable foods (Cohen's d = 2.4) and 0.8 s 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 3.8 g 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 (Fig. 3.1A and Table 3.3) 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.

Table 3.2: 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 3.3: 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	F (Cohen's d)	Young	Elderly	F (Cohen's d)	Young	Elderly	F (Cohen's d)
Consumption time (s)	2.9 ± 0.5	4.4 ± 0.8	18.8 (2.4)***	5.5 ± 0.9	6.3 ± 1.3	16.8 (0.8)**	18.5 ± 1.6	25.5 ± 2.5	11.3 (3.4)***
Bite size (g)	12.7 ± 0.3	16.5 ± 0.5	4.4 (8.9)*	8.9 ± 0.3	11.3 ± 0.5	0.3 (6.1)	4.5 ± 0.1	5.1 ± 0.2	0.5 (3.6)
Number of swallows (-)	1.3 ± 0.1	1.3 ± 0.2	0.8 (0.0)	1.5 ± 0.2	1.5 ± 0.3	0.1 (0.3)	1.8 ± 0.1	1.8 ± 0.2	0.3 (0.1)
Eating rate (g/s)	5.8 ± 0.2	5.0 ± 0.3	6.7 (2.6)*	2.52 ± 0.2	2.45 ± 0.3	9.1 (0.3)**	0.3 ± 0.01	0.2 ± 0.01	12.6 (4.0)**
Chews per bite (-)	-	-	-	-	-	-	25.9 ± 2.1	35.8 ± 3.3	10.4 (3.7)**
Chewing rate (chews/s)	-	-	-	-	-	-	1.4 ± 0.01	1.4 ± 0.01	0.1 (0.0)

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

Table 3.4: 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)	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)	20.3 ± 1.7	21.5 ± 2.1	0.0 (0.7)
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)***	4.1 ± 0.1	5.4 ± 0.2	7.9 (8.5)***
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)	1.9 ± 0.1	1.8 ± 0.2	0.2 (0.8)
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)	0.2 ± 0.01	0.3 ± 0.01	6.9 (6.0)***
Chews per bite (-)	-	-	-	-	-	-	27.7 ± 2.2	31.0 ± 2.8	0.0 (1.3)
Chewing rate (chews/s)	-	-	-	-	-	-	1.4 ± 0.01	1.4 ± 0.02	0.2 (4.0)

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

Table 3.5: 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)	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)**	22.7 ± 1.6	17.3 ± 2.4	0.0 (2.8)
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)***	5.3 ± 0.1	3.5 ± 0.2	10.2 (10.7)***
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)	1.9 ± 0.1	1.7 ± 0.2	0.0 (0.7)
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)***	0.3 ± 0.01	0.2 ± 0.01	7.6 (7.0)***
Chews per bite (-)	-	-	-	-	-	-	31.7 ± 2.1	24.1 ± 3.2	0.0 (2.8)
Chewing rate (chews/s)	-	-	-	-	-	-	1.4 ± 0.01	1.4 ± 0.03	0.2 (2.0)

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

Table 3.6: Mean values and SE for parameters describing oral processing behavior of consumers with low (=< 50% of masticated particles had an average size of < 3.5 mm, n = 32) and high (> 50% of masticated particles had an average size of < 3.5 mm, 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)	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)	21.0 ± 2.2	20.8 ± 1.7	0.8 (0.1)
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)	4.8 ± 0.2	4.6 ± 0.1	0.8 (1.0)
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)	1.8 ± 0.2	1.8 ± 0.1	1.5 (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)	0.3 ± 0.01	0.3 ± 0.01	0.0 (1.0)
Chews per bite (-)	-	-	-	-	-	-	28.9 ± 3.0	29.4 ± 2.2	1.0 (0.2)
Chewing rate (chews/s)	-	-	-	-	-	-	1.4 ± 0.02	1.4 ± 0.01	0.2 (4.0)

Table 3.7: 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)	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)	21.2 ± 1.2	19.8 ± 3.8	0.1 (0.6)
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)	4.8 ± 0.1	4.4 ± 0.3	0.0 (2.2)
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)	1.8 ± 0.1	1.9 ± 0.3	0.0 (0.4)
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)	0.3 ± 0.01	0.3 ± 0.02	0.0 (0.7)
Chews per bite (-)	-	-	-	-	-	-	29.1 ± 1.6	29.5 ± 5.1	0.2 (0.1)
Chewing rate (chews/s)	-	-	-	-	-	-	1.4 ± 0.01	1.5 ± 0.03	0.2 (3.5)

3.3.2 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 3.4. 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 3.8 g larger sip size for drinkable foods (Cohen's d = 9.5), 3.3 g larger average bite size (g) for spoonable foods (Cohen's d = 8.9) and 1.3 g 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 (Fig. 3.1B and Table 3.4). 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.

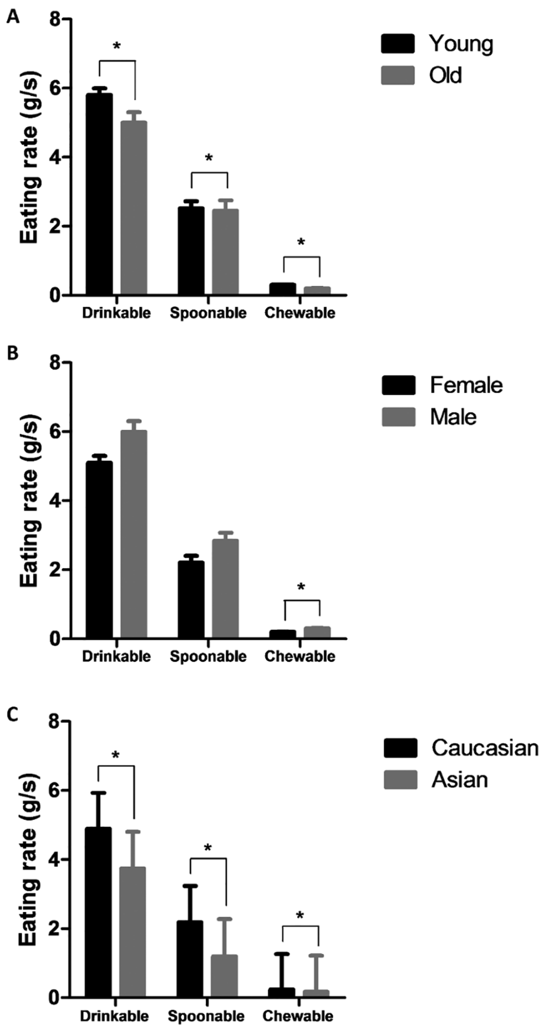

Figure 3.1: Eating rate (g/s) for the drinkable, spoonable and chewable food for the various consumer groups, (A) Comparison between young (n = 93, 18-30 yrs) vs. elderly consumers (n = 31, > 60 yrs), (B) female (n = 86) vs. male (n = 49) consumers and (C) Dutch, Caucasian (n = 93) vs. Chinese, Asian (n = 42) consumers.

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

Table 3.5 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 4.8 g smaller for Chinese, Asian compared to Dutch, Caucasian consumers (Cohen's d = 11.2). Average bite size (g) of spoonable foods was 3.8 g smaller for Chinese, Asian compared to Dutch, Caucasian consumers (Cohen's d = 9.7) and average bite size (g) of chewable foods was 1.8 g smaller for Chinese, Asian compared to Dutch, Caucasian consumers (Cohen's d = 10.7). Ethnicity significantly affected eating rate (g/s) (Fig. 3.1C and Table 3.5) 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.

3

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

Tables 3.6 and 3.7 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 <3.5 mm, n=103) and low mastication efficiency (=< 50% of masticated particles had an average size of <3.5 mm, 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.

3.3.5 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.

3.4 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 (Kohyama et al., 2002; Mioche et al., 2004a; Peyron et al., 2004). 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 neglible 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 (Mioche et al., 2004a). 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 (Kohyama et al., 2002; Mioche et al., 2004b; Peyron et al., 2004). 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 (Alsanei & Chen, 2014). 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 (Hill & McCutcheon, 1984; Park & Shin, 2015). Park and Shin (Park & Shin, 2015) found larger bite size (g) and higher eating rate (g/s) for males than females. 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 (Aguayo-Mendoza et al., 2019). 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 (Park & Shin, 2015), 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 (Palinkas et al., 2010; Percival et al., 1994). 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 (Bakke et al., 1990; Kamegai et al., 2005). 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 males (Henry et al., 2018).

Henry et al. found a positive association between eating rate (g/s) and basal metabolic rate (BMR), 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 American Caucasian consumers (Xue & Hao, 2006). 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 (Herman et al., 2003). As Asian cultures are known to be more group-focused compared to the individual-focused Western cultures (Triandis, 1989), 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 (Sun et al., 2015). In the current study, spoonable foods were consumed using spoons and chewable foods where consumed by most participants using their hands (chocolate, carrots, tofu and all cheeses) of using fork and knife (beef, noodles). Drinking from a cup and eating with a spoon is as common for

Chinese Asians as for Dutch Caucasians. 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 is 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.

3.5 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.

Acknowledgements

The authors have declared that no competing interests exist. The project is funded by TiFN, a public - private partnership on precompetitive research in food and nutrition. The public partners are responsible for the study design, data collection and analysis, decision to publish, and preparation of the manuscript. The private partners have contributed to the project through regular discussion. The private partners are Royal FrieslandCampina, Fromageries Bel and Unilever. This research was performed with additional funding from the Top Consortia for Knowledge and Innovation of the Dutch Ministry of Economic Affairs.

The authors would like to thank Claudia Montserrat Briseno Ozumbilla and Kysha Kraaijvanger for their help during data collection.

CHAPTER 4

4

Relating oral physiology and anatomy of consumers varying in age, gender and ethnicity to food oral processing behavior

Eva C. Ketel
René A. de Wijk
Cees de Graaf
Markus Stieger

Published in Physiology & Behavior (2020) 215, 112766.

Abstract

The aim of this study was to link parameters describing oral physiology and anatomy of consumers varying in age, gender and ethnicity to food oral processing behavior. Three groups of healthy consumers were compared: Dutch, Caucasian adults (18–30 yrs, n =32), Chinese, Asian adults (18–30 yrs, n =32) and Dutch, Caucasian older adults (65–85 yrs, n =32). Mastication performance, salivary flow rate (stimulated and unstimulated) and dental status were quantified to characterize oral physiology. Volume of oral cavity, tongue dimensions, facial anthropometry, height and weight were quantified to characterize anatomy. Oral processing behavior of three solid foods (carrot, cheese and sausage) was quantified by video recordings and eating rate (g/s), average consumption time (s), chews per bite (-) and average bite size (g) were determined. Dutch, Caucasian older adults had smaller volume of oral cavity, lower number of teeth and larger head width compared to Dutch, Caucasian adults. Chinese, Asian adults showed significantly higher mastication performance and larger head width compared to Dutch, Caucasian consumers, while dental status did not significantly differ between groups. Males had significantly larger volumes of oral cavity and larger head height and width compared to females. Dutch, Caucasian adults had a shorter average consumption time (s), less chews per bite and consumed the three foods with higher eating rate (g/s) compared to Dutch, Caucasian older adults. Chinese, Asian adults had a significantly longer average consumption time (s), more chews per bite, smaller average bite size (g) and lower eating rate (g/s) compared to Dutch, Caucasian adults. Twenty-one significant relationships were found between oral physiological and anatomical parameters and oral processing behavior. Body weight resulted in the largest β-values, indicating to be the anatomical parameter of largest influence on oral processing behavior. We conclude that only few oral physiological and anatomical parameters related with food oral processing behavior. We suggest that other factors, including cultural factors contribute to variation in food oral processing behavior between different consumer groups more than saliva flow, volume of oral cavity, mastication performance and dental status.

4.1 Introduction

Food oral processing behavior is known to be affected by food properties and consumer characteristics (Koç et al., 2013), but critical details are lacking which hamper the application to consumer segmentation. There has been an increasing scientific and industrial interest in understanding food oral processing to apply this knowledge to design palatable and healthier food products for specific consumer groups (Kim et al., 2015). During oral processing solid foods are broken down by chewing to form a bolus that can be safely swallowed (Chen, 2009). When consumers cannot process and handle foods in the oral cavity sufficiently, this can result in choking and reduced food intake (Gray-Stuart et al., 2017; Krop et al., 2018; Tada & Miura, 2014). By modifying food texture eating rate can be modified, which impacts food intake (Bolhuis et al., 2014; Forde et al., 2013a, 2013b; Ohkuma et al., 2015). Hence, foods for vulnerable consumers can be developed by modifying texture. Therefore, it is important to better understand the oral processing behavior of different consumer groups.

Food oral processing behavior is strongly related to rheological and mechanical properties of foods (Aguayo-Mendoza et al., 2019). Eating rate and bite size of liquid and semi-solid foods are mainly related to the rheological properties of foods such as its viscosity. Eating rate and bite size of solids foods have been related to mechanical food properties such as modulus, stress needed to compress foods to a certain strain and instrumental texture properties obtained by texture profile analysis (TPA) (Aguayo-Mendoza et al., 2019; Wee et al., 2018). Several suggestions have been made to explain the variation in oral processing behavior. Chen suggested that the oral individuality should not be underestimated and suggests that gender, age, race and health status influence texture perception (Chen, 2009). Consumer characteristics such as age, gender and ethnicity also impact oral processing behavior.

Ageing can impact food oral processing behavior by a decline in dental status and changes in oral physiology (Ketel et al., 2019; Kohyama et al., 2002; Mioche et al., 2004b; Peyron et al., 2004). A decrease in number of teeth has been found to impact mastication performance of older adults and is associated with an increase in number of chewing cycles until swallowing (Fontijn-Tekamp et al., 2004; Ikebe et al., 2011; van der Bilt et al., 1993). The decline in muscle forces for older adults consumers also impacts eating behavior by an increase in chewing duration and number of chews (Kohyama et al., 2002; Mioche et al., 2004b; Peyron et al., 2004). Aging is associated with a decrease in salivation (Affoo et al., 2015; Percival et al., 1994; Vandenberghe - Descamps et al., 2016; Yeh et al., 1998), bite force (Laguna et al., 2015a), tongue pressure (Alsanei & Chen, 2014; Laguna et al., 2015a; Youmans et al., 2009), tongue thickness (Tamura et al., 2012), volume of oral cavity (Alsanei & Chen, 2014). These physiological parameters might contribute to food oral processing behavior and a decreased functionality with increasing age might impair effective oral processing behavior. Oral functionalities such as mastication performance and swallowing problems might also affect oral processing behavior and are therefore important to consider. Changes in anatomy during ageing, including a decrease in body height and weight and narrowing of face can also impact oral processing behavior (Sorkin et al., 1999; Steen, 1988; Zhuang et al., 2010). Numerous studies investigated the effect of age on oral physiology (Affoo et al., 2015; Alsanei & Chen, 2014; Laguna et al., 2015a; Percival et al., 1994; Tamura et al., 2012; Vandenberghe-Descamps et al., 2016; Yeh et al., 1998; Youmans et al., 2009). However, only few studies investigated the link between oral physiological parameters such as dental status and mastication efficiency with food oral processing behavior. To better understand the influence of age on the link between physiology and food oral processing, further studies are needed.

Gender also impacts oral processing behavior. Males consume foods with larger bite size and at higher eating rate compared to females (Hill & McCutcheon, 1984; Ketel et al., 2019; Park & Shin, 2015). Males display higher masticatory frequencies (Woda et al., 2006) and shorter consumption times (Ketel et al., 2019; Nagasawa et al., 1997; Park & Shin, 2015) than females. These differences in oral processing behavior between males and females might be linked to the difference in energy requirements due to differences in basal metabolic rate (BMR) (Henry et al., 2018). We hypothesize that differences in oral processing behavior can be linked to differences oral physiology between genders. Males display higher bite force (Julien et al., 1996; Palinkas et al., 2010), salivary flow (Inoue et al., 2006; Percival et al., 1994), cheek strength (Clark & Solomon, 2012) and masticatory performance (Shiga et al., 2012) than females. Males tend to have larger anatomical features, including body height, body weight and face size (Sorkin et al., 1999; Zhuang et al., 2010). Other physiological parameters might also differ between genders such as oral cavity volume. To the best of our knowledge the impact of differences in oral physiology between male and female consumers has not yet been linked to food oral processing behavior.

Ethnicity also influences oral processing behavior. Chinese, Asian adults displayed lower eating rate due to smaller bite size compared to Dutch, Caucasian adults (Ketel et al., 2019). Differences in oral physiology and eating culture could explain differences in oral processing behavior between different ethnicities or nationalities. Oral physiology of Asian consumers has not been compared extensively to Caucasian consumers. Xue and Hao found that the oral cavity volume of Chinese Asian consumers was larger compared to Caucasian Americans (Xue & Hao, 2006). These results from two separate studies suggest an inverse relation between volume of oral cavity and bite size. Tongue dimensions have also been suggested to be influenced by ethnicity. Tongue length of African ancestry was significant longer than tongue length of European ancestry (Beghini et al., 2017). However, no studies have investigated tongue dimensions of Caucasian compared to Asian consumers. Anatomical features of humans with different ethnicities have been extensively studied. Asians have a lower body height and body weight and wider face compared to Caucasians (Collaboration N.R.F., 2016; Zhuang et al., 2010). Cultural factors might also impact oral processing behavior via differences in consumption context, importance of food consumption and cutlery use (Herman et al., 2003; Ma, 2015).

The aim of this study was to link parameters describing oral physiology and anatomy of consumers varying in age, gender and ethnicity to food oral processing behavior of solid foods. Several physiological (salivary flow rate, mastication performance, dental status, self-reported swallowing problems) and anatomical parameters (volume of oral cavity, tongue dimensions, facial anthropometry, height and weight) were quantified in Dutch, Caucasian adults, Chinese, Asian adults and Dutch, Caucasian older adults. Oral processing behavior (consumption time, bite size, eating rate, number of chews) of three solid foods (carrot, sausage, cheese) was quantified and regression analysis performed.

4.2 Materials & method

4.2.1 Participants

Three groups of healthy consumers were recruited including 32 Dutch, Caucasian adults (20 females, mean age of 21.5 ± 1.9 yrs), 32 Dutch, Caucasian older adults (20 females, mean age of 70.4 ± 4.3 yrs) and 32 Chinese, Asian adults (20 females, mean age of 24.2 ± 2.1 yrs). The Dutch, Caucasian adults and older adults had Dutch nationality and Caucasian ethnicity. The Chinese, Asian Adults all had Chinese nationality and Asian ethnicity. Dutch, Caucasian and Chinese, Asian adults were included only when no teeth were missing. Dutch, Caucasian older adults were included only when two or less teeth were missing. Other inclusion criteria were BMI between 18.5 and 25 kg/m2 and normal taste and smell capabilities. An inclusion questionnaire was used to ensure that the participants fit to all inclusion criteria. Participants were recruited via a study website, posters on the University Campus, social media and a participant database. Participants were invited to an information meeting and gave written informed consent to participate in the study. Participants received a financial reimbursement for participation. The study was approved by the medical ethical committee of Wageningen University (NL62694.081.17).

4.2.2 Oral physiological and anatomical parameters

Four oral physiological parameters (mastication performance, salivary flow, dental status, self-reported swallowing problems) and four anatomical parameters (volume of oral cavity, tongue dimensions, facial anthropometry, height and weight) were quantified by a trained researcher during one test session of 60 min. Participants were instructed to not eat, drink coffee or chew chewing gum two hours before the start of the test session.

4.2.2.1 Mastication performance

Mastication performance was determined as previously described (Wium et al., 1997). Participants' ability to masticate a solid model food was quantified with the following procedure. Participants were instructed to chew 20 times on 14 cubes of Optosil (size of each cube 5 × 5 × 5 mm; total weight ~3.5 g). Optosil is an artificial test material often used as standardized model material to assess mastication performance (Fontijn-Tekamp et al., 2000). After 20 chewing cycles participants expectorated the broken down Optosil particles. Participants were asked to rinse their mouth with water and spit this out again to ensure the majority of particles were expectorated. Particles were collected and dried overnight. After drying particles were separated manually in a petri-dish without further breaking particles. A black-white scan was made using a scanner (Canon 9000F Mark ||) and median particle size (X50) was determined using ImageJ (National Institutes of Health, USA, version 1.52a).

4.2.2.2 Salivary flow rate

Stimulated and unstimulated salivary flow rate were determined. Five minutes before the measurements participants were not allowed to drink and a short break was included between two measurements. For the measurement of unstimulated salivary flow rate, participants were asked to spit out their unstimulated saliva every 30 s for 5 min into a pre-weighed plastic tube. The researcher indicated every time point when the participant needed to spit out saliva. The cup was weighed before and after the test session and unstimulated saliva flow rate (mL/min) was obtained. A saliva density of 1 g/mL was assumed. A second saliva collection was done to determine stimulated saliva flow rate. Participants were asked to spit out their saliva every 30 s for 5 min while chewing on a piece of Parafilm (5 × 5 cm). Chewing on the Parafilm mimics mastication behavior and provides mechanical stimulation inducing salivation (Mackie & Pangborn, 1990). Stimulated saliva flow rate (mL/min) was determined by weighing the cup before and after the measurement.

4.2.2.3 Dental status

The dental status was determined by the researcher by counting total number of teeth, number of molars, number of wisdom teeth and determining the occlusion status. Occlusion status was classified according to Angle (Angle, 1899) into one of four categories: malocclusion class 1, 2, 3 or normal occlusion. Malocclusion class 1 included participants with the presence of a cross-bite, teeth are tilted towards cheek or tongue; or an open bite, upper and lower teeth cannot make contact; or a deep bite, upper teeth cover the lower teeth. Malocclusion class 2 included participants with the presence of an overjet indicated by the upper teeth proclining the lower teeth with more than 4 mm. Malocclusion class 3 included participants with the presence of under-bite, indicated by the proclining of the lower teeth. The fourth category of the occlusion status included participants with none of the above mentioned deviations, in other words with normal occlusion.

4.2.2.4 Self-reported swallowing problems

Participants filled in the EAT-10 questionnaire consisting of 10 statements on swallowing problems (Belafsky et al., 2008). For every statement, participants indicated the presence and severity of swallowing problems from 0 (no problems) to 4 (severe problems) points. A total score was calculated by the sum of all 10 statements. A total score below 3 indicates no to minor swallowing difficulties. A score of 3 or larger indicates abnormal swallowing difficulties.

4.2.2.5 Volume of oral cavity

The volume of the oral cavity was determined with a water-retaining test (Alsanei & Chen, 2014). Participants received a cup with 500 mL water and were instructed to keep as much water in the oral cavity as possible. Participants had to seal their lips and inflate their cheeks with water. When participants reached the maximum volume of water in their mouth, participants spat out the water in another cup. Spit out cups were weighted before and after the measurement and the differences was taken as a measure of the volume of the oral cavity (mL). It should be noted that the volume of the oral cavity determined with this method depends on (1) the anatomical volume of the oral cavity, (2) the capability to seal the mouth with the lips when it is filled with water and (3) the willingness of participants to fill their mouth with as much water as they can. Participants practiced the method before the start of the measurement. Measurements were conducted in duplicate for all participants. A paired t-test showed no significant difference between the two measurements (p = .143), so that the average of the two measurements was used for data analysis.

4

4.2.2.6 Tongue dimensions

Dimensions of the protruding tongue were measured by the researcher to obtain length, width and thickness of the anterior tongue. Participants were asked to protrude their tongue as far as possible and place it on top of a Plexiglas element with known dimensions (width x length mm of Plexiglas). Two pictures of the tongue were taken, (1) a frontal view of the tongue, and (2) a lateral view of the tongue. Images were analyzed with the software ImageJ to obtain length, width and thickness of the protruding, anterior tongue based on the known dimensions of the Plexiglas element.

4.2.2.7 Facial anthropometry, height and weight

Facial anthropometry was determined by the height and width of participants' head estimations using a frontal image of the participants, while keeping the mouth closed. Head height (mm) was measured as the distance between the bottom of the chin (menton) to the top of the head. Head width (mm) was measured as the distance between the right and left tragion, the cartilage at the front of the ear. A ratio parameter was calculated by dividing the height by the width of the head. Height and weight of participants was measured by the researcher during the information meeting.

4.2.3 Oral processing behavior

Oral processing behavior of carrots, sausages and cheeses was quantified. Raw carrots, old Gouda cheeses (private label), and hotdog sausages (Unox, The Netherlands) were bought at a local supermarket. Participants were offered 50 g of carrots, sausages or cheeses on a plate. Three pieces of raw carrots and three pieces of sausages were provided to offer 50 g. Cheeses were cut into one piece of rectangular shape weighing 50 g. All foods were consumed by participants using their fingers. Participants were instructed to take three bites of the food products as they would normally do. Participants were not restricted in any other way. Participants could decide on bite size, consumption time, etc. The end of consumption was indicated by the participant by raising the hand.

Participants were video recorded with a camera (Canon IXUS-500HS) positioned in front of them. Oral behavior movements were tracked by placing two stickers on the face of the participants; one sticker on the nose, as a reference point; one sticker on the chin, as a mobile point. Participants were asked to not block stickers with their hands, to not talk and to look in the direction of the camera. The distance between the mobile point and the reference point was used to extract the following oral behavior parameters using Kinovea (v0.8.15) similar to previous studies (M. G. Aguayo-Mendoza et al., 2019; Ketel et al., 2019): total eating duration (s), number of chews and eating rate (g/s). Average bite size (g) was determined for all three bites by weighing the food with a scale underneath the plate during food consumption. Average consumption time (s) was calculated by the average consumption time (s) of the three bites. The number of swallows was defined as the number of times the participants raised his or her hand, indicating one swallow. The number of chews was calculated from the vertical displacement of the jaw, calculated as the difference between the position of the stickers on the nose and chin over time. The maxima in difference between the position of the stickers on the nose and chin indicate a chewing cycle. Chews per bite was calculated by counting the maxima divided by three bites. Average bite size (g) was the average bite size of the 3 bites calculated by difference of the weight of the sample before and after consumption and dividing it by three. Eating rate (g/s) was calculated by dividing bite size (g) of all 3 bite by the consumption time (s) of all 3 bites.

4.2.4 Statistical data analysis

Data was analyzed with SPSS (IBM SPSS statistics, version 23). Normality of the variables was checked and non-normal distributed data was log-transformed. The data is presented as mean value and standard deviation (SD). Multivariate ANOVA's were conducted separately for salivary flow rate (unstimulated and stimulated saliva flow rate), dental status (number of teeth, number of molars, number of wisdom teeth), tongue dimensions (tongue length, width and thickness), facial anthropometry (head height and width), height and weight. Height was included as covariate in the multivariate ANOVA for head height, weight was included as covariate for head width. Separate univariate ANOVA's were conducted for EAT-10 score, average volume of oral cavity and mastication performance (median particle size). Height and weight of subjects were included as covariates for average volume of oral cavity. Consumer group and gender were included as fixed factor for all analyses. Post-hoc pairwise comparisons were performed for the multivariate and univariate ANOVA's using Bonferroni's adjustment. Two Chi-Square test were conducted, (1) to relate occlusion status to consumer group and (2) to relate occlusion status to gender.

Four multivariate ANOVA's were performed for all oral processing parameters (consumption time (s), chews per bite, average bite size (g), eating rate (g/s)). Oral processing parameters for all three foods (carrot, sausage, cheese) were included as dependent variables and the consumer groups and gender as fixed factors and food as covariate. Posthoc pairwise comparisons were performed using Bonferroni's adjustment.

A multivariate linear regression was conducted to study the link between parameters describing oral physiology and anatomy and oral processing parameters. All oral processing, physiological and anatomical parameters were standardized to allow for comparison of standardized β-coefficients. All oral processing parameters for all products and all three consumer groups were included as dependent variables and 14 physiology and anatomy parameters were included as covariates. Multicollinearity of the variables was checked by visual inspection of the data by bi-plots, highly correlated variables ($r > 0.7$) and high variance inflation factor (VIF> 5). Based on these variables, number of wisdom teeth and head width were removed from analysis. Pearson correlations of all 4 oral processing parameters were conducted to explore inter-relationships for all oral processing parameters. The within consumer group variation in oral processing behavior and oral physiology and anatomy was checked with boxplots and standard deviations of all parameters.

4.3 Results

4.3.1 Comparison of oral physiology of Chinese, Asian and Dutch, Caucasian adults and Dutch, Caucasian older adults

4.3.1.1 Mastication performance

Mastication performance measured by median particle size (X50) was significantly affected by consumer group ($F(2,90) = 5.4$, $p = .006$, Fig. 4.2). Chinese, Asian adults displayed a significant smaller median particle size compared to Dutch, Caucasian adults ($p = .029$) and Dutch, Caucasian older adults ($p = .009$). Dutch, Caucasian adults and Dutch, Caucasian older adults did not significantly differ in median particle size. The masticated samples of the Chinese, Asian adults had an average median particle size of 0.2 mm. Dutch, Caucasian adults had an average median particles size of 0.3 mm, indicating a better mastication performance by the Chinese, Asian adults compared to Dutch, Caucasian adults. Mastication samples of Dutch, Caucasian older adults consumers had an average median particle size of 0.3 mm. No significant effect of gender on median particle size was found, indicating no difference in mastication performance between gender.

4.3.1.2 Saliva flow rate

A significant effect of consumer group on stimulated saliva flow rate ($F(2,90) = 3.3$, $p = .04$) was found (Fig. 4.3), with Dutch, Caucasian older adults (1.6 ± 0.7 mL/min) having a significant higher stimulated saliva flow rate compared to Dutch, Caucasian adults (1.3 ± 0.5 mL/min). No significant differences in saliva flow rate were found between Dutch, Caucasian and Chinese, Asian adults; and between the Dutch, Caucasian older adults and the Chinese, Asian adults. No significant effect of consumer group was found on unstimulated salivary flow rate (Fig. 4.3) and no gender effect was found for both saliva flow rates. Concluding, stimulated saliva flow rate only differed between Dutch, Caucasian older adults and Dutch, Caucasian adults.

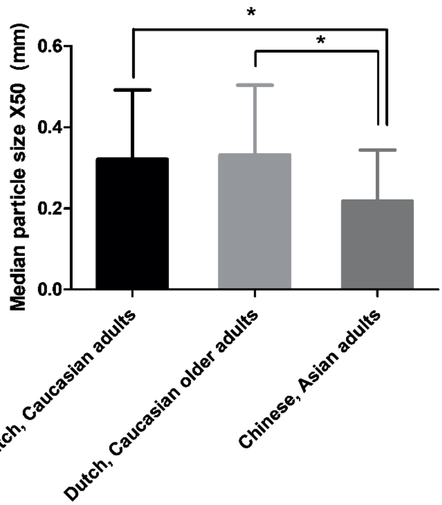

Figure 4.2: Mastication performance quantified by the median particle size (X50) of Optosil cubes chewed 20x by Dutch, Caucasian adults (n = 32, 20 females, 18-30yrs), Dutch, Caucasian older adults (n = 32, 20 females, 65-85yrs) and Chinese, Asian adults (n = 32, 20 females, 18-30yrs). Error bars indicate standard deviation.

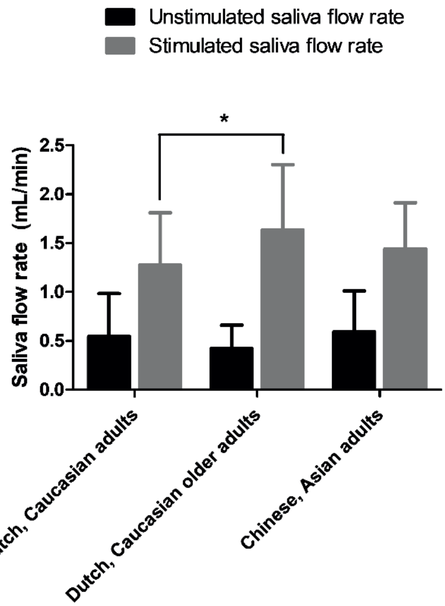

*Figure 4.3: Unstimulated and stimulated saliva flow rate (mL/min) of Dutch, Caucasian adults (n = 32, 20 females, 18-30yrs), Dutch, Caucasian older adults (n = 32, 20 females, 65-85yrs) and Chinese, Asian adults (n = 32, 20 females, 18-30yrs). * Effect is significant at p < .05. Error bars indicate standard deviation.*

4

4.3.1.3 Dental status

Dental status was significantly different between consumer groups for all three dental parameters, number of teeth ($F(2,90) = 11.7$, $p < .001$), number of molars ($F(2,90) = 3.4$, $p = .036$) and number of wisdom teeth ($F(2,90) = 5.0$, $p = .009$). As expected, Dutch, Caucasian older adults had a significant lower number of teeth compared to both Dutch, Caucasian adults ($p < .001$) and Chinese, Asian adults (p = 003). Dutch, Caucasian older adults had on average 27.9 teeth, Dutch, Caucasian adults had 29.5 teeth and Chinese, Asian adults had 29.0 teeth. The difference in total number of teeth is caused by the difference in number of wisdom teeth. The number of wisdom teeth was significantly lower for Dutch, Caucasian older adults consumers compared to Dutch, Caucasian adults (p = .007). Dutch, Caucasian adults had on average 0.4 wisdom teeth, Dutch, Caucasian adults had 1.5 wisdom teeth and Chinese, Asian adults had 1.0 wisdom teeth. Dutch, Caucasian older adults did not significantly differ in number of molars compared to both Dutch, Caucasian adults (p = .077) and Chinese, Asian adults (p = .077). Dutch, Caucasian older adults had on average 15.7 molars, Dutch, Caucasian adults had 16.0 molars and Chinese, Asian adults had 16.0 molars. A significant effect of gender was found for the number of wisdom teeth ($F(1,90) = 4.9$, $p = .029$), with females having on average 0.8 wisdom teeth and males 1.3 wisdom teeth. To summarize, minor differences in dental status were found especially between the Dutch, Caucasian adults and Dutch, Caucasian older adults.

4.3.1.4 Self-reported swallowing problems

No significant effect of consumer group or gender was found for the self-reported swallowing problems ($p > .05$). Eighty-one participants out of 96 had a score between 0 and 2 falling in the group of consumers with no to minor swallowing problems (Belafsky et al., 2008). Fifteen participant had a score of 3 to 9 falling in the group with swallowing problems.

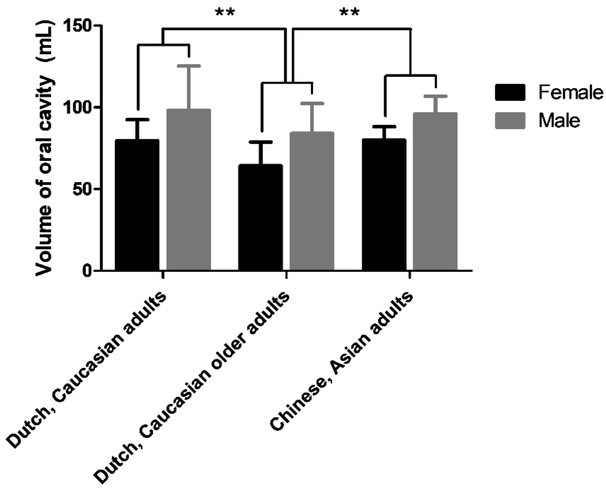

*Figure 4.4: Volume of oral cavity (mL) of Dutch, Caucasian adults (n = 32, 20 females, 18-30yrs), Dutch, Caucasian older adults (n = 32, 20 females, 65-85yrs) and Chinese, Asian adults (n = 32, 20 females, 18-30yrs). ** Effect is significant at p < .01. Error bars indicate standard deviation.*

4.3.1.5 Volume of oral cavity

Volume of oral cavity was significantly affected by consumer group ($F(2,87) = 15.9$, $p < .05$, Fig. 4.4) and gender ($F(1,87) = 13.0$, $p < .05$). Dutch, Caucasian older adults had a significant smaller volume of oral cavity compared to Dutch, Caucasian adults ($p = .001$) and Chinese, Asian adults ($p = .04$). Dutch, Caucasian older adults had an average oral cavity of 72 mL, Dutch, Caucasian adults had an average oral cavity of 87 mL and Chinese, Asian adults of 86 mL. Females consumers had an average oral cavity of 75 mL and males of 93 mL. To summarize, differences in volume of oral cavity are found between consumer groups and gender.

4.3.1.6 Tongue dimensions

A consumer effect was found for the thickness of the anterior tongue ($F(2,90) = 9.6$, $p < .001$), with Dutch, Caucasian older adults having significantly thicker anterior tongues compared to Dutch, Caucasian adults ($p < .001$) and Chinese, Asian adults ($p = .002$). Dutch, Caucasian older adults had an average thickness of 23.9 mm, Dutch, Caucasian adults consumers had an average of 19.8 mm and Chinese, Asian adults had an average of 20.1 mm. The length and width of the tongue was not significantly different between the three groups. No effect of gender was found for any of the tongue measurements. The results indicate minor differences in thickness of the anterior tongue between consumer groups.

4.3.1.7 Facial anthropometry, height and weight

Consumer group had a significant effect on the head width ($F(2,89) = 8.9$, $p < .001$) and the ratio height-width ($F(2,95) = 12.2$, $p < .001$). Dutch, Caucasian adults had a significant smaller head (125.1 mm compared to Dutch, Caucasian older adults (131.0 mm, $p = .048$) and Chinese, Asian adults (135.6 mm, $p < .001$). Chinese, Asian adults had a lower ratio height-width (factor: 1.59) compared to Dutch, Caucasian adults (factor: 1.90, $p < .001$) and Dutch, Caucasian older adults (factor: 1.65, $p = .013$). Gender had a significant effect on head height ($F(1,89) = 14.2$, $p < .001$) and head width ($F(1,89) = 5.2$, $p < .05$). Females had a significant smaller head height (207.4 mm) and head width (127.8 mm) compared to males (height: 220.4 mm, $p < .001$; width: 133.4 mm, $p = .025$). The results indicate Dutch, Caucasian adults have a smaller and more rectangular shape head compared to Chinese, Asian adults and Dutch, Caucasian older adults. Females were found to have a smaller head, both height and width, compared to males.

4

Consumer group had a significant effect on height ($F(2,95) = 8.6$, $p < .001$) and weight ($F(2,95) = 4.9$, $p = .010$). Dutch, Caucasian adults were significantly taller (1.77 m) compared to Dutch, Caucasian older adults (1.71 m, $p = .012$) and Chinese, Asian adults (1.69 m, $p < .001$). Dutch, Caucasian adults had a significantly higher weight (68.9 kg) compared to Chinese, Asian adults (62.8 kg, $p = .013$). Gender had a significant effect on height ($F(1,95) = 43.4$, $p < .001$) and weight ($F(1,95) = 39.0$, $p < .001$). Females were significantly shorter (1.63 m) and weigh less (61.2 kg) compared to males (height: 1.78 m, $p < .001$; weight: 71.8 kg, $p < .001$). To summarize, Dutch, Caucasian adults are taller and heavier compared to Chinese, Asian adults. Females are shorter and weigh less compared to males.

4.3.2 Comparison of oral processing behavior of solid foods by Chinese, Asian and Dutch, Caucasian adults and Dutch, Caucasian older adults

4.3.2.1 Average consumption time

Average consumption time (s) was significantly affected by consumer group ($F(2,90) = 10.2$, $p < .001$, Fig. 4.5A), with Dutch, Caucasian adults consumers having a shorter average consumption time (19.3 s) of the solid foods compared to Dutch, Caucasian older adults (27.7 s, $p < .001$) and Chinese, Asian adults (25.7 s, $p = .009$). No effect of gender on average consumption time (s) was found. Product type also affected average consumption time (F(2,90) = 20.5, p < .001) with the sausage resulting in the shortest average consumption time of 21.4 s compared to 25.0 s for cheese (p < .001) and 26.3 s for carrots (p < .001). No significant interaction effect of consumer group and product was found. To summarize, Dutch, Caucasian adults have the shortest consumption time until swallowing compared to Dutch, Caucasian older adults and Chinese, Asian adults.

4.3.2.2 Chews per bite

A significant effect of consumer group on the chews per bite was found (F(2,90) = 10.7, p = .003, Fig. 4.5B). Dutch, Caucasian adults had significantly less chews per bite (27.0 chews) compared to Dutch, Caucasian older adults (39.9 chews, p < .001) and Chinese, Asian adults (37.9 chews, p = .001). No significant effect of gender on chews per bite was found. Product type significantly affected chews per bite (F(2,90)= 5.9, p = .003), with the sausage being consumed with less chews compared to carrots (p = .013). Consumers needed on average 31.8 chews for the sausage and 39.8 chews for carrots. No significant interaction effect of consumer group and product was found. Similar to the results of consumption time, Dutch, Caucasian adults had the least number of chews per bite compared to Dutch, Caucasian older adults and Chinese, Asian adults.

4.3.2.3 Average bite size

A significant effect of consumer group on average bite size (g) was found (F(2,90) = 8.2, p = .001, Fig. 4.5C). Chinese, Asian adults having a significant smaller average bite size (6.9 g) compared to Dutch, Caucasian older adults (6.7 g, p = .003) and Dutch, Caucasian adults (5.4 g, p = .001). Gender had a significant effect on average bite size (g) (F(1,90) = 5.6, p = .020), with males having a larger average bite size (7.2 g) compared to females (5.8 g). An effect of product on average bite size (g) was found (F(2,90) = 58.788, p < .001). Average bite size of sausage was significantly larger (bite size = 8.0 g) than average bite size of carrot (p < .001, bite size = 5.3 g) and cheese (p < .001, bite size = 5.8 g). An significant interaction effect of Consumer and Product was found for average bite size (F(4,90)=15.3, p < .001). This implies that the average bite size of the different consumer groups depended on the product. To summarize, Chinese, Asian adults had a smaller average bite size compared to both Dutch, Caucasian consumer groups. Males had a larger average bite size compared to females.

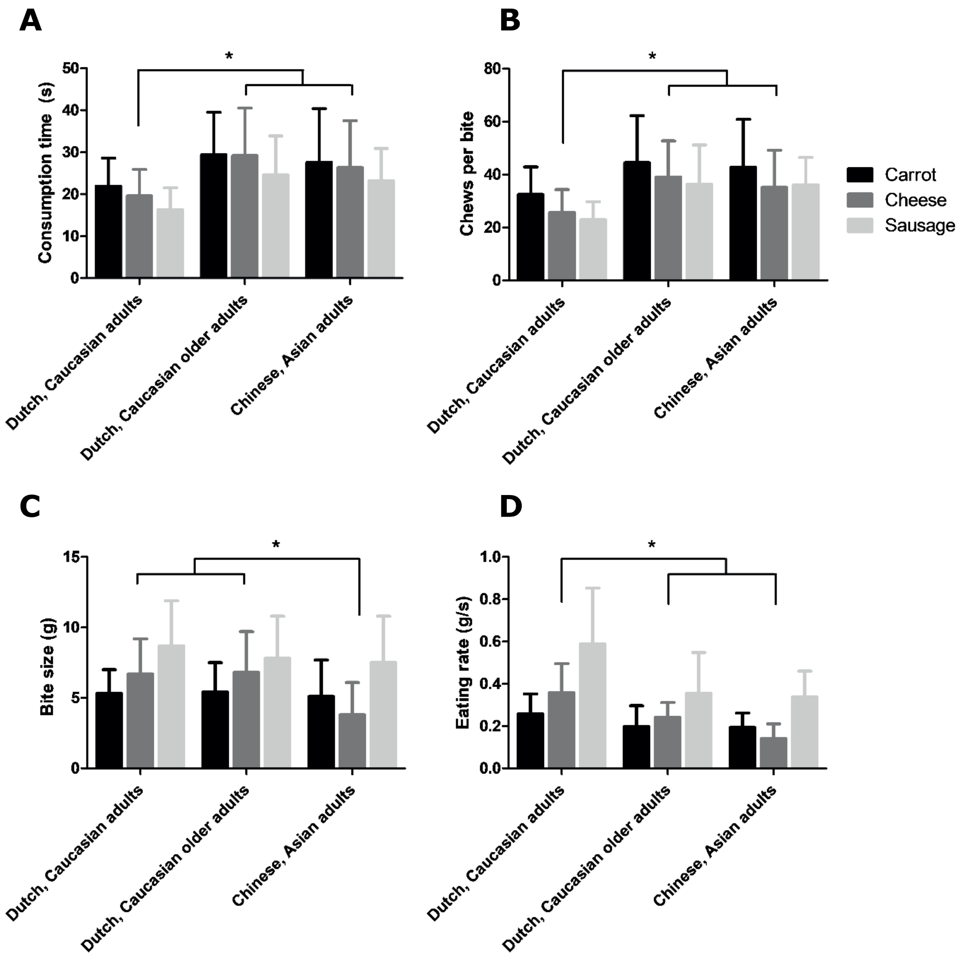

*Figure 4.5: Oral processing behavior of raw carrots, cheese and sausages determined by (A) consumption time , (B) chews per bite, (C) bite size and (D) eating rate for Dutch, Caucasian adults (n = 32, 20 females, 18-30yrs), Dutch, Caucasian older adults (n = 32, 20 females, 65-85yrs) and Chinese, Asian adults (n = 32, 20 females, 18-30yrs). ** Effect is significant at p < .01. Error bars indicate standard deviation.*

4.3.2.4 Eating rate

Consumer group had a significant effect on eating rate (g/s) ($F(2,90) = 23.1$, $p < .001$, Fig. 4.5D), with Dutch, Caucasian adults showing a higher eating rate (0.40 g/s) compared to Dutch, Caucasian older adults ($p < .001$, 0.27 g/s) and Chinese, Asian adults ($p < .001$, 0.22 g/s). An effect of gender on eating rate (g/s) was found ($F(1,90) = 9.0$, $p = .004$), males (0.34 g/s) had a higher eating rate than females (0.10 g/s). Product had a significant effect on eating rate (g/s) ($F(2,90) = 166.2$, $p < .001$), with the consumption of the sausage resulting in a higher eating rate compared to the consumption of carrots ($p < .001$) and cheese ($p < .001$). Participants had an average eating rate of 0.43 g/s for sausage, 0.22 g/s for carrot and 0.25 g/s for cheese. An significant interaction effect of Consumer and Product was found for eating rate (g/s) ($F(4,90) = 22.4$, $p < .001$). This implies the eating rate (g/s) of the different consumer groups depends on the product. Similar to the results of bite size, Dutch, Caucasian adults had the higher eating rate.

Table 4.1: Pearson correlations of the four oral processing parameters.

	Consumption time (s)	Bite size (g)	Eating rate (g/s)	Chews per bite (-)
Consumption time (s)	-			
Bite size (g)	0.255*	-		
Eating rate (g/s)	-0.448*	0.639*	-	
Chews per bite (-)	0.899*	0.227*	-0.422*	-

* Correlation is significant with p < .001.

Several of the oral processing parameters were highly correlated, since several parameters are derived from other oral processing parameters (Table 4.1), including consumption time and chews per bite with a Pearson correlation of 0.899 ($p < .001$). Box plots are shows in Fig. 4.1A and B to visualize variations in oral processing behavior within consumer groups. Dutch, Caucasian older adults group showed a larger variation in average consumption time and chews per bite compared to Dutch, Caucasian adults (Fig. 4.1A and B).

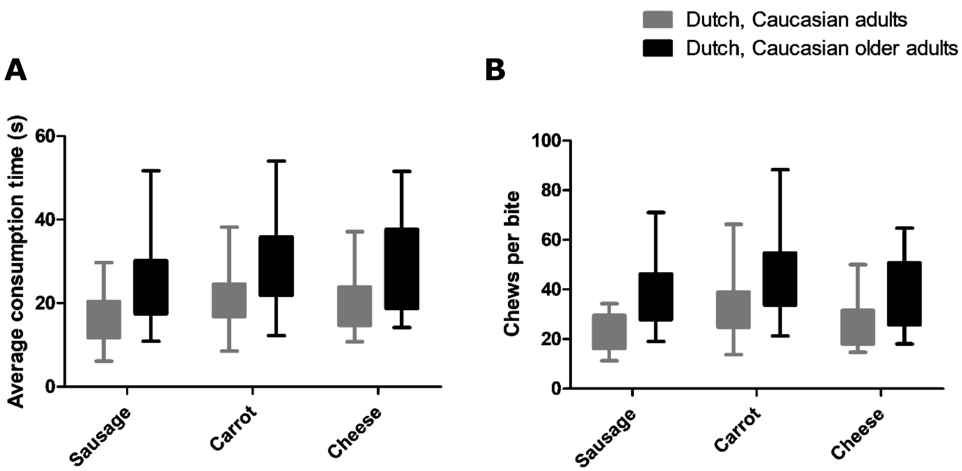

Figure 4.1: Variation in oral processing behavior of Dutch, Caucasian adults and Dutch, Caucasian older adults determined by (A) average consumption time (s) and (B) chews per bite.

4.3.3 Relationships between parameters describing oral physiology and oral processing behavior of solid foods

A multivariate linear regression was performed to assess the relationships between the 14 parameters describing oral physiology and the four oral processing behavior parameters per product (three products).

Stimulated saliva flow rate was positively related to bite size (g) of cheese ($\beta = 0.33$, $p < .01$), indicating a higher stimulated saliva flow rate is associated to an increased bite size of the cheese product.

Number of molars is negatively related to average consumption time (s) of carrot ($\beta = -0.23$, $p < .05$) and cheese ($\beta = -0.21$, $p < .05$). Number of molars is also negatively related to chews per bite of sausage ($\beta = -0.19$, $p < .05$), carrots ($\beta = -0.24$, $p < .05$) and cheese ($\beta = -0.21$, $p < .05$). Average bite size (g) of cheese is negatively related to number of molars ($\beta = -0.21$, $p < .05$). A positive relationship was found between number of molars and eating rate (g/s) of sausage ($\beta = 0.20$, $p < .05$) and carrot ($\beta = 0.34$, $p < .001$). Concluding, a higher number of molars is associated to a shorter consumption time, fewer chews per bite, smaller bite size and higher eating rate. However these results are not consistently found for all products.

Tongue thickness is positively related to average bite size (g) of cheese ($\beta = 0.18$, $p < .05$) and eating rate (g/s) of carrots ($\beta = 0.17$, $p < .05$). The results suggest an increased thickness of the tongue is associated with increased bite size and eating rate, however only for carrots.

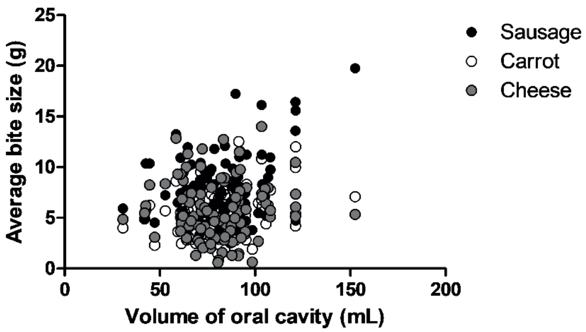

Figure 4.6: Relationship between volume of oral cavity and bite size of sausage, carrot and cheese.

Volume of oral cavity is positively related to average bite size (g) of sausage ($\beta = 0.30$, $p < .01$), suggesting an increased volume of oral cavity is associated with increased bite size. Fig. 4.6 visualizes the relationships between the volume of oral cavity and average bite size (g).

Mastication performance, assessed with median particle size, is negatively related to average consumption time (s) (β = −0.22, $p < .05$) and chews per bite (β = −0.23, $p < .05$) of cheese. The results indicate a good mastication performance is associated with a shorter consumption time and less chews per bite.

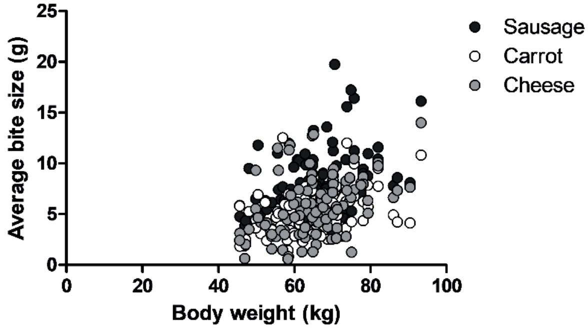

Figure 4.7: Relationship between body weight and bite size of sausage, carrot and cheese.

Body weight was positively related to average bite size (g) of sausage (β = 0.46, $p < .01$), carrot (β =0.42, $p < .05$) and cheese (β = 0.48, $p < .01$), suggesting an increase body weight is associated with an increased bite size. Fig. 4.7 visualizes the relationships between the body weight and average bite size (g).

Height of the head was positively related to eating rate (g/s) of carrot (β = 0.19, $p < .05$), indicating an increased head by height results in a higher eating rate. The ratio parameter of height by width of the head was positively related to chews per bite of sausage (β = 0.21, $p < .05$) and cheese (β = 0.29, $p < .05$), and average bite size (g) of cheese (β = 0.31, $p < .05$). These results indicate a more rectangular shape of head results in more chews and a larger bite size.

4.4 Discussion

The aim of this study was to link parameters describing oral physiology and anatomy of consumers varying in age, gender and ethnicity to food oral processing behavior of solid foods. Considerable differences were found between age groups, gender and ethnicities in oral physiology, oral anatomy and oral behavior. Only few significant relationships were found between parameters describing oral physiology, anatomy and food oral processing behavior of solid foods by consumer varying in age, gender and ethnicity. A total of twenty-one significant relationships were found between the selected oral physiological and anatomical parameters and the oral processing behavior out of 168 relationships that were tested.

Body weight showed the largest β-values with the average bite size of all three foods. The association between eating rate and body weight could result in a higher body weight. Stimulated saliva flow rate related the strongest with bite size of cheese as indicated by one of the largest β-values, suggesting to be of large importance to the oral processing behavior. The results indicated a positive relationship (β = 0.33) of stimulated saliva flow rate on the average bite size of cheese. Since saliva is essential for bolus formation, it was expected that high saliva flow rate could facilitate oral processing and possibly reduce consumption time. Number of molars was found to be negatively related to consumption time, chews per bite and average bite size, and positively related to eating rate. This is in line with previous research indicating the strong impact of dental status on oral processing behavior (Fontijn-Tekamp et al., 2004; Ikebe et al., 2011; van der Bilt et al., 1993). Since we included relatively healthy participants, the other dental status parameters did not differ much and therefore did not impact oral processing behavior. The volume of oral cavity and bite size were only found to be significantly related for sausages. A trending effect was found for carrot (β = 0.20, *p* = .057), suggesting that volume of oral cavity might also influence bite size for other products. Mastication performance was negatively related to consumption time and chews per bite for cheese. This relationship suggests that a good mastication performance can assist oral processing by reducing consumption time and chews per bite. The results indicate that body weight, number of molars and stimulated salivary flow rate have the relative largest impact on oral processing behavior.

4

Since the measured physiological and anatomical parameters seem to explain the variation in oral processing behavior to a limited extend, other physiological parameters not measured in this study, may also explain some of the variation in oral processing behavior. For example, maximum bite force is a physiological measurement which has been often investigated and found to have a large variability amongst individuals. However, the maximum bite force might not be representative of the bite force needed to break down foods. Forces required to break down food products average 8 N/cm2 for soft foods such as feta cheese (Wium et al., 1997) and 60 N/cm2 for firmer foods, such as apples (Varela et al., 2007). Maximum bite forces are much higher. Healthy adults have an range in bite force of 284 - 778 N (Bakke et al., 1990; de Abreu et al., 2014; Takaki et al., 2014; Varga et al., 2010). The maximum bite force is not necessary for fracturing food products. The comfortable maximum bite force may be a more relevant oral physiological measure that links to oral processing behavior compared to maximum bite force. Maximum tongue pressure is another physiological measurement which has been often investigated and found to have a large variability amongst individuals (Alsanei & Chen, 2014; Alsanei et al., 2015; Taniguchi et al., 2008). Several studies have found a decrease in maximum tongue pressure with increasing age (Alsanei & Chen, 2014; Crow & Ship, 1996; Fei et al., 2013). Similar to the maximum the bite force, this maximum tongue pressure is not always necessary during oral processing and was therefore not selected to quantify in the current study. Other measurements of tongue pressure might be more relevant for oral processing behavior of foods, including in vivo measurements of tongue pressure (Alsanei et al., 2015) and mean swallowing pressure of the tongue (Youmans et al., 2009). Another possible factor could be the large inter-individual variation in saliva composition that can influence sensory perception and liking (Engelen et al., 2007; Neyraud et al., 2012). Mosca and colleagues found that both age and ethnicity impact protein concentration, with Asians having a higher protein concentration compared to Caucasians; and protein concentration increasing with age (Mosca et al., 2018). Understanding the saliva composition for different consumer groups might give insights in the link with product perception.

Cultural parameters could also be important for oral processing behavior of consumers with different ethnicities. In Asian cultures, a meal is an important family activity, incorporated in many family traditions and often eaten together (Ma, 2015). Consumption with others is known to influence eating behavior and increases food intake (Herman et al., 2003). This cultural factor could have influenced the oral processing behavior of the Chinese, Asian adults in the current study, however the exact influence of consumption context has not been tested. Secondly, the common use of chopsticks during food consumption could have affected the processing behavior of the Chinese, Asian adults in our study. Chinese, Asian adults are used to consumption with chopsticks, which are known to result in smaller bite sizes compared to consumption with cutlery (Sun et al., 2015). The Chinese, Asian adults might have adapted their bite size in this study to their regular bite size with chopsticks. However, it is not known whether the smaller bite size of the Chinese, Asian adults is due to a cultural factor, such as the use of chopsticks.

Ageing was found to impact both oral physiology and oral processing behavior. Dutch, Caucasian older adults consumed longer and with more chews until swallowing compared to Dutch, Caucasian adults, similar to previous studies (Ketel et al., 2019; Kohyama et al., 2002; Peyron et al., 2004). The decline in muscle mass and dental status during aging, results in a reduced muscle activity during consumption for older consumers and consequently an adaptation of oral processing behavior by chewing more and for a longer time before swallowing (Kohyama et al., 2002; Peyron et al., 2004). The current study found that Dutch, Caucasian older adults had a smaller oral cavity and higher stimulated salivary flow compared to Dutch, Caucasian adults. The volume of oral cavity for young (87 mL) and old consumers (72 mL) are similar to previous research, with 78 mL and 56 mL respectively (Alsanei & Chen, 2014). The outcome of the water-holding method, used in both studies, is dependent on anatomical volume, capability to seal lips and inflation of the cheeks and willingness of participants to keep as much water as possible in their oral cavity. Therefore the outcome of the method does not necessarily reflect a direct measurement of the volume of oral cavity. Several studies found a decrease in salivary flow rate with increasing age (Affoo et al., 2015; Percival et al., 1994; Vandenberghe-Descamps et al., 2016; Yeh et al., 1998), which is in contrast to the findings of this study which observed higher stimulated salivary flows for the Dutch older adults. The current study found only a single effect of p = .04, while no significant effects were found for the unstimulated salivary flow rate. This marginal effect could be an error due to the small sample size of the current study, 32 subjects per consumer group were included, while previous studies included a minimum of 75 subjects. Minor differences in the thickness of the tongue were found between Dutch, Caucasian adults and Dutch, Caucasian older adults, with a larger thickness for the Dutch, Caucasian older adults. These differences are in contradiction to previous research that found a negative correlation of tongue thickness and age (Tamura et al., 2012). However, the study of Tamura and colleagues only included older adults consumers with an age of 80.3 ± 7.9 yrs. Therefore, a clear comparison of tongue length between young and old consumers has not been made before. The results of the current study could reflect actual physiological differences, but may also be an artefact of the used method, i.e. the willingness of the participant to stick out their tongue, could have affected the results of the tongue dimensions. Therefore, this method is highly influential by the participants execution of the method and is hard to standardize. The authors recommend to use other, objective methods which can be standardized to assess the tongue dimensions, such as ultrasonography. To reduce experimental costs, this method was not selected for the current study. Dutch, Caucasian older adults showed to have a larger variation in average consumption time and chews per bite compared to the Dutch, Caucasian adults (Fig. 4.1A and B). The older adults population is known to be a heterogeneous group having a wide range of physical abilities (den Uijl et al., 2016; Laguna et al., 2015a; van der Zanden et al., 2014). This has resulted in a large variation in consumption time and chews per bite for the older adults in the current study. The current study does not have a large enough sample size to investigate the heterogeneity of older adults.

Gender had an influence on oral processing behavior. Differences in oral processing behavior could be due to differences in oral physiology. Males had a larger average bite size (g) and higher eating rate (g/s) compared to females, which is in line with several previous studies (Hill & McCutcheon, 1984; Ketel et al., 2019; Park & Shin, 2015). Males had a larger oral cavity and slightly more wisdom teeth compared to females. The influence of gender on volume of oral cavity has not been compared before and therefore this is the first study to find a larger oral cavity for males than females. The larger oral cavity could be related to the height of participants, this was positively correlated (r = 0.367, p < .001). The larger oral cavity for males could also explain the larger number of wisdom teeth, due to a larger capacity for additional teeth. The volume of oral cavity and the number of wisdom teeth showed a weak positive correlation (r = 0.247, p = .015). A previous study has found a higher salivary flow and masticatory performance for males compared to females (Percival et al., 1994; Shiga et al., 2012). The females in the current study did have a lower stimulated and unstimulated salivary flow compared to males, however these differences were not significantly different. This could be due to the smaller group of participants in the current study compared to the study of Percival et al. (Percival et al., 1994).

Oral processing behavior and oral physiology was affected by ethnicity. Asian Chinese consumers had shorter average consumption time (s), more chews per bite, smaller average bite size (g) and lower eating rate (g/s) compared to young Caucasian Dutch consumers. Similar differences in average bite size (g) and eating rate (g/s) have been found in a previous study (Ketel et al., 2019), but the difference in consumption time (s) and chews per bite has not been reported yet. This could be due to the type of products used in both studies, with the previous study using 18 foods including liquids, semi-solids and solids while the current study only included carrots, cheese and sausage. The relative low eating rate for the Chinese, Asian adults (0.22 g/s) is driven by the low eating rate for the cheese (0.14 g/s), compared to the carrot (0.19 g/s) and sausage (0.34 g/s). Differences in the parameters describing oral physiology were found for the mastication performance, with Asian Chinese consumers resulting in a better mastication performance. These differences have not been studied yet. A better mastication performance could indicate an easier oral processing behavior, however this did not reduce their consumption time. Chinese Asian consumers were found to have a larger oral cavity compared to Caucasian Americans (Xue & Hao, 2006). However this difference was not found in the current study with an average oral cavity of 87 mL for the Dutch, Caucasian adults and 86 mL for the Chinese, Asian adults. The lack of difference could be due to the execution of the method, i.e. the willingness or capability of the participants to keep as much water in their mouth as possible. The Chinese participants might have felt less comfortable to take a lot of water in their mouth, compared to the Dutch participants who might be more familiar with sensory testing.

The sample size of the three consumer groups in this study is relatively low and could be a possible cause of the minor effect of age, gender and ethnicity on oral physiology and oral processing behavior. Futures studies should validate the findings of the current study by including a larger sample size.

4.5 Conclusions

The aim of this study was to link parameters describing oral physiology and anatomy of consumers varying in age, gender and ethnicity to food oral processing behavior.

Understanding the oral processing behavior is important as ineffective processing of foods might result in choking and digestion problems. Eating rate is also known to be positively related to food intake and consequently impacts body weight (Robinson et al., 2014; Viskaal-van Dongen et al., 2011). Oral physiology and oral processing behavior differed between consumer groups and genders. Mastication performance, stimulated salivary flow rate and volume of the oral cavity showed clear differences between the three consumer groups. Oral processing behavior of raw carrot, cheese and sausage differed for the three consumer groups, with differences for consumption time, chews per bite, bite size and eating rate. Several of the physiological and anatomical parameters were related to the oral processing parameters. Body weight resulted in the largest β-values with a positive relationship with bite size. The parameters did not always show consistent relationships across products. The parameters describing oral physiology and anatomy explain the variation in oral processing behavior only to a limited extend. Other physiological parameters and other cultural factors might be more suitable to explain variation in oral processing behavior between consumer groups differing in age, gender and ethnicity.

Acknowledgments

The authors have declared that no competing interests exist. The project is funded by TiFN, a public - private partnership on precompetitive research in food and nutrition. The public partners are responsible for the study design, data collection and analysis, decision to publish, and preparation of the manuscript. The private partners have contributed to the project through regular discussion. The private partners are Royal FrieslandCampina, Fromageries Bel and Unilever. This research was performed with additional funding from the Top Consortia for Knowledge and Innovation of the Dutch Ministry of Economic Affairs.

The authors would like to thank Liza Kester, Judith Schuijs and Ellen Koedam for their help during data collection.

CHAPTER 5

5

Comparison of and relationships between oral physiology, anatomy and food oral processing behavior of Chinese, Asian and Dutch, Caucasian consumers differing in age

Eva C. Ketel
Yifan Zhang
Jingke Jia
Xinmiao Wang
René A. de Wijk
Jianshe Chen
Markus Stieger

Submitted for publication.

Abstract

The aims of the study were (1) to compare oral physiology, anatomy and food oral processing behavior of four consumer groups: Chinese, Asian adults and older adults, and Dutch, Caucasian adults and older adults and (2) to explore relationships between oral physiology, anatomy and food oral processing behavior of Chinese consumers differing in age. Oral physiology (mastication performance, saliva flow rate and dental status) and oral anatomy (volume of oral cavity, tongue dimensions, facial anthropometry, height and weight) were determined in Chinese, Asian adults (n=32; 18-30 yrs) and Chinese, Asian older adults (n=32; 60-85 yrs) and compared to previously determined oral physiology and anatomy of Dutch, Caucasian adults (n=32; 18-30 yrs) and Dutch, Caucasian older adults (n=32; 65-85 yrs). Oral processing behavior (consumption time, chews per bite, bite size, eating rate) of solid foods (raw carrot, cooked carrot, sausage and tofu-gan) was quantified using video recordings. Chinese, Asians had lower percentages of normal occlusion, slightly wider and shorter tongues, lower head height:width ratio and lower BMI compared to Dutch, Caucasians. Overall, Chinese adults displayed similar food oral processing behavior compared to Dutch adults. Consumption time, chews per bite and bite size did not differ between Chinese and Dutch adults. Only small difference in eating rate were observed between these groups. Chinese, Asian older adults consumed all foods with lower eating rates compared to Chinese, Asian adults probably due to changes in oral physiology and anatomy. Body weight and number of teeth were the physiological and anatomical parameters that related the strongest with oral processing behavior of solid foods. We conclude that ethnicity and age impact oral physiology, anatomy and oral processing behavior of solid foods. Oral physiology and anatomy only partially explain the variation in oral processing behavior of solid foods in consumer groups differing in ethnicity and age. Other factors such as culture and consumption habits are suggested to have a stronger influence on oral processing behavior.

5.1 Introduction

Oral processing behavior is determined by food properties and consumer characteristics. With increasing viscosity of liquid foods or hardness of solid foods consumption time increases and eating rate decreases (Aguayo-Mendoza et al., 2019; Wee et al., 2018). Consumer characteristics, such as age, gender and ethnicity, are known to impact oral processing behavior. Consumers differ in oral physiology and anatomy which might affect food oral processing behavior. Recently, there has been an increasing interest in understanding relationships between consumer characteristics such as oral physiology and anatomy and food oral processing behavior. This knowledge can help to facilitate the design of more palatable and healthier foods for specific consumer groups (Kim et al., 2015).

With increasing age consumption time is prolonged and more chews per bite are used to masticate foods (Fontijn-Tekamp et al., 2004; Ikebe et al., 2011; Ketel et al., 2019; Kohyama et al., 2002; Peyron et al., 2004; van der Bilt et al., 1993). Physiological parameters, including salivation and mastication efficiency, are affected by consumer characteristics such as age and ethnicity and have been suggested to influence oral processing behavior. A decline in muscle mass and dental status leads to changes in oral behavior upon ageing (Fontijn-Tekamp et al., 2004; Ikebe et al., 2011; Kohyama et al., 2002; Peyron et al., 2004; van der Bilt et al., 1993). Older consumers have decreased salivary flow rate, smaller volume of oral cavity, lower number of teeth, lower maximum tongue pressure and decreased bite force compared to adults (Affoo et al., 2015; Ketel et al., 2020; Laguna et al., 2015a; Liu et al., 2019; Percival et al., 1994; Vandenberghe-Descamps et al., 2016; Yeh et al., 1998). Dutch, Caucasians consume liquid, semi-solid and solid foods with higher eating rate compared to Chinese, Asians (Ketel et al., 2019). These studies clearly suggest that oral processing behavior is influenced by age and ethnicity. Chinese, Asian adults have increased mastication performance and wider and less rectangular shaped heads compared to Dutch, Caucasian adults (Ketel et al., 2020). Longer tongue length of Africans compared to Europeans have been reported (Beghini et al., 2017). However, only few systematic comparisons of food oral processing behavior between different ethnic groups have been made so far.

Eating capability is the individual's capability of oral food consumption, including the breakdown of foods into smaller particles during mastication until the bolus can be safely swallowed (Laguna & Chen, 2016). Oral capability might influence oral processing behavior and is determined by multiple factors including positioning and mobility of the tongue (Matsuo & Palmer, 2009; Mioche et al., 2002; Prinz & Lucas, 2000), salivation (Carpenter, 2012) and mastication performance (Ross & Hoye, 2012). Relationships between oral physiology and oral processing behavior have been suggested multiple times (Chen, 2016; Laguna & Chen, 2016), but only few studies actually investigated these relationships. Poor dental status in older adults has been linked to longer consumption time (Assad-Bustillos et al., 2019). Bite size has been positively related to BMI and dental arch size, an indirect measurement of tongue volume (Shiozawa et al., 2019). Oral physiology (saliva flow rate, chewing efficiency, biting force and particle size sensitivity) did not predict preferred mouth-behavior classified with the JBMB mouth behavior tool (Kim & Vickers, 2020). Neither food texture liking nor oral physiological measurements predicted membership in the four mouth-behavior groups obtained with the JBMB mouth behavior tool (Jeltema et al., 2015). A recent study found that oral physiology and anatomy explained differences in oral processing behavior between consumers only to a limited extend (Ketel et al., 2020). Only few relationships between oral physiology and anatomy and oral processing behavior were found. Little consistency was observed across oral processing parameters and food products. Several significant relationships were for only one of the foods tested, while no relationships were found for the other foods. Body weight and bite size had the strongest relationships with oral processing behavior. This previous study included Dutch, Caucasian adults, Dutch, Caucasian older adults and Chinese, Asian adults. A comparison of oral physiology, anatomy and oral processing behavior with Chinese, Asian older adults has not been made.

The current study expands the previous study by including Chinese, Asian older adults and Chinese, Asian adults. The aim of this study was (1) to compare oral physiology, anatomy and oral processing behavior of four consumer groups: Chinese, Asian adults and older adults, and Dutch, Caucasian adults and older adults and (2) to explore relationships between oral physiology and anatomy and oral processing behavior of Chinese consumers varying in age. The current study included Chinese, Asian adults and Chinese, Asian older adults. Comparisons are made with Dutch, Caucasian adults, Dutch, Caucasian older adults which have been studied previously (Ketel et al., 2020). Oral physiology, anatomy and oral processing behavior were determined with the same methods in both studies. We hypothesize that ethnicity has only a small effect on oral physiology. We hypothesize that ageing has a similar effect on oral processing behavior for both Chinese consumers and Dutch consumers.

5.2 Materials and methods

5.2.1 Participants

Two groups of healthy consumers were recruited in Hangzhou, China including Chinese, Asian adults (n = 32; 20 females, mean age of 23.8 ± 1.0 yrs) and Chinese, Asian older adults (n = 32; 20 females, mean age of 72.3 ± 7.9 yrs). The Chinese, Asian consumers, both adults and older adults, were Han Chinese. For the sake of simplicity we refer to them as Chinese, Asian adults and Chinese, Asian older adults. Chinese, Asian adults were included when no teeth were missing. Chinese, Asian older adults were included when four or less teeth were missing. Additional inclusion criteria were BMI between 18 and 25 kg/m^2 and normal taste and smell capabilities (self-reported). An inclusion questionnaire was used to ensure that participants compiled with all inclusion criteria. Participants were recruited via social media and by contacting several elderly homes in Hangzhou, China. Participants received an information brochure and gave written informed consent to participate in the study. Participants received a financial reimbursement for participation. The study was approved by the medical ethical committee of Zhejiang Gongshang University (approval number: 2018011701).

The two Chinese consumer groups were compared to two Dutch consumer groups which have been investigated in a previous study in Wageningen, The Netherlands (Ketel et al., 2020). These groups included Dutch, Caucasian adults (n = 32, 20 females, mean age of 21.5 ± 1.9 yrs), Dutch, Caucasian older adults (n = 32, 20 females, mean age of 70.4 ± 4.3 yrs) and Chinese, Asian adults (n = 32, 20 females, mean age of 24.2 ± 2.1 yrs). Dutch, Caucasian adults and Chinese Asian adults were included with no missing teeth. Dutch, Caucasian older adults were included when two or less teeth were missing. Chinese, Asian older adults were included when four or less teeth were missing.

5.2.2 Oral physiological and anatomical parameters

Four oral physiological parameters (mastication performance, saliva flow rate, dental status, self-reported swallowing problems) and four anatomical parameters (volume of oral cavity, tongue dimensions, facial anthropometry, height and weight) were quantified by a trained researcher during one test session of 60 min. The measurements were conducted as previously described (Ketel et al., 2020).

5.2.2.1 Mastication performance

Participants were instructed to chew 14 cubes of Optosil (size of each cube 5x5x5 mm; total weight ~3.5g) for 20 times. Optosil is an artificial rubber test material used to assess mastication performance (Fontijn-Tekamp et al., 2000). After 20 chewing cycles participants expectorated the broken down Optosil particles. Participants were asked to rinse their mouth with water and spit out again. Particles were collected and dried in an oven at 80°C for 1 hour. After drying particles were separated manually in a petri-dish without further breaking particles. A black-white scan was made using a scanner (Canon 9000F Mark ||) and median particle size (X50) was determined using ImageJ (National Institutes of Health, USA, version 1.52a).

5.2.2.2 Saliva flow rate

Stimulated and unstimulated saliva flow rate were determined for Chinese, Asian adults. To minimize duration of test sessions for the older adults, only stimulated saliva flow rate was determined for Chinese, Asian older adults. For the measurement of unstimulated saliva flow rate, participants were asked to spit out unstimulated saliva every 30 s for 5 min into a pre-weighed plastic tube. The researcher indicated every time point when the participant needed to spit out their saliva. The cup was weighed before and after the test session and unstimulated saliva flow rate (mL/min) was obtained. A saliva density of 1g/mL was assumed. For determination of stimulated saliva flow rate, participants were asked to spit out saliva every 30 s for 5 min while chewing on a piece of parafilm (5x5 cm). Chewing on the parafilm mimics mastication behavior and provides mechanical stimulation inducing salivation (Mackie & Pangborn, 1990). Stimulated saliva flow rate (mL/min) was determined by weighing the cup before and after the measurement.

5.2.2.3 Dental status

The dental status of participants was quantified by the researcher by counting total number of teeth, number of molars, number of wisdom teeth and determining occlusion status. Occlusion status was classified according to Angle (Angle, 1899) into four categories: malocclusion class 1, 2, 3 or normal occlusion. Malocclusion class 1 included participants with the presence of a cross-bite, teeth are tilted towards cheek or tongue; or an open bite, upper and lower teeth cannot make contact; or a deep bite, upper teeth cover the lower teeth. Malocclusion class 2 included participants with the presence of an overjet indicated by the upper teeth proclining the lower teeth by more than 4 mm. Malocclusion class 3 included participants with the presence of under-bite, indicated by the proclining of the lower teeth. The fourth category of occlusion status included participants with none of the above mentioned deviations, in other words with normal occlusion.

5.2.2.4 Self-reported swallowing problems

Participants filled in the EAT-10 questionnaire which consists of 10 statements on swallowing problems (Belafsky et al., 2008). For each statement, participants indicated the severity of swallowing problems from 0 (no problems) to 4 (severe problems) points. The sum of all 10 statements results in a total score of the EAT-10 questionnaire. A total score below 3 indicates no to minor swallowing difficulties. A score of 3 or larger indicates abnormal swallowing difficulties. The EAT-10 questionnaire was translated from English into Chinese.

5.2.2.5 Volume of oral cavity

Volume of the oral cavity was determined with the water-retaining test (Alsanei & Chen, 2014). Participants received a cup with 500 mL water and were instructed to keep as much water in the oral cavity as possible by inflating their cheeks. When participants reached the maximum volume of water in their mouth, participants spat out the water in another cup. The volume of oral cavity was determined by the difference in weight (mL) of the spit out cups before and after the measurement. The volume of the oral cavity determined with this method depends on (1) the anatomical volume of the oral cavity, (2) the capability to seal the mouth with the lips when it is filled with water and (3) the willingness of participants to fill their mouth with as much water as they can. Participants practiced the method before the start of the measurement. Measurements were conducted in duplicate for all participants. A paired t-test showed significant and small differences in volume of the oral cavity between the two measurements ($p = .005$), with a difference of 2.4 mL (2.8%) for the Chinese, Asian adults and 3.5 mL (4.5%) for the Chinese, Asian elderly between the two measurements. Since the differences in volume of the oral cavity between the two measurements were smaller than 5%, the authors consider the differences not relevant and used the average of the two measurements for data analysis.

5.2.2.6 Tongue dimensions

Dimensions of the protruding tongue of participants were measured by the researcher to obtain length, width and thickness of the anterior tongue. Participants were asked to protrude their tongue as far as possible and place it on top of a Plexiglas element with known dimensions (width x length mm of plexiglas). Two pictures of the tongue were taken, (1) a frontal view of the tongue, and (2) a lateral view of the tongue. Images were analyzed with the software ImageJ to obtain length, width and thickness of the protruding, anterior tongue based on the known dimensions of the Plexiglas element.

5.2.2.7 Facial anthropometry, height and weight

Facial anthropometry was determined by the height and width of participants' head using a frontal image of the participants, while keeping the mouth closed. Head height (mm) was measured as the distance between the bottom of the chin (menton) to the top of the head. Head width (mm) was measured as the distance between the right and left tragion, the cartilage at the front of the ear. A ratio parameter was calculated by dividing the height by the width of the head. Height and weight of participants was measured at the start of the test session.

5.2.3 Oral processing behavior

Oral processing behavior of raw carrots, cooked carrots, sausages and tofu-gan (dried tofu) was quantified. Raw carrots, sausages (private label) and tofu-gan (private label) were bought at a local supermarket in Hangzhou, China. Participants were offered 50 g of raw carrots, cooked carrots, sausages or tofu-gan on a plate. Carrots and sausage were boiled in water for 5 minutes and three pieces of product were provided for consumption. Tofu-gan was cut into three pieces of rectangular shape weighing together 50 g. All foods were consumed by participants using their fingers. Participants were instructed to take three bites of the 50 g of foods as they normally do. Participants were not restricted in any other way. The end of consumption was indicated by the participant by raising the hand.

Carrots, tofu-gan and sausage were included in the current study to compare oral processing behavior of Chinese, Asian adults and Chinese, Asian older adults. In the previous study conducted with three different consumer groups in Wageningen, The Netherlands, (Ketel et al., 2020) raw carrots (private label), sausages (Hotdog sausage, Unox) and cheese (private label) were used to quantify oral processing behavior of solid foods. Since cheese is not commonly consumed in China, a flavorless tofu-gan was chosen instead for the current study. Uniaxial compression tests using a Texture Analyzer (TA.XT plus, Stable Micro Systems-SMS) were performed to compare the fracture properties of the foods. The uniaxial compression was performed at room temperature with a speed of 1 mm/s up to a compression strain of 80% using a plate-plate geometry. Carrots and sausage were cut into cylindrical pieces with a height of approximately 15 mm. Tofu-gan was cut into a cube of 15x15x5mm (length x width x height). Ten replicates were measured and the mean value for fracture stress and fracture strain was determined. Fracture stress ($p = .619$) and fracture strain ($p = .063$) of the sausage used in this study did not significantly differ compared to the sausage used in the previous study (Ketel et al., 2020). Fracture stress ($p = .109$) and fracture strain ($p = .078$) of the raw carrots used in this study did not significantly differ compared to the raw carrots used in the previous study. A comparison of oral processing behavior between the Chinese, Asian adults and older adults of the current study, and Dutch, Caucasian adults and older adults of the previous study is made only for the sausages and raw carrots since these foods displayed similar fracture properties. Cooked carrots, tofu-gan (only used in this study) and cheese (only used in the previous study) were excluded from data analysis.

Participants were video recorded with a camera (Canon IXUS-500HS) positioned in front of the participant. Oral behavior movements were tracked by placing two stickers on the face of the participants; one sticker on the nose, as a reference point; one sticker on the chin, as a mobile point. Participants were asked to not block stickers with their hands, to not talk and to look in the direction of the camera. The distance between the mobile point and the reference point was used to extract the following oral behavior parameters using Kinovea (v0.8.15) similar to previous studies (Aguayo-Mendoza et al., 2019; Ketel et al., 2019): total consumption time (s), number of chews and eating rate (g/s). Average bite size (g) was determined for all three bites by weighing the food with a scale underneath the plate during food consumption. Average consumption time (s) was calculated by the average consumption time (s) of the three bites. The number of chews was determined from the vertical displacement of the jaw, calculated as the difference between the position of the stickers on the nose and chin over time. The maxima in difference between the position of the stickers on the nose and chin indicate a chewing cycle. Chews per bite was calculated by counting the maxima divided by three bites. Average bite size (g) was the average bite size of the 3 bites calculated by difference of the weight of the sample before and after consumption and dividing it by three. Eating rate (g/s) was calculated by dividing bite size (g) of all 3 bite by the consumption time (s) of all 3 bites.

5.2.4 Statistical data analysis

Data was analyzed with SPSS (IBM SPSS statistics, version 25). Normality of the variables was checked and non-normal distributed data was log-transformed. Data is presented as mean value and standard deviation (SD). Difference in oral physiology, anatomy and oral processing behavior was compared for (1) age by comparing Chinese, Asian adults and Chinese, Asian older adults and for (2) ethnicity by comparing Chinese, Asian consumers (older adults and adults) with Dutch, Caucasian consumers (older adults and adults).

For both comparisons multivariate ANOVA's were conducted separately for dental status (number of teeth, number of molars, number of wisdom teeth), tongue dimensions (tongue length, width and thickness), facial anthropometry (head height, head width), saliva flow rate (unstimulated and stimulated), height and weight. Height was included as covariate in the multivariate ANOVA for head height, weight was included as covariate for head width. Separate univariate ANOVA's were conducted for mastication performance (median particle size), EAT-10 score and average volume of oral cavity. Height and weight of participants were included as covariates for average volume of oral cavity. Ethnicity was included as fixed factor for all analyses. Post-hoc pairwise comparisons were performed for the multivariate and univariate ANOVA's using Bonferroni's adjustment. One Chi-Square test was conducted to relate occlusion status to ethnicity.

Four multivariate ANOVA's were performed for all oral processing parameters (average consumption time (s), chews per bite, average bite size (g), eating rate (g/s)). Oral processing parameters for all four foods (raw carrot, cooked carrot, sausage, tofu-gan) were included as dependent variables and ethnicity as fixed factor and food as covariate. Post-hoc pairwise comparisons were performed using Bonferroni's adjustment. Pearson correlations of all oral processing parameters for both Chinese groups were conducted to explore inter-relationships. The within consumer group variation in oral processing behavior and oral physiology and anatomy was checked with boxplots and standard deviations of all parameters.

One multivariate linear regression was conducted to study the link between parameters describing oral physiology and oral processing parameters for the Chinese, Asian adults and Chinese, Asian older adults. All oral processing, physiological and anatomical parameters were standardized to allow for comparison of standardized beta-coefficients. Oral processing parameters of sausages and raw carrots were included as 8 dependent variables and 12 physiology and anatomy parameters were included as covariates. Multicollinearity of the variables was checked by visual inspection of the data by bi-plots, highly correlated variables (r > 0.7) and high variance inflation factor (VIF > 5). Based on the selection criteria, number of molars, number of wisdom teeth and head width were removed from analysis.

5.3 Results

First, the effect of age on oral physiology, anatomy and oral processing behavior is described by comparing Chinese, Asian adults and Chinese, Asian older adults (section 3.1.1 and 3.2.1). Secondly, the effect of ethnicity on oral physiology, anatomy and oral processing behavior is described by comparing Chinese, Asian adults and older adults with Dutch, Caucasian adults and older adults (section 3.1.2 and 3.2.2).

5.3.1 Comparison of oral physiology and anatomy

5.3.1.1 Effect of age on oral physiology and anatomy: Comparison between Chinese, Asian adults and Chinese, Asian older adults

Age had a significant effect ($F(1,60) = 12.7$, $p = .001$) on mastication performance assessed by median particle size (X_{50}), with Chinese, Asian adults ($X_{50} = 1.9$ mm) having a lower median particle size than Chinese, Asian older adults ($X_{50} = 3.0$ mm, Figure 5.1 and Table 5.1).

Stimulated saliva flow rate was significantly higher ($F(1,60) = 4.5$, $p = .038$) for Chinese, Asian adults (1.3 mL/min) than Chinese, Asian older adults (1.1 mL/min, Figure 5.2 and Table 5.1).

Occlusion status was significantly affected by age (Pearson Chi-Square = .035). The majority of Chinese, Asian adults had normal occlusion (59.4%), while this was not the case for Chinese, Asian older adults (normal occlusion: 34.4%). Malocclusion class 1, presence of cross-bite, open bite or deep bite, was higher for Chinese, Asian older adults (25.0%) compared to Chinese, Asian adults (3.1%). Malocclusion class 2, presence of overjet, did not differ by age. The malocclusion class 3, presence of under-bite, showed minor differences by age (Table 5.1). Number of teeth, number of molars and number of wisdom teeth were not affected by age.

Table 5.1: Effect of age and ethnicity on physiological and anatomical parameters. For the effect of age a comparison was made between Chinese, Asian adults and Chinese, Asian older adults. For the effect of ethnicity a comparison was made between Chinese, Asian consumers (adults and older adults) with Dutch, Caucasian consumers (adults and older adults).

	Effect of age			Effect of ethnicity		
	p-value	Chinese, Asian adults, mean age 23.8 ± 1.0 yrs (n = 32)	Chinese, Asian older adults, mean age 72.3 ± 7.9 yrs (n = 32)	p-value	Chinese, Asian consumers, mean age 48.1 ± 4.5 yrs (n = 64)	Dutch, Caucasian consumers, mean age 46.0 ± 3.1 yrs (n = 64)
Median particle size (mm)	**.001 ***	1.9 ± 0.9	3.0 ± 1.8	**.002 * ****	2.5 ± 1.5	2.7 ± 0.9
Saliva flow rate						
Unstimulated (mL/min)		0.6 ± 0.3		.167	0.6 ± 0.3	0.5 ± 0.2
Stimulated (mL/min)	**.038 ***	1.3 ± 0.6	1.1 ± 0.5	**.018 * ****	1.2 ± 0.6	1.5 ± 0.6
Occlusion status	**.035 ***			**< .001 ***		
Normal occlusion (%)		59.4	34.4		46.9	90.6
Malocclusion class 1 (%)		3.1	25.0		14.1	3.1
Malocclusion class 2 (%)		37.5	37.5		37.5	6.3
Malocclusion class 3 (%)		0.0	3.1		1.6	0.0
Number of teeth (-)	.093	28.8 ± 1.4	25.9 ± 2.6	**< .001 * ****	27.4 ± 2.0	28.7 ± 1.4
Number of molars (-)	.409	16.0 ± 0.0	14.1 ± 1.5	**< .001 * ****	15.0 ± 0.8	15.8 ± 0.5
Number of wisdom teeth (-)	.926	0.8 ± 1.4	0.4 ± 1.1	.076	0.6 ± 1.3	1.0 ± 1.2
EAT-10 score	.450	0.6 ± 1.1	0.7 ± 1.0	.226	0.6 ± 1.1	0.9 ± 1.3
Volume of oral cavity (mL)	**< .001 ***	86.2 ± 15.8	74.3 ± 14.9	.441	80.2 ± 15.4	78.6 ± 20.4
Tongue length (mm)	**.018 ***	25.0 ± 5.6	21.5 ± 6.6	**.029 ***	23.3 ± 6.1	27.4 ± 7.4
Tongue width (mm)	.144	42.3 ± 9.6	45.3 ± 7.2	**.004 * ****	43.8 ± 8.4	40.4 ± 6.6
Tongue thickness (mm)	.052	19.6 ± 4.1	21.6 ± 4.4	.116	20.6 ± 4.2	21.8 ± 4.0
Head height (mm)	.520	204.7 ± 12.3	208.3 ± 10.5	.059	206.5 ± 11.4	211.6 ± 16.9
Head width (mm)	.327	131.2 ± 7.5	130.0 ± 6.1	**.019 * ****	130.6 ± 6.8	127.3 ± 9.6
Ratio head height:width	**.030 ***	1.56 ± 0.07	1.60 ± 0.06	**< .001 * ****	1.58 ± 0.06	1.66 ± 0.07
Height (m)	**.003 ***	1.67 ± 0.09	1.62 ± 0.07	**< .001 ***	1.65 ± 0.08	1.73 ± 0.09
Weight (kg)	.203	57.0 ± 8.7	59.6 ± 8.3	**< .001 ***	58.3 ± 8.5	67.1 ± 9.0

* Consumers are significantly different at $p < .05$ ** Consumers show a significant interaction effect of age by ethnicity. Malocclusion classes: 1 Presence of cross-bite, open bite or deep bite; 2 Presence of overjet; 3 Presence of under-bite.

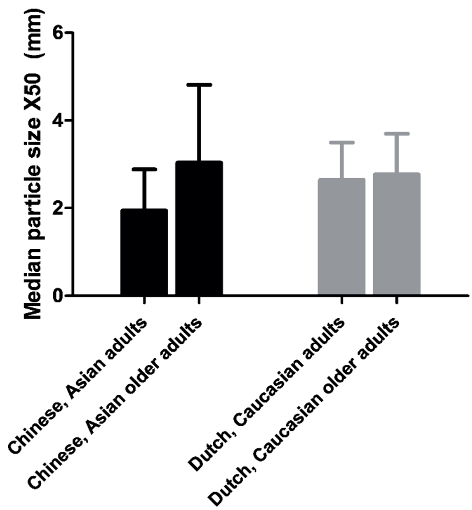

Figure 5.1: Mastication performance quantified by median particle size (X50) of Optosil cubes chewed 20x by Chinese, Asian adults (mean age 23.8 ± 1.0 yrs, n = 32), Chinese, Asian older adults (mean age 72.3 ± 7.9 yrs, n = 32), Dutch, Caucasian adults (mean age 21.5 ± 1.9 yrs, n = 32) and Dutch, Caucasian older adults (mean age 70.4 ± 4.3 yrs, n = 32). Error bars indicate standard deviation.

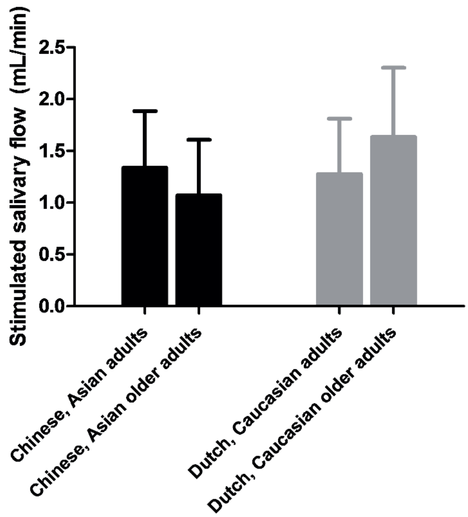

Figure 5.2: Stimulated saliva flow rate by Chinese, Asian adults (mean age 23.8 ± 1.0 yrs, n = 32), Chinese, Asian older adults (mean age 72.3 ± 7.9 yrs, n = 32), Dutch, Caucasian adults (mean age 21.5 ± 1.9 yrs, n = 32) and Dutch, Caucasian older adults (mean age 70.4 ± 4.3 yrs, n = 32). Error bars indicate standard deviation.

Volume of oral cavity (Figure 5.3 and table 5.1) was significantly affected by age ($F(1,60) = 16.3$, $p < .001$). Chinese, Asian adults had a larger volume of oral cavity (86.2 mL) than Chinese, Asian older adults (74.3 mL).

Tongue length was significantly affected by age ($F(1,60) = 5.9$, $p = .018$) with Chinese, Asian adults (25.0 mm) having a longer tongue than Chinese, Asian older adults (21.5 mm).

Age had a significant effect on the ratio height:width of the head ($F(1,60) = 4.9$, $p = .030$), with Chinese, Asian adults having a ratio of 1.56 compared to Chinese, Asian older adults with a ratio of 1.60. Chinese, Asian older adults had a slightly more rectangular shape head compared to Chinese, Asian adults. Height was significantly affected by age ($F(1,60) = 9.3$, $p = .003$), with Chinese, Asian adults being taller (1.67 m) compared to Chinese, Asian older adults (1.62 m).

Age did not affect self-reported swallowing problems assessed by the EAT-10 questionnaire (Table 5.1).

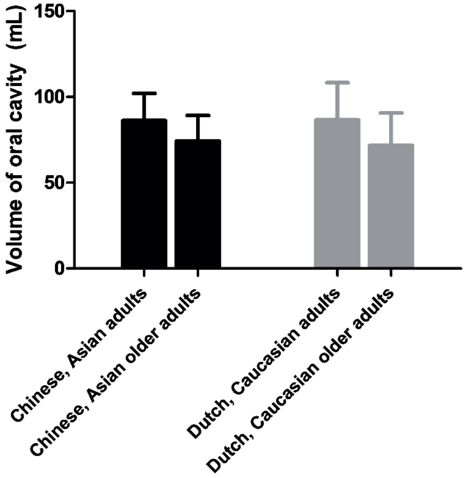

Figure 5.3: Volume of oral cavity by Chinese, Asian adults (mean age 23.8 ± 1.0 yrs, n = 32), Chinese, Asian older adults (mean age 72.3 ± 7.9 yrs, n = 32), Dutch, Caucasian adults (mean age 21.5 ± 1.9 yrs, n = 32) and Dutch, Caucasian older adults (mean age 70.4 ± 4.3 yrs, n = 32). Error bars indicate standard deviation.

5.3.1.2 Effect of ethnicity on oral physiology and anatomy: Comparison between Chinese, Asian older adults and adults with Dutch, Caucasian older adults and adults

Ethnicity had a significant effect ($F(1,124) = 10.1$, $p = .002$) on mastication performance with a significant interaction effect between ethnicity and age ($F(1,124) = 9.6$, $p = .002$) (Table 5.1). Chinese, Asian consumers had a significant higher median particle diameter ($X50 = 9.7$ mm for Chinese, Asian older adults, $X50 = 3.6$ mm for Chinese, Asian adults) compared to Dutch, Caucasian consumers ($X50 = 2.8$ mm for Dutch, Caucasian older adults, $X50 = 2.6$ mm for Dutch, Caucasian adults, Table 5.1). These results indicate a worse mastication performance for Chinese, Asian consumers compared to Dutch, Caucasian consumers. The interaction effect indicates that a larger difference between groups was found between the old consumers compared to the young consumers.

Ethnicity had a significant effect ($F(1,124) = 5.7$, $p = .018$) on stimulated saliva flow rate with a significant interaction effect of ethnicity and age ($F(1,124) = 9.6$, $p = .002$). Chinese, Asian consumers had a lower stimulated saliva flow (1.1 mL/min for Chinese, Asian older adults, 1.3 mL/min for Chinese, Asian adults) compared to Dutch, Caucasian consumers (1.6 mL/min for Dutch, Caucasian older adults, 1.3 mL/min for Dutch, Caucasian adults). These results indicate a lower saliva flow rate for Chinese, Asian consumers, that is driven by the larger difference for the old consumers. No significant difference in unstimulated saliva flow rate was observed (Table 5.1).

Ethnicity had a significant effect on occlusion status (Pearson Chi-Square < .001). Dutch, Caucasian consumers had a higher percentage of normal occlusion (90.6% of both Dutch,

5

Caucasian adults and older adults) compared to Chinese, Asian consumers (59.4% of Chinese, Asian adults and 34.4% of Chinese, Asian older adults). Malocclusion was less frequent in both Dutch, Caucasian consumer groups compared to both Chinese, Asian consumer groups. Ethnicity had a significant effect on number of teeth ($F(1,124) = 18.5$, $p < .001$) with a significant interaction effect of ethnicity and age ($F(1,124) = 5.6$, $p = .020$). Chinese, Asian consumer groups had fewer teeth compared to Dutch, Caucasian consumer groups. The interaction effect indicates a larger difference for the old consumer groups than the young consumer groups. Ethnicity had a significant effect on number of molars ($F(1,124) = 22.5$, $p < .001$) with a significant interaction effect of ethnicity and age ($F(1,124) = 22.6$, $p < .001$). These results indicate a lower number of molars for Chinese, Asian consumers, however this effect is driven by the large difference between the old consumers.

Ethnicity had a significant effect on tongue width ($F(1,124) = 4.9$, $p = .029$) and tongue length ($F(1,124) = 8.6$, $p = .004$; Table 5.1). Chinese, Asian consumers had a wider (Chinese, Asian older adults 45.3 mm, Chinese, Asian adults 42.3 mm) and shorter tongue (Chinese, Asian older adults 21.5 mm; Chinese, Asian adults 25.0 mm) compared to Dutch, Caucasian consumers (Dutch, Caucasian older adults width: 41.4 mm, length: 28.3 mm; Dutch, Caucasian adults width: 39.4 mm, length: 26.5mm).

Ethnicity had a significant effect on head width ($F(1,124) = 5.7$, $p = .019$) with a significant interaction effect between ethnicity and age ($F(1,124) = 5.5$, $p = .020$). The Chinese had a slightly smaller head width (Chinese, Asian older adults 130.0 mm, Chinese, Asian adults 131.2 mm) compared to the Dutch (Dutch, Caucasian older adults 130.2 mm, Dutch, Caucasian adults 124.4 mm). This effect is due the large differences between the young groups. Ethnicity had a significant effect on ratio height:width of the head ($F(1,124) = 46.2$, $p = .001$) with a significant interaction effect between ethnicity and age ($F(1,124) = 11.1$, $p = .001$). The Chinese groups had a slightly lower ratio (mean Chinese, Asian adults of 1.56, mean Chinese, Asian older adults of 1.60) compared to the Dutch groups (mean Dutch, Caucasian adults of 1.68, mean Dutch, Caucasian older adults of 1.65). A higher ratio of the Dutch consumer groups indicated a more rectangular shaped head. The significant interaction effect indicates a larger difference between the young consumers.

Ethnicity had a significant effect on height ($F(1,124) = 29.1$, $p < .001$) and weight ($F(1,124) = 33.9$, $p < .001$) with Chinese, Asian consumer groups being shorter (Chinese, Asian older adults 1.62 m, Chinese, Asian adults 1.67 m,) weighing less (Chinese, Asian older adults 59.6 kg, Chinese, Asian adults 57.0 kg) compared to Dutch, Caucasian consumer groups (Dutch, Caucasian older adults 1.70 m and 66.4 kg, Dutch, Caucasian adults 1.76 m and 67.8 kg). BMI was significantly ($F(1,124) = 12.1$ $p = .001$) lower for Chinese, Asian consumers groups (Chinese, Asian older adults 22.5 kg/m^2, Chinese, Asian adults 20.4 kg/m^2) compared to Dutch, Caucasian consumer groups (Dutch, Caucasian older adults m 23.0 kg/m^2, Dutch, Caucasian adults 22.1 kg/m^2).

Ethnicity did not have an effect on self-reported swallowing problems and volume of oral cavity.

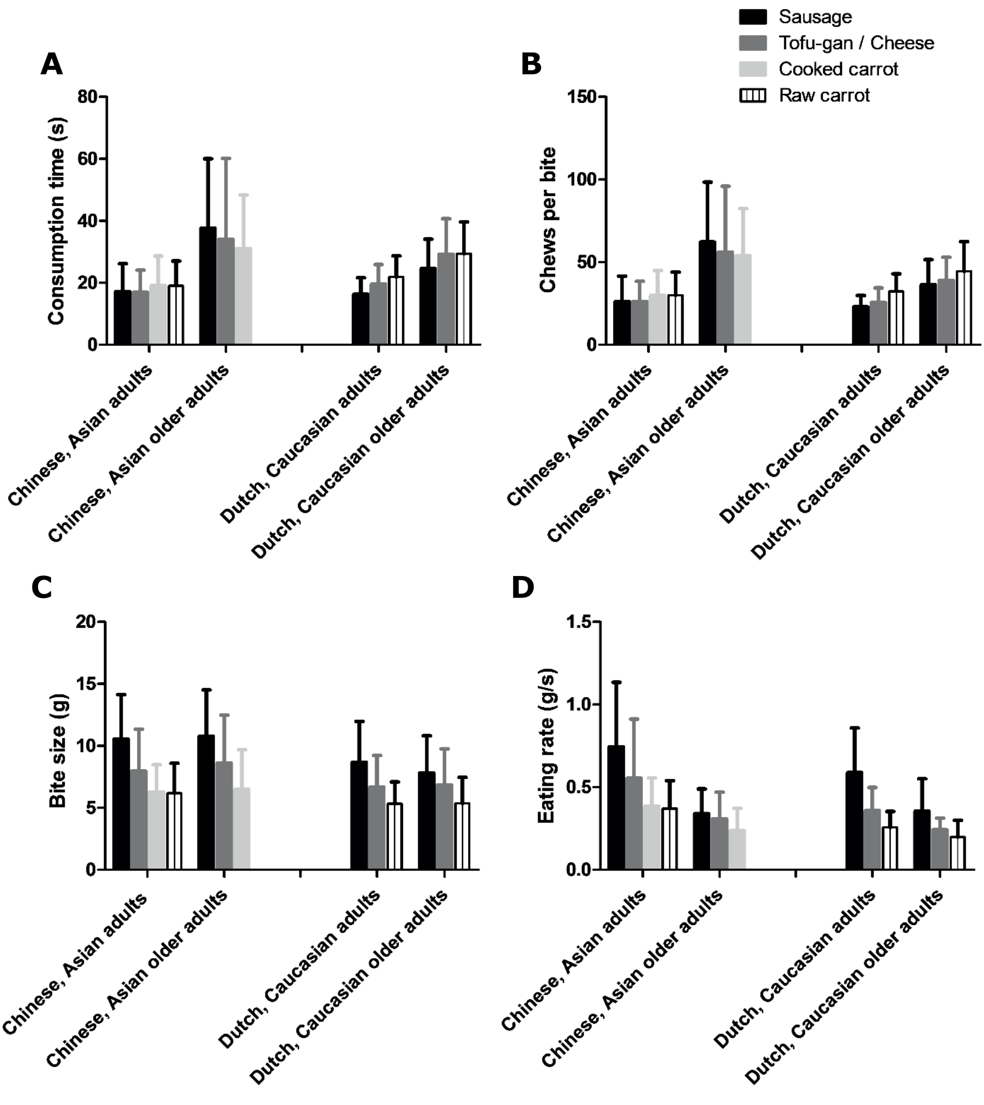

Figure 5.4: Oral processing behavior of sausage, tofu-gan / cheese, cooked carrot and raw carrot determined by (A) consumption time, (B) chews per bite, (C) average bite size (g) and (D) eating rate by Chinese, Asian adults (mean age 23.8 ± 1.0 yrs, n = 32), Chinese, Asian older adults (mean age 72.3 ± 7.9 yrs, n = 32), Dutch, Caucasian adults (mean age 21.5 ± 1.9 yrs, n = 32) and Dutch, Caucasian older adults (mean age 70.4 ± 4.3 yrs, n = 32). Error bars indicate standard deviation.

5

5.3.2 Comparison of oral processing behavior of solid foods

5.3.2.1 Effect of age on oral processing behavior: Comparison between Chinese, Asian adults and Chinese, Asian older adults

Average consumption time (s) was significantly affected by age ($F(1,59) = 26.5$, $p < .001$, Figure 5.4A) and a significant interaction effect between food and age was found ($p = .001$). Chinese, Asian older adults had longer average consumption time (s) of all foods (37.6 s for sausage, 34.0 s for tofu-gan, 31.1 for cooked carrot) than Chinese, Asian adults (17.2 s for sausage, 17.0 s for tofu-gan, 19.1s for cooked carrot). Chews per bite was significantly affected by age ($F(1,59) = 29.2$, $p < .001$) and a significant interaction effect between food and age was found ($p = .004$, Figure 5.4B). Chinese, Asian older adults consumed all foods with more chews per bite (62.2 chews/bite for sausage, 56.1 chews/bite for tofu-gan and 53.9 chews/bite for cooked carrot). Chinese, Asian adults had 26.1 chews/bite for sausage, 26.2 chews/bite for tofu-gan and 29.8 chews/bite for cooked carrot. No significant effect of age on chews per bite was found ($p > .05$, Figure 5.4C). Product had a significant effect on average bite size ($F(2,120) = 80.5$, $p < .001$), with 10.7 g for sausage, 8.3 g for tofu-gan, 6.4 g for cooked carrot and 6.2 g for raw carrot. Eating rate was significantly affected by age ($F(1,59) = 22.5$, $p < .001$) and food ($F(2, 118) = 59.9$, $p < .001$) and a significant interaction effect between age and food was found ($p = .048$, Figure 5.4D). Chinese, Asian older adults consumed all food with a lower eating rate (0.34 g/s for sausage, 0.31 g/s for tofu-gan and 0.24 g/s for cooked carrot) compared to Chinese, Asian adults (0.74 g/s for sausage, 0.55 g/s for tofu-gan and 0.38 g/s for cooked carrot).

5.3.2.2 Effect of ethnicity on oral processing behavior: Comparison between Chinese, Asian older adults and adults with Dutch, Caucasian older adults and adults

Ethnicity had a significant effect on eating rate ($F(1,93) = 292.7$, $p < .001$) with Chinese, Asian consumers having a higher eating rate (Chinese, Asian older adults mean of 0.29 g/s, Chinese, Asian adults: 0.51 g/s) compared to Dutch, Caucasian consumers (Dutch, Caucasian older adults mean: 0.27 g/s, Dutch, Caucasian adults mean: 0.40 g/s). Ethnicity did not influence average consumption time, chews per bite and average bite size.

Table 5.2: Pearson correlations of four oral processing parameters of Chinese, Asian adults and older adults.

	Average consumption time (s)	**Chews per bite (-)**	**Average bite size (g)**	**Eating rate (g/s)**
Average consumption time (s)	-			
Chews per bite (-)	0.949 **	-		
Average bite size (g)	0.192 **	0.207 **	-	
Eating rate (g/s)	-.197 **	-0.244 **	0.122 **	-

** Correlation is significant at $p < .01$

The Pearson's correlation coefficients of all oral processing parameters of the Chinese, Asian consumers indicate a very strong and positive correlation between average consumption time (s) and chews per bite ($r = .949$, $p < .001$) (Table 5.2). Box plots in Figure 5.5A and 5.5B visualize the within-group variation in oral processing behavior for the Chinese, Asian adults and Chinese, Asian older adults. Chinese, Asian older adults display a larger within-group variation compared to Chinese, Asian adults.

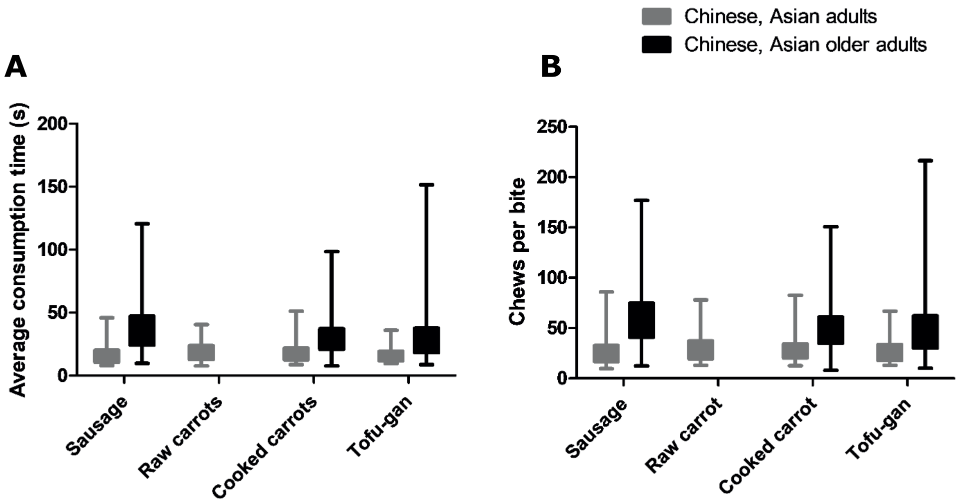

Figure 5.5: Within-group variation in oral processing behavior of Chinese, Asian adults (mean age 23.8 ± 1.0 yrs, n = 32) and Chinese, Asian older adults (mean age of 72.3 ± 7.9 yrs, n = 32) quantified by (A) average consumption time and (B) chews per bite. Whiskers indicate minimum and maximum.

5.3.3 Relationships between oral physiology, anatomy and oral processing behavior in Chinese, Asian adults and Chinese, Asian older adults

A multivariate linear regression analysis was performed to assess the relationships between the parameters describing oral physiology and anatomy and the four oral processing behavior parameters per product for Chinese, Asian consumers.

Unstimulated saliva flow rate was negatively related to average consumption time ($B = -0.272$, $p = .022$) and chews per bite ($B = -0.263$, $p = .012$) of sausage. Positive relationships were found between unstimulated saliva flow rate and eating rate of sausage ($B = 0.644$, $p = .013$), raw carrot ($B = 0.562$, $p = .015$) and cooked carrot ($B = 0.417$, $p = .047$). Stimulated saliva flow rate was negatively related to average consumption time of raw carrot ($B = -0.588$, $p = .020$).

Number of teeth was negatively related to eating rate of sausage ($B = -0.807$, $p = .020$), raw carrot ($B = -0.802$, $p = .012$) and cooked carrot ($B = -0.915$, $p = .003$). The relationship of number of teeth and eating rate of tofu-gan follows the same trend, but was not significant (B = -0.726, p = .063). Number of teeth was negatively related to average bite size of cooked carrot (B = -0.576, p = .039) and tofu-gan (B = -0.703, p = .022).

Mastication performance, assessed by median particle size, was negatively related to average consumption time of sausage (B = -0.404, p = .034) and raw carrot (B = -0.798, p = .039). A negative relationship was found between mastication performance and chews per bite of sausage (B = -0.330, p = .042).

Volume of oral cavity was positively related to average consumption time of raw carrot (B = 0.746, p = .015). A positive relationship was found between volume of oral cavity and chews per bite of sausage (B = 0.318, p = .014), raw carrot (B = 0.764, p = .018) and tofu-gan (B = 0.283, p = .034). Volume of oral cavity was negatively related to eating rate of raw carrot (B = -0.654, p = .022) and cooked carrot (B = -0.701, p = .011).

Self-reported swallowing problems, assessed with the EAT-10 score, were positively related to average consumption time (B = 0.189, p = .034) and chews per bite (B = 0.177, p = .022) of sausage. A negative relationship was found between the EAT-10 score and eating rate of sausage (B = -0.395, p = .037), raw carrot (B = -0.396, p = .023), cooked carrot (B = -0.382, p = .020) and tofu-gan (B = -0.490, p = .029). The EAT-10 score was negatively related to average bite size of cooked carrot (B = -0.335, p = .034) and tofu-gan (B = -0.333, p = .046).

Body weight was negatively related to average consumption time of raw carrot (B = -1.080, p = .013, Figure 5.6A) and positively related to eating rate of raw carrot (B = 0.859, p = .031, Figure 5.6B). No significant relationships were found for body height.

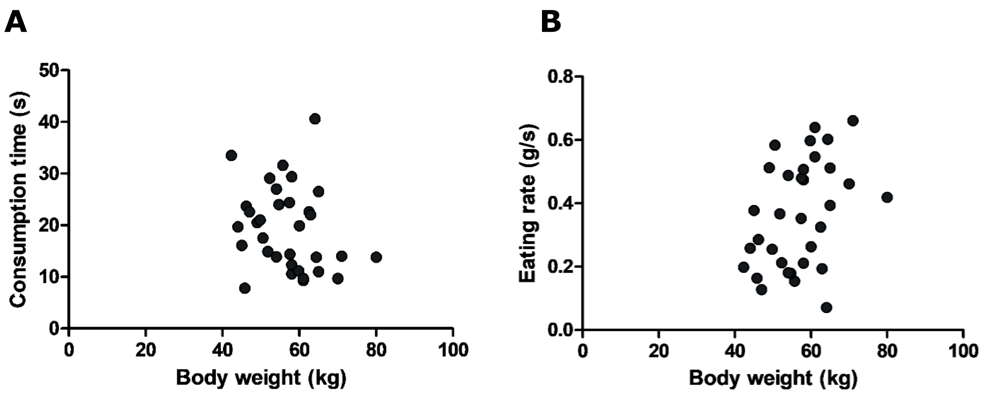

Figure 5.6: Relationship between body weight and (A) consumption time and (B) eating rate of raw carrots (B = .859, p = .031) by Chinese, Asian consumers (adults and older adults, mean age 48.1 ± 4.5 yrs, n = 64).

Head height was negatively related to chews per bite (B = -0.203, p = .022) and positively related to eating rate (B = 0.562, p = .012) of sausage. A positive relationship was found between head height and average bite size of cooked carrot (B = 0.377, p = .036). No significant relationships were found for head width and the ratio of head height by width.

5.4 Discussion

This study aimed to (1) compare oral physiology, anatomy and oral processing behavior of four consumer groups: Chinese, Asian adults and older adults, and Dutch, Caucasian adults and older adults understand; and (2) to compare the link between oral processing behavior and oral physiology and anatomy of consumers varying in age and ethnicity. Oral processing behavior, oral physiology and anatomy differed between Chinese, Asian adults and Chinese, Asian older adults. Thirty-three significant relationships were found between oral processing behavior and oral physiology and anatomy, with the relationship between body weight and consumption time as well as number of teeth and eating rate being the strongest. The results of the current study were compared to the results of a previous study (Ketel et al., 2020). The previous study found twenty-one significant relationships with the strongest relationships between body weight and oral processing behavior. Several differences between Dutch, Caucasian older adults and Chinese, Asian older adults with respect to their oral processing behavior and oral physiology and anatomy were found.

The current study found that Chinese, Asian adults had a better mastication performance, higher saliva flow rate, larger volume of oral cavity and a higher percentage of normal occlusion, compared to Chinese, Asian older adults. The decline in mastication performance with age might be caused by a decline in bite force with age as previously suggested (Laguna et al., 2015a). A previous study with a relatively healthy group of older adults did not find an effect of age on mastication performance (Ketel et al., 2020). The current study had slightly less strict selection criteria for the number of teeth. Chinese, Asian older adults were allowed to have a maximum of 4 missing teeth, compared to a maximum of 2 missing teeth for the Dutch, Caucasian older adults in the previous study. This slight difference could have contributed to a declined mastication performance. The alleviation of the selection criteria was necessary to be able to recruit a sufficient number of Chinese, older adults in China. The decline in saliva flow rate (Affoo et al., 2015; Percival et al., 1994; Vandenberghe-Descamps et al., 2016; Yeh et al., 1998) and the decrease in volume of oral cavity with age is in line with previous studies (Alsanei & Chen, 2014; Ketel et al., 2020). Length of tongue decreased slightly with age in the Chinese, Asians maybe due to execution of task, i.e. the willingness of the participant to stick out their tongue, as discussed in the previous study (Ketel et al., 2020). Chinese, Asian older adults had a longer average consumption time, needed more chews per bite until swallowing and therefore consumed foods with lower eating rate compared to Chinese, Asian adults. These results are in line with several previous studies, demonstrating that ageing increases consumption time and chews per bite and reduces eating rate regardless of the consumer's ethnicity (Ketel et al., 2019; Ketel et al., 2020; Kohyama et al., 2002; Peyron et al., 2004). The current study found a large variation in oral processing behavior and oral physiology within the Chinese, Asian older adults (Figure 5.5A & B). Previous studies indicated that the older adults form a highly heterogeneous group with respect to health status, nutritional needs and wants (den Uijl et al., 2016; Laguna et al., 2015a; van der Zanden et al., 2014).

Chinese, Asian consumers had a lower percentage of normal occlusion, a slightly wider and shorter tongue, lower height:width ratio of the head, and are shorter, weigh less and have a lower BMI compared to Dutch, Caucasian consumers. Minor differences for tongue dimensions were found, these effects could be due to physiological differences or due to the execution of the task, i.e. the willingness of the participants to stick out their tongue (Ketel et al., 2020). Therefore, we cannot conclude with certainty whether these differences are real physiological effects or noise caused by the limitation of the method. Chinese, Asian consumers had a higher median particle diameter, lower stimulated saliva flow, fewer teeth and molars and smaller head compared to Dutch, Caucasian consumers. However, these effects were driven by the large differences in above mentioned physiological parameters of the older consumers suggesting that physiological differences between Chinese, Asian adults and Dutch, Caucasian adults might actually be smaller. Chinese, Asian consumed foods with slightly higher eating rate compared to Dutch, Caucasian consumers, with a 7.4% increased eating rate for the older adults and 27.5% increased eating rate for the adults. This is in contrast to a previous study finding a smaller bite size and lower eating rate for Chinese, Asian consumers (Ketel et al., 2020). It should be noted that the experimental protocol followed to determine eating rate differed between this and the previous study. Chinese, Asian consumers of the current study were instructed to spit out the foods at the moment of swallowing, whereas Chinese, Asians of the previous study were instructed to swallow the food. A pilot test was conducted with n=20 Chinese, Asian adults (18-30 yrs), a subset of participants of the main study, to test whether consumption time increases when participants were instructed to chew and swallow the food. Three out of four foods had a significantly ($p < .05$) higher consumption time (consumption time increased by 26.4% for raw carrot, 24.5% for cooked carrot and 62.0% for tofu-gan) when foods were chewed until swallowing compared to chewed until expectorating. Consumption time of sausage did not differ between both mastication conditions. We speculate that these differences in consumption time could have increased consumption time of all Chinese, Asian consumers in the current study consequently leading to lower eating rates. This would then be in line with the results of the previous studies, indicating Chinese, Asian consumers having a longer consumption time and lower eating rate compared to Dutch, Caucasian consumers (Ketel et al., 2019; Ketel et al., 2020). The current study did not find an effect of ethnicity on bite size, which might be related to eating norms. Eating norms are known to be affected by consumption with a familiar person compared to someone unfamiliar, with a higher food intake in the presence of familiar people (Salvy et al., 2009). These eating norms could have influenced consumption time in the presence of familiar researchers in the current study compared to unfamiliar researchers in the previous study.

From the regression model, body weight and number of teeth resulted in the highest beta values, indicating to be of largest influence on oral processing behavior. An increase in body weight was associated with a decrease in consumption time and an increase in eating rate and bite size. Similar relationships between body weight and oral processing behavior were found previously (Bolhuis et al., 2014; Forde et al., 2013a, 2013b; Ketel et al., 2020; Ohkuma et al., 2015). High eating rates have previously been linked to higher BMI (Ohkuma et al., 2015). It is wondered whether eating rate is cause or effect. Number of teeth was found to be positively related to bite size and eating rate, indicating larger number of teeth facilitates oral processing behavior. The effect on bite size was found for all foods and therefore seems to be rather stable and essential for oral processing behavior. A decrease of saliva flow rate was associated with an increase in consumption time, chews per bite and a decrease in eating rate. These results confirm the facilitating role of saliva during oral processing by reducing consumption time and therefore increasing eating rate (Chen, 2009, 2014; Prinz & Lucas, 1997; Vandenberghe-Descamps et al., 2016). The previous study did not find these relationships with saliva flow rate (Ketel et al., 2020). This was probably due to the relatively high saliva flow rate of Dutch older adults, resulting in a relatively small range of variation in saliva. A decrease in mastication performance was associated with an increase in consumption time, chews per bite and bite size. These associations suggest sufficient mastication performance can assist oral processing behavior similar to sufficient saliva flow rate, this is in line with previous research (Ketel et al., 2020). A decrease in volume of oral cavity was associated with a decrease in consumption time, chews per bite and an increase in eating rate. An increase in the self-reported swallowing problems, assessed with the EAT-10 questionnaire, was associated with an increase in consumption time, chews per bite and a decrease in eating rate and bite size. These results suggest that swallowing problems could inhibit efficient oral processing behavior and therefore slow down consumption by decreasing eating rate. The previous study did not find any relationships between EAT-10 score and oral processing behavior (Ketel et al., 2020). This study included a relatively healthy population, which could have resulted in a relatively small range of EAT-10 scores. A larger height of the head is associated with a decrease in chews per bite and an increase in eating rate and bite size. These associations might be facilitated by volume of oral cavity, however volume of oral cavity and head height were not found to be significantly correlated ($r = .135$, $p = .090$).

To conclude, the results suggest that a decrease in body weight, number of teeth, saliva flow rate and mastication performance can inhibit oral processing by decreasing eating rate. Therefore, it is essential for consumers to maintain a healthy and proper functioning oral physiology to avoid issues with oral processing behavior. Food industry can also implement this knowledge by developing foods which can be easily masticated by consumers with decreased body weight, number of teeth, saliva flow rate and mastication performance. Facilitating easy and quick food consumption can be done by reducing product's hardness and increasing food moisture content.

Several minor issues in the design of the current study should be discussed, that could have influenced the outcomes of the current study. While the total of 128 participants were characterized for oral physiology, anatomy and oral processing behavior, the sample size per group was relatively small (n = 32). Future studies could investigate larger groups to quantify oral physiology, anatomy and oral processing behavior. The large variation in consumption time of the Chinese, Asian older adults suggests that there might be several sub-groups present within the Chinese, Asian older adults. Since the measurements were perceived as a relative high burden by the Chinese, Asian older adults, it was decided to not assess unstimulated salivary flow rate to reduce the duration of the test session. Consequently, it was not possible to look into the effect of age on unstimulated saliva flow rate of Chinese consumers. Chinese, Asian older adults were not instructed to consume the raw carrots since they perceived the raw carrots are too hard to consume comfortably and not for normal consumption. Therefore, the Chinese, Asian older adults consumed only the cooked carrot that slightly differed in fracture strain compared to the Chinese raw carrot and Dutch raw carrot. These minor product differences could have influenced the oral processing behavior.

5.5 Conclusions

Differences in food oral processing behavior can affect food intake and possibly BMI and health status. Therefore, it is relevant to better understand inter-individual differences in food oral processing behavior and differences between consumer groups. Age and ethnicity influenced oral physiology and anatomy and oral processing behavior. Several of the physiological and anatomical parameters were related to oral processing behavior of solid foods. Body weight and number of teeth were found to have the largest influence on the oral processing behavior. A decrease in number of teeth, saliva flow rate and mastication performance can inhibit oral processing by slowing consumption time and decreasing eating rate. Other factors, such as cultural factors, might explain the variation in oral processing behavior further.

Acknowledgements

The authors have declared that no competing interests exist. The project is funded by TiFN, a public - private partnership on precompetitive research in food and nutrition. The public partners are responsible for the study design, data collection and analysis, decision to publish, and preparation of the manuscript. The private partners have contributed to the project through regular discussion. The private partners are Royal FrieslandCampina, Fromageries Bel and Unilever. This research was performed with additional funding from the Top Consortia for Knowledge and Innovation of the Dutch Ministry of Economic Affairs.

The authors would like to thank Dr. Yong Chen for his assistance during data collection.

CHAPTER 6

6

Thickness, firmness and sweetness sensitivity do not differ between Chinese, Asian and Dutch, Caucasian adults

Eva C. Ketel
René A. de Wijk
Cees de Graaf
Markus Stieger

Submitted for publication.

Abstract

Sensitivity of the somatosensory system may be influenced by multiple physiological parameters and consumer characteristics. Variations in oral physiology can arise from differences in gender and ethnicity which may potentially affect sensory sensitivity. The aim of this study was to quantify texture and taste sensitivity in relation to consumer characteristics in consumers differing in ethnicity and gender. Eighty-five healthy subjects were recruited including n=44 Dutch, Caucasian (29 females, 22.8 ± 2.3 yrs) and n=41 Chinese, Asian adults (30 females, 24.5 ± 2.1 yrs). Three sets of stimuli were used to quantify sensitivity of thickness (maltodextrin solutions differing in viscosity), firmness (agar gels differing in fracture stress) and sweetness (sucrose solutions differing in concentration) perception using the 2-Alternative Forced Choice ascending staircase method. Saliva flow rate, fungiform papillae density (FPD), lingual tactile threshold and PROP taster status were determined to describe consumer characteristics. No significant differences were observed between Chinese, Asian and Dutch, Caucasian adults for thickness (Dutch 2.60 mPas, Chinese 2.19 mPas), firmness (Dutch 10.5 kPa, Chinese 10.3 kPa) and sweetness sensitivity (Dutch 0.012 g/mL, Chinese 0.017 g/mL). No significant differences were observed between Chinese, Asian and Dutch, Caucasian adults for saliva flow rate, FPD, lingual tactile threshold and PROP taster status. While no significant differences were observed between females and males for thickness and sweetness sensitivity, firmness threshold was significantly higher for females (11.1 kPa) than males (8.5 kPa). Females had significantly higher FPD (17.2 ± 3.9 count/cm^2) than males (13.7 ± 2.9 count/cm^2). Only one out of 15 relationships between sensory sensitivity (thickness, firmness, sweetness) and consumer characteristics (saliva flow rate, FPD, lingual tactile threshold, PROP taster status) was significantly and weakly related suggesting that inter-individual variation in these consumer characteristics is almost unrelated to sensory sensitivity. We conclude that texture (thickness, firmness) and taste (sweetness) sensitivity do not differ between Dutch, Caucasian and Chinese, Asian adults. Saliva flow rate, fungiform papillae density, lingual tactile threshold and PROP taster status do not explain inter-individual variation in sensory sensitivity between these consumers.

6.1 Introduction

Consumers show large variation in oral physiology and anatomy depending on age, gender and ethnicity (Ketel et al., 2020). It has been suggested that oral physiological parameters and consumer characteristics determine sensory sensitivity of consumers, such as detection and discrimination thresholds for texture and taste properties of foods (Nachtsheim & Schlich, 2013; Yackinous & Guinard, 2001). Changes in sensory sensitivity can lead to inadequate dietary behavior and consequently increase risk of malnutrition (Schiffman, 1993). Decreased sensory sensitivity can lead to increased consumption of sodium or sugar increasing risk of hypertension and diabetes mellitus (Rolls, 1999). Simpson et al. compared taste acuity in elderly in several European countries (Simpson et al., 2012). Age, gender and country of living were main predictors of taste acuity while each of these predictors influenced taste acuity differently depending on taste modality.

During ageing, texture (Kremer et al., 2007), taste and smell sensitivity (Cowart et al., 1994; Methven et al., 2012; Mojet et al., 2001; Stevens et al., 1998; Wiriyawattana et al., 2018) are well-known to decline. Several studies reported that females have higher taste sensitivity than males (Ahne et al., 2000; Gudziol & Hummel, 2007; Hyde & Feller, 1981; Landis et al., 2009; Michon et al., 2009; Pingel et al., 2010). However, few studies did not find differences in taste sensitivity between genders (Chang et al., 2006; James et al., 1997). In contrast to several studies exploring the effect of gender on taste sensitivity, the influence of gender on texture sensitivity has not be studied yet. Very little is known about the influence of ethnicity or country of living on taste and texture sensitivity. Ethnicity is known to influence oral processing behavior and sensory perception, possibly affecting sensory sensitivity (Ketel et al., 2019; Pedrotti et al., 2019). Geographical location has been suggested to influence taste perception. Baharuddin and Sharifudin found differences in sourness sensitivity between Malaysians living at the coast or inlands (Baharuddin & Sharifudin, 2015). However, multiple studies did not find differences in sensory perception between ethnicities (Blancher et al., 2008; Lundgren et al., 1986; Prescott & Bell, 1995; Teo et al., 2018). It is not clear which mechanism underlies the influence of geographical location or ethnicity on taste sensitivity and perception. Differences in dietary habits of consumers belonging to different ethnicities and/or living in different geographical locations can contribute to differences in taste sensitivity and perception (Rozin et al., 1981). Sensitivity of the somatosensory system may also be influenced by multiple physiological parameters and consumer characteristics. Sensory sensitivities of consumers have been related to consumer characteristics, such as saliva flow rate, fungiform papillae density (FPD), lingual tactile threshold and 6-n-propylthiouracil (PROP) taster status.

Saliva is known to facilitate oral processing behavior by providing lubrication to foods (Engelen & van Der Bilt, 2008; Nachtsheim & Schlich, 2013; van Eck et al., 2019) and can influence sensory perception and sensitivity. Saliva flow rate has been related to fat perception of milks (Nachtsheim & Schlich, 2013). Higher FPD has been related to more intense perception of sweetness and creaminess (Hayes & Duffy, 2007), saltiness (Miller Jr & Reedy Jr, 1990b), increased liking of coffee (Masi et al., 2015) and high-fat foods (Duffy & Bartoshuk, 2000). This suggests that inter-individual differences in FPD can contribute to inter-individual differences in sensory perception and liking. Aktar et al. found no correlations between texture sensitivity (firmness of gels and thickness of syrups) and lingual tactile thresholds (Aktar et al., 2015a, 2015b). PROP taster status has been linked to more intensive sweetness and bitterness perception (Bartoshuk et al., 1994) and to higher sweetness and bitterness sensitivity (Chang et al., 2006). PROP supertasters have lower lingual tactile thresholds than PROP non-tasters and medium-tasters, indicating higher tactile sensitivity (Yackinous & Guinard, 2001).

Variations in oral physiology and consumer characteristics can arise from differences in gender and ethnicity which may potentially affect sensory sensitivity. Gender seems to impact saliva flow rate with females having lower saliva flow rate than males (Inoue et al., 2006; Percival et al., 1994). Ethnicity does not seem to influence saliva flow rate (Ketel et al., 2020; Pedrotti et al., 2019; Santagiuliana et al., 2019). Regarding the influence of gender on FPD, previous studies are contradictionary. Several studies found higher FPD for females than males (Bartoshuk et al., 1994; Fischer et al., 2013; Hayes et al., 2008; Prutkin et al., 2000), while other studies found no difference in FPD between genders (Hayes & Duffy, 2007; Masi et al., 2015; Shen et al., 2016). Several studies did not find an effect of ethnicity on FPD (Miller Jr, 1986; Pedrotti et al., 2019; Santagiuliana et al., 2019), while a recent study found higher FPD in Chinese consumers compared to Danish consumers (Cattaneo et al., 2020). Komiyama et al. found higher tactile thresholds on the cheek for males than females, but no differences in lingual tactile thresholds between genders (Komiyama & De Laat, 2005). Lingual tactile thresholds did not differ between Belgian and Japanese consumers (Komiyama et al., 2007) and also not between Dutch and Chinese consumers (Santagiuliana et al., 2019) suggesting that ethnicity and/or country of living do not influence lingual tactile thresholds. PROP taster status differs between genders, with females being more often a supertaster than males (Bartoshuk et al., 1994). The distribution of PROP taster status in a population has been suggested to depend on ethnicity (Cattaneo et al., 2020; Tepper, 2008). However, this effect has not been confirmed by other studies (Genick et al., 2011; Santagiuliana et al., 2019). To summarize, variations in oral physiology can arise from differences in gender and ethnicity which potentially may affect sensory sensitivity and perception.

The aim of this study was to quantify texture (thickness, firmness) and taste (sweetness) sensitivity in relation to consumer characteristics in consumers differing in ethnicity and gender. Three sets of stimuli were used to quantify sensitivity of thickness (maltodextrin solutions differing in viscosity), firmness (agar gels differing in fracture stress) and sweetness (sucrose solutions differing in concentration) perception using the 2-Alternative Forced Choice ascending staircase method. Saliva flow rate, fungiform papillae density (FPD), lingual tactile threshold and PROP taster status were determined to describe consumer characteristics. We hypothesize that ethnicity and gender influence texture and taste sensitivity. Understanding variation in sensory sensitivity between different consumer groups might help to better understand differences in food choice behavior and food preferences between groups.

6.2 Materials and methods

6.2.1 Participants

Eighty-five healthy subjects were recruited, including 44 Dutch, Caucasian adults (29 females, 22.8 ± 2.3 yrs) and 41 Chinese, Asian adults (30 females, 24.5 ± 2.1 yrs). Dutch, Caucasian adults had Dutch nationality and Caucasian ethnicity, whereas Chinese adults had Chinese nationality and Asian ethnicity. All participants of the study lived in The Netherlands when the study was performed. Chinese, Asian adults lived outside China for less than one year. All participants had a BMI between 18.5 and 25 kg/m^2, no swallowing or mastication disorders, no missing teeth (with the exception of third molars or wisdom teeth), no taste or smell disorders (self-reported) and were generally healthy (self-reported). Participants were recruited via a study website, posters on the university campus, social media and a database. Most participants were students at Wageningen University. Interested participants were invited to an information meeting to fill in an inclusion questionnaire. All participants gave written informed consent to participate in the study. Participants received a financial compensation for their participation. The study was approved by the medical ethical committee of Wageningen University (NL51747.081.14).

6.2.2 Determination of texture and taste sensitivity

Participants were invited to three sessions of approximately 30 minutes to quantify texture and taste sensitivity. Within one session, only one set of samples and consequently only one attribute was evaluated by the participants. Data was collected on computers using EyeQuestion (version 4.11.57) in sensory booths of Wageningen University. Participants were instructed to not eat, drink coffee or chew chewing gum two hours before the start of the test session.

Texture and taste sensitivity were assessed using the 2-AFC ascending staircase method (Lawless & Heymann, 2013). Maltodextrin solutions, agar gels and sucrose solutions differing in concentration were used to assess thickness, firmness and sweetness sensitivity (Table 6.1). Participants received a pair of two samples (one test sample (Table 6.1:

samples 1-8) and one control sample) and were asked to indicate which sample of the pair was perceived as thicker, firmer or sweeter. Participants received the sets of samples in the same order, starting with sucrose solutions, maltodextrin solutions and agar gels. Maltodextrin solutions (thickness) and sucrose solutions (sweetness) were provided in medicine cups (15 mL). Agar gels (firmness) were provided as cylindrical disks of 5 mm height and 26 mm diameter. The concentration of the test sample in the 2-AFC test was increased stepwise from one pair to the next pair for up to 8 pairs following the 2-AFC ascending staircase method (Table 6.1). All participants completed the test for all 8 pairs per session. The sensitivity threshold was determined for each participant for thickness, firmness and sweetness as the test sample with the lowest concentration that has been correctly identified as the more intensive stimulus.

Table 6.1: Overview of composition, rheological and mechanical properties of all stimuli used for determination of thickness, firmness and sweetness sensitivity using the 2-Alternative Forced Choice ascending staircase method.

	Thickness			**Firmness**			**Sweetness**
Stimulus	Maltodextrin (g/mL)	Maltodextrin (% w/w/)	Viscosity (mPas)	Agar (g/mL)	Agar (% w/w)	Fracture stress (kPa)	Sucrose (g/mL)
Control sample	0	0	0.89	$1.07 * 10^{-5}$	1.07	70.0	0
1	0.0001	0.01	1.00	$1.09 * 10^{-5}$	1.09	72.1	0.0025
2	0.042	4.17	1.50	$1.11 * 10^{-5}$	1.11	74.3	0.005
3	0.083	8.34	2.25	$1.12 * 10^{-5}$	1.12	76.5	0.01
4	0.125	12.51	3.38	$1.14 * 10^{-5}$	1.14	78.8	0.02
5	0.167	16.69	5.06	$1.16 * 10^{-5}$	1.16	81.2	0.04
6	0.209	20.86	7.59	$1.18 * 10^{-5}$	1.18	83.6	0.08
7	0.250	25.03	11.39	$1.20 * 10^{-5}$	1.20	86.1	0.16
8	0.292	29.20	17.09	$1.22 * 10^{-5}$	1.22	88.7	0.32

Sensitivity thresholds were determined following two procedures. Individual Best Estimated Thresholds (BET) were calculated as the geometric mean of the highest concentration missed and the next higher concentration correctly identified as more intensive (Lawless & Heymann, 2013). Cumulative frequency of correct answers obtained with the 2-Alternative Forced Choice ascending staircase method were calculated for all pairs for thickness as a function of viscosity difference between control stimulus (water) and test sample (maltodextrin solution), for firmness as a function of fracture stress difference between control stimulus (agar gel) and test sample (agar gels) and for sweetness as a function of sucrose concentration difference between control stimulus (water) and test sample (sucrose solutions). Cumulative frequency of correct answers of 75% (half way between chance level (50%) and perfect performance (100%)) was determined as estimate of sensitivity threshold by interpolation of the data assuming linearity.

6.2.2.1 Sample preparation and characterization

Table 6.1 provides an overview of all stimuli used. Eight maltodextrin solutions differing in concentration were prepared (Table 6.1). Maltodextrin (Nutricia, The Netherlands) was dissolved in demineralized water. Maltodextrin concentrations were chosen so that viscosity increased stepwise between solutions by a factor of 1.5x. Rheological properties of all maltodextrin solutions were determined using a Modular Compact Rheometer 302 (MCR 302, Anton Par, Graz Austria). 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 again. Three replicates were measured and the average viscosity obtained. All maltodextrin solutions displayed Newtonian flow behavior. Sucrose (Van Gilse Kristalsuiker, the Netherlands) was added to all solutions to match sweetness between solutions. Concentration of added sucrose decreased with increasing maltodextrin concentration since maltodextrin provided a slight sweet taste to the solutions (control sample (water, no maltodextrin): 0.033 g/g sucrose, sample 1: 0.033 g/g sucrose, sample 2: 0.031 g/g sucrose, sample 3: 0.028 g/g sucrose, sample 4: 0.026 g/g sucrose, sample 5: 0.023 g/g sucrose, sample 6: 0.021 g/g sucrose, sample 7: 0.018 g/g sucrose, sample 8: 0.016 g/g sucrose). All solutions were perceived as equally sweet but differed in thickness during a pilot test (data not shown).

Eight agar gels were prepared (Table 6.1) by hydrating different amounts of agar (Ferwo agar 700, Caldic Ingredients B.V., Oudewater, The Netherlands) and vanilla aroma (Dr. Oetker, The Netherlands) in demineralized water while stirring for 30 minutes. Vanilla aroma (0.3 mg/g agar solution) was added to increase palatability. After hydration, agar solutions were heated in a water bath at 95 °C for 45 minutes while stirring. Warm agar solutions were poured into cylindrical plastic tubes (Omnifix 65mL syringes, B. Braun), which were lightly coated with sunflower oil. Gels were kept in the fridge at 4°C for at least 12 h to let the agar gels set. After gelation, gels were removed from the tubes and cut into cylindrical disks of 5 mm height and 26 mm diameter. Gels were removed from the fridge 2 h before the start of the test sessions. A previous study suggested that a difference in fracture stress of approximately 10 kPa can be perceived as a difference in firmness of agar gels (Santagiuliana et al., 2018). Agar concentrations were therefore chosen so that fracture stress increased stepwise between agar gels by a factor of 1.2x relative to the control sample (fracture stress of 70 kPa). Mechanical properties of all eight agar gels were determined by uniaxial compression tests using a Texture Analyzer (TA.XT plus, Stable Micro Systems-SMS). The uniaxial compression was performed at room temperature with a speed of 1 mm/s up to a compression strain of 80% using a plate-plate geometry. Paraffin oil was added on top of the gels to minimize friction between gel and plate. Ten replicates were measured and the mean value for fracture stress determined.

Eight sucrose solutions differing in sucrose concentration were prepared by dissolving sucrose (Van Gilse, The Netherlands) in demineralized water. Sucrose concentrations were chosen so that concentration increased stepwise between sucrose solutions by a factor of 2x Demineralized water was used as control sample. Samples were cooled and served at room temperature.

6.2.3 Consumer characteristics

Four parameters describing consumer characteristics (saliva flow rate, fungiform papillae density (FPD), lingual tactile threshold, PROP taster status) were quantified during one session of 60 minutes. The measurements were performed by a trained researcher on one subject per session.

6.2.3.1 Stimulated and unstimulated saliva flow rate

Stimulated and unstimulated saliva flow rate of all participants was determined. Five minutes before the measurements participants were not allowed to drink any water and a short break was included between the two measurements. Participants were asked to spit out saliva every 30 s for 5 min into a pre-weighed plastic tube. Every time point when the participant needed to spit out saliva was indicated by the researcher. The cup was weighed before and after the test session and the unstimulated saliva flow rate (mL/min) obtained. A density of 1 g/mL was assumed for saliva to calculate saliva flow rate. A second saliva collection was done to determine stimulated saliva flow rate. Participants were again asked to spit out saliva every 30 s for 5 min while chewing on a piece of parafilm (5x5 cm). Chewing on the parafilm mimics mastication behavior and provides mechanical saliva stimulation. Stimulated saliva flow rate (mL/min) was determined by weighing the cup before and after the measurement.

6.2.3.2 Fungiform papillae density (FPD)

Fungiform papillae density was determined following the Denver Papillae Protocol (Nuessle, Garneau, Sloan, & Santorico, 2015). In brief, participants rinsed their mouth with water and the anterior part of the tongue was stained with blue food coloring (Dr. Oetker, The Netherlands). Pictures on the left and right side of the tongue were taken with a camera (Canon IXUS-500HS). The number of papillae was counted within a circular area of 10 mm diameter on the left and right side of the tongue, approximately 5 mm from the tip of the tongue and 5 mm from the midline. FPD did not differ significantly on the left and right side of the tongue. Therefore, the average FPD was used for data analysis.

6.2.3.3 Lingual tactile threshold

Lingual tactile threshold was determined with a set of Von Frey monofilaments (Baseline, Tactile, Fabrication Enterprises, USA). Von Frey monofilaments consist of nylon threads and are often used to measure tactile sensitivity on hand, feet or facial surfaces (Aktar et al., 2015b; Breen et al., 2019; Etter et al., 2017; Levin et al., 1978). Von Frey filaments differ in the force needed to bend the filament on the tongue, resulting in a specific point pressure that is applied on the tongue. Participants were blind-folded. Then a filament was pressed against the tip of the tongue of the participant or no filament was pressed against the tip of the tongue. Presentation order within pairs was randomized over subjects. Participants were asked to indicate during which trial they perceived the presence of pressure. Two small circles were marked on the left and right side of the tongue with blue food coloring (Dr. Oetker, The Netherlands) to indicate the locations for contact with the Von Frey filament. The location was approximately 5-10 mm from the tip and the midline of the tongue. An descending staircase method (2-AFC) was used with 3 correct identifications resulting in a filament with lower pressure and one incorrect indication of a filament with higher pressure. Participants started the first selection with the filament with the highest force. The oral tactile point pressure threshold was determined by the minimal force of correctly indicated pressure for three filaments in a row. Eight filaments were used with target forces of 0.08, 0.20, 0.39, 0.68, 1.57 and 3.92 mN. A previous study determined the stress applied on the tongue by these Von Frey filaments by determining the mean force of each filament on a lab balance and quantifying the contact area of the filaments (Santagiuliana et al., 2019). The stress applied by the filaments corresponds to 16.08, 21.48, 36.77, 49.62, 86.79 and 133.08 mN mm^{-2}. Lingual tactile threshold did not differ significantly on the left and right side of the tongue. Therefore, the average threshold was used for data analysis.

6

6.2.3.4 PROP taster status

PROP taster status was determined using 6-n-propylthiouracil (PROP) tasting strips (Bartovation, USA). One strip was placed on the top of the anterior tongue of the participant for 10 s by the researcher. Participants first classified perception of bitterness as no bitter taste (non-tasters), regular bitter taste (medium-tasters) or revolting bitter taste (supertasters). Secondly, participants rated the bitterness intensity on a general Labelled Magnitude Scale (gLMS). Participants with a PROP rating of ≥ 51 ('very strong') were classified as supertasters, with rating ≤ 15.5 ('moderate') as non-tasters and medium-tasters scored in between (Tepper, Christensen, & Cao, 2001). The two measurements of the PROP taster grouping were highly correlated (Pearson Chi-Square < .001, Phi coefficient = .863). For the sake of clarity, the PROP taster status obtained by gLMS (continuous parameter) was used for the comparison of consumer groups.

6.2.3 Statistical data analysis

Data was analyzed using SPSS (IBM SPSS statistics, version 25). Normality of the variables was checked and non-normal distributed data was log-transformed. Data is presented as mean value and standard deviation (SD). Univariate ANOVA's were conducted separately for thickness, firmness and sweetness sensitivity with ethnicity and gender as fixed factors. Univariate ANOVA's were performed for average FPD, average lingual tactile threshold and PROP taster status by gLMS with ethnicity and gender as fixed factors. A multivariate ANOVA was performed for unstimulated and stimulated saliva flow rate with ethnicity and gender as fixed factors.

A multivariate linear regression was conducted to study the link between thickness, firmness and sweetness sensitivity and the parameters describing consumer characteristics. All parameters were standardized to allow for comparison of standardized beta-coefficients. All sensitivity parameters (thickness, firmness and sweetness) were included as dependent variables and 5 consumer characteristics (unstimulated saliva flow, stimulated saliva flow, FPD, lingual tactile threshold and PROP taster status measured by gLMS) were included as covariates. Multicollinearity of variables was checked by visual inspection of the data using bi-plots, highly correlated variables ($r > 0.7$) and high variance inflation factor (VIF > 5). Based on these criteria no variables were removed from analysis. Pearson correlations of individual thickness, firmness and sweetness sensitivity scores and the five consumer characteristics were conducted to explore inter-relationships.

Table 6.2: Best Estimate Thresholds (BET) for thickness, firmness and sweetness. Mean values are shown with standard deviation for different consumer groups.

	Dutch, Caucasian adults (n = 44)	**Chinese, Asian adults (n = 41)**	**Females (n = 59)**	**Males (n = 26)**
Thickness sensitivity (mPas)	2.60 ± 3.24	2.19 ± 3.20	2.58 ± 3.62	2.01 ± 2.00
Firmness sensitivity (kPa)	10.47 ± 5.09	10.34 ± 4.57	11.13 ± 4.44 *	8.52 ± 5.40 *
Sweetness detection threshold (g/mL)	0.012 ± 0.038	0.017 ± 0.050	0.013 ± 0.042	0.018 ± 0.049

* Effect is significant at $p < 0.05$

6.3 Results

6.3.1 Effect of ethnicity and gender on texture and taste sensitivity

Best Estimate Threshold (BET) values for thickness, firmness and sweetness sensitivity are shown in Table 6.2 and cumulative frequency of correct answers obtained with the 2-Alternative Forced Choice ascending staircase method for thickness, firmness and sweetness in figure 6.1 A-C.

Ethnicity did not significantly influence BET for thickness ($p > .05$), firmness ($p > .05$) and sweetness sensitivity ($p > .05$). The BET values for thickness was 2.60 ± 3.24 mPas for Dutch, Caucasian adults and 2.19 ± 3.20 mPas for Chinese, Asian adults. The estimated thickness threshold that corresponds to 75% correct answers was 3.12 mPas for Dutch, Caucasian adults and 2.52 mPas for Chinese, Asian adults (Figure 6.1A). The BET values for firmness were 10.5 ± 5.1 kPa for Dutch, Caucasian adults and 10.3 ± 4.6 kPa for Chinese, Asian adults. The estimated firmness threshold that corresponds to 75% correct answers was 17.5 kPa for Dutch, Caucasian

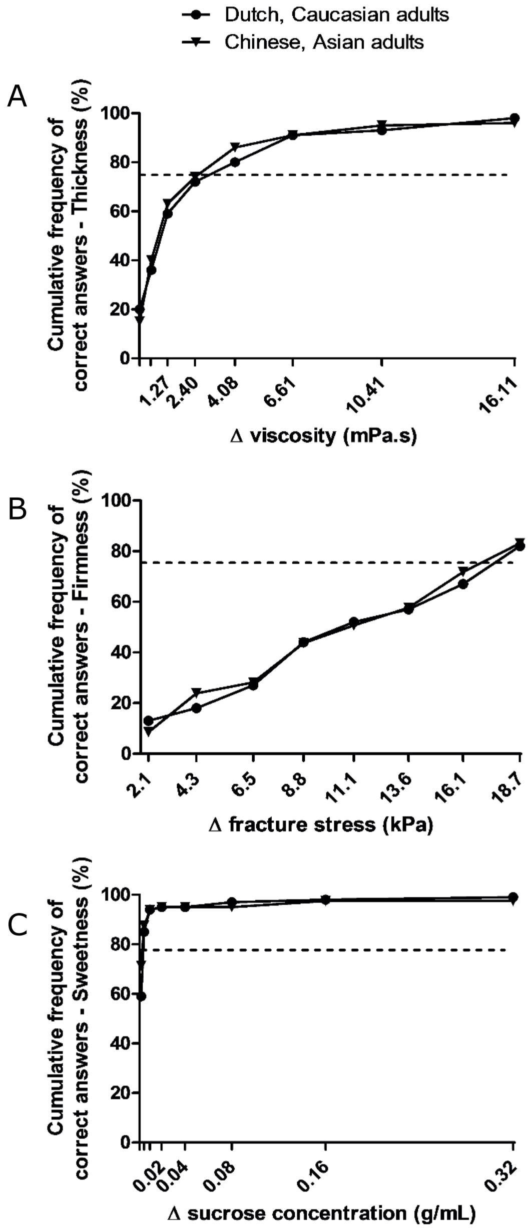

Figure 6.1: Cumulative frequency of correct answers obtained with the 2-Alternative Forced Choice ascending staircase method for (A) thickness as a function of viscosity difference between control stimulus (water) and maltodextrin solutions, (B) firmness as a function of fracture stress difference between control stimulus (agar gel) and agar gels and (C) sweetness as a function of sucrose concentration difference between control stimulus (water) and sucrose solutions. Dutch, Caucasian adults (n=44) are represented as circles and Chinese, Asian adults (n=41) as triangles. Dotted lines indicate a cumulative frequency of correct answers of 75%.

adults and 16.8 kPa for Chinese, Asian adults (Figure 6.1B). The BET values for sweetness was 0.013 ± 0.038 g/mL for Dutch, Caucasian adults and 0.017 ± 0.050 g/mL for Chinese, Asian adults. The estimated sweetness threshold that corresponds to 75% correct answers was 0.0040 g/mL for Dutch, Caucasian adults and 0.0031 g/mL for Chinese, Asian adults (Figure 6.1C).

Gender did not significantly impact thickness ($p > .05$) and sweetness sensitivity ($p > .05$). The BET for thickness was 2.58 ± 3.62 mPas for females and 2.01 ± 2.00 mPas for males. The thickness threshold that corresponds to 75% correct answers was is 4.08 mPas for both consumer groups. The BET for sweetness sensitivity was 0.0128 ± 0.042 g/mL for females and 0.0179 ± 0.049 g/mL for males. The sweetness threshold that corresponds to 75% correct answers was 0.005 g/mL sucrose for both consumer groups. In contrast to thickness and sweetness sensitivity, firmness sensitivity was significantly affected by gender ($F(1,73) = 7.4$, $p = .008$). Females had a significantly higher BET for firmness (11.1 ± 4.4 kPa) compared to males (8.5 ± 5.4 kPa). The estimated firmness threshold that corresponds to 75% correct answers was 18.1 kPa for females and 16.1 kPa for males.

Pearson's correlations revealed that thickness, firmness and sweetness thresholds were not significantly correlated ($p > .05$).

6.3.2 Effect of ethnicity and gender on consumer characteristics

Stimulated and unstimulated saliva flow rate, fungiform papillae density (FPD), lingual tactile threshold and PROP taster status of all participants are shown in Table 6.3.

Table 6.3: Effect of ethnicity and gender on consumer characteristics such as saliva flow rate, PROP taster status, fungiform papillae density, lingual tactile threshold.

	Dutch, Caucasian adults (n = 44)	**Chinese, Asian adults (n = 41)**	**Females (n = 59)**	**Males (n = 26)**
Saliva flow rate				
Unstimulated (g/mL)	0.54 ± 0.38	0.50 ± 0.29	0.52 ± 0.34	0.51 ± 0.33
Stimulated (g/mL)	1.35 ± 0.61	1.33 ± 0.67	1.31 ± 0.57	1.41 ± 0.78
PROP taster status				
Non-taster (%)	27.3	24.4	21.7	36.0
Medium-taster (%)	52.3	43.9	58.3	24.0
Super-taster (%)	20.5	31.7	20.0	38.5
Fungiform papillae density (count/cm^2)	16.9 ± 3.7	15.4 ± 4.1	17.2 ± 3.9 *	13.7 ± 2.9 *
Lingual tactile threshold (g mm^{-2})	2.26 ± 0.79	2.05 ± 0.78	2.17 ± 0.84	2.11 ± 0.67

* Effect is significant at $p < 0.05$

6.3.2.1 Saliva flow rate

Saliva flow rate, both unstimulated and stimulated, was not significantly affected by ethnicity ($p > .05$) or gender ($p > .05$). Dutch, Caucasian adults had an unstimulated saliva flow rate of 0.54 ± 0.38 g/mL compared to 0.50 ± 0.29 g/mL for Chinese, Asian adults. Stimulated saliva flow was 1.35 ± 0.61 g/mL for Dutch, Caucasian adults and 1.33 ± 0.67 g/mL for Chinese, Asian adults. Females had an unstimulated saliva flow of 0.52 ± 0.34 g/mL compared to 0.51 ± 0.33 g/mL for males. Stimulated saliva flow was 1.31 ± 0.57 g/mL for females and 1.41 ± 0.78 g/mL for males.

6.3.2.2 Fungiform papillae density (FPD)

Fungiform papillae density (FPD) was not significantly ($p > .05$) different for Dutch, Caucasian adults (16.9 ± 3.7 count/cm^2) and Chinese, Asian adults (15.4 ± 4.1 count/$cm^{2)}$. Females (17.2 ± 3.9 count/cm^2) had a significantly ($F(1,74) = 17.2$, $p < .001$) higher FPD compared to males (13.7 ± 2.9 count/cm^2).

6.3.2.3 Lingual tactile threshold

Lingual tactile threshold was not affected by ethnicity ($p > .05$) or gender ($p > .05$). Dutch, Caucasian adults had a lingual tactile threshold of 2.26 ± 0.79 g mm^{-2} compared to 2.05 ± 0.78 g mm^{-2} for Chinese, Asian adults. Females had a lingual tactile threshold of 2.17 ± 0.84 g mm^{-2} compared to 2.11 ± 0.67 g mm^{-2} for males.

6.3.2.4 PROP taster status

PROP taster status was not significantly affected by ethnicity ($p > .05$) or gender ($p > .05$). For Dutch, Caucasian adults 27.3% were non-tasters, 52.3% medium-tasters and 20.5% supertasters of PROP. Chinese, Asian adults had a similar distribution with 24.4% non-tasters, 43.9% medium-tasters and 31.7% supertasters of PROP. For females 21.7% were non-tasters, 58.3% medium-tasters and 20.0% supertaster and for males 36.0% non-tasters, 24.0% medium-tasters and 38.5% supertasters of PROP.

6.3.3 Linking texture and taste sensitivity to consumer characteristics

A multivariate linear regression model was performed to assess relationships between thickness, firmness and sweetness sensitivity and saliva flow rate (stimulated and unstimulated), FPD, lingual tactile threshold and PROP taster status. Fourteen out of 15 relationships between texture and taste sensitivity and consumer characteristics were not significantly correlated ($p > .05$). The only significant and weakly positive correlation ($B = 0.286$, $p = .036$) found was between firmness sensitivity and FPD indicating that participants with a higher FPD were associated with a slightly higher firmness threshold, so with a slightly lower firmness sensitivity. The MANOVA indicated that PROP taster status, measured as categorical parameter, did not have a significant effect ($p > .05$) on thickness, firmness and sweetness sensitivity.

6.4 Discussion

The aim of this study was to quantify texture (thickness, firmness) and taste (sweetness) sensitivity in relation to consumer characteristics in consumers differing in ethnicity and gender. No significant differences in thickness, firmness and sweetness sensitivity were observed between Dutch, Caucasian and Chinese, Asian adults. No significant differences in saliva flow rate, FPD, lingual tactile threshold and PROP status were observed between Dutch, Caucasian and Chinese, Asian adults. Gender had no significant effect on thickness and sweetness sensitivity, but had a significant effect on firmness sensitivity with females having higher firmness thresholds than males. Fourteen out of 15 relationships between texture and taste sensitivity and consumer characteristics were not significantly related. The only significant and weakly positive correlation found was between firmness sensitivity and FPD, indicating that participants with a higher FPD were associated with a slightly higher firmness threshold. FPD was the only consumer characteristic that differed significantly between genders with females having a higher FPD than males.

Texture and taste sensitivity were not affected by ethnicity and only firmness sensitivity was affected by gender. These results are in line with a previous study investigating particle size detection thresholds in various foods giving rise to grittiness perception. Particle size detection threshold did not differ between Dutch, Caucasian and Chinese, Asian adults (Santagiuliana et al., 2019). This suggests that texture sensitivity in general (thickness, firmness, grittiness) seems to be stable across populations originating from different geographical locations and belonging to different ethnicities. Little evidence can be found demonstrating an effect of ethnicity on sensory perception (Bertino et al., 1983), while the majority of studies found remarkable similarities in sensory properties of foods assessed by consumers varying in ethnicity (Blancher et al., 2008; Lundgren et al., 1986; Prescott & Bell, 1995; Teo et al., 2018). Differences in dietary habits by consumers varying in ethnicity have been suggested to affect taste sensitivity (Rozin et al., 1981). The relationships between dietary habits and taste sensitivity have not been investigated in the current study, so future studies are needed to explore these relationships.

The BET value for sweetness in our study was on average 0.015 g/mL. Previously, lower sweetness thresholds of 0.0036 g/mL have been reported (Hyde & Feller, 1981). The difference in sweetness threshold between the current and previous studies could be due to the selected sucrose concentrations in the current study. The majority of participants (67.2%) was able to correctly select the sweetest sample already in the 2-AFC pair that compared the lowest sucrose concentration (0.0025 g/mL) with water. Including lower sucrose concentrations than 0.0025 g/mL in the current study would have allowed to determine the sweetness BET value more accurately. The sweetness threshold found in this study might therefore be an overestimation. We acknowledge this limitation and emphasize that the sweetness BET value should be interpreted with caution.

Ethnicity did not affect any of the consumer characteristics. Saliva flow did not differ between Dutch, Caucasian adults and Chinese, Asian adults, which is in line with previous studies (Ketel et al., 2020; Santagiuliana et al., 2019). The current study did not find an effect of ethnicity on FPD which is also in line with previous studies (Miller Jr, 1986; Pedrotti et al., 2019; Santagiuliana et al., 2019). Lingual tactile threshold was not affected by ethnicity in the current study. Several studies investigated the effect of ethnicity on lingual tactile threshold and found no difference between different ethnicities (Cattaneo et al., 2020; Essick et al., 2003; Komiyama et al., 2007; Santagiuliana et al., 2019). The average lingual tactile threshold of the current study was rather low (mean: 2.16 g mm^{-2}). Most participants (69.4%) correctly sensed already a tactile stimulation of the weakest Von Frey filament used (1.64 g mm-2). This suggests that a floor effect occurred and that the lingual tactile threshold of these participants of our study might be lower. Consequently, the current study might overestimate the lingual tactile threshold and an accurate determination of the lingual tactile thresholds was not possible with these Von Frey filaments. Similar limitations of these Von Frey filaments have been reported previously (Santagiuliana et al., 2019). Since the Von Frey filaments are originally developed to test tactile finger sensitivity, the filaments seem to be not sufficiently sensitive to determine lingual tactile thresholds accurately. More sensitive methods need to be developed to do so. The current study did not find an effect of ethnicity on PROP taster status. Previous studies proposed that ethnicity could influence PROP taster status (Baranowski et al., 2010; Tepper, 2008). However, no studies so far have been able to find this relationship. Gender only affected FPD while no effect of gender on the other consumer characteristics was found. Several studies reported higher saliva flow rate for males compared to females (Inoue et al., 2006; Percival et al., 1994), while other studies did not find differences in saliva flow rate between genders (Ketel et al., 2020). This could be due to a relatively small sample size of the current study. Females had a significantly higher FPD compared to males which is in line with multiple other studies (Bartoshuk et al., 1994; Fischer et al., 2013; Hayes et al., 2008; Prutkin et al., 2000). Gender did not influence lingual tactile threshold, but as acknowledged before, the limited accuracy of the determination of the lingual tactile thresholds using the Von Frey filaments might have prevented us to find smaller differences in thresholds between genders. PROP taster status did not differ between females and males. Previous studies found that females were more often supertasters than males (Bartoshuk et al., 1994). It should be noted that in the current study more females (n = 59) than males (n = 26) participated, which might have led to the lack of significance when comparing genders.

The current study investigated the relationships between sensory sensitivity and consumer characteristics. Only one significant and weak relationship was found between firmness sensitivity and FPD out of 15 possible relationships. Small within-group variation could have contributed to the lack of significant relationships, however, we consider the within-group variation of the current to be not small. PROP taster status, saliva flow rate (both unstimulated and stimulated) and lingual tactile threshold did not significantly relate with firmness, thickness and sweetness sensitivity. This is in line with a recent study investigating the relationships between grittiness sensitivity and the same consumer characteristics in similar consumer groups (Santagiuliana et al., 2019). Particle size detection was only related to salivary flow in semi-solid foods and no other significant relationships were found between grittiness sensitivity and consumer characteristics. Higher sucrose detection threshold in PROP non-tasters compared to tasters have been reported in South-Korean adults (Chang et al., 2006; Hong et al., 2005) and Irish children (Feeney et al., 2014). The current study did not find a relationship between sucrose detection threshold and PROP taster status measured by grouping and gLMS. It is not clear why the relationship was not found in the current study. Several studies found links between FPD and sweetness, creaminess and fattiness sensitivity (Hayes et al., 2008; Hayes & Duffy, 2007; Nachtsheim & Schlich, 2013), while other studies did not find links between FPD and bitterness and roughness sensitivity (Bakke & Vickers, 2008, 2011). The link between FPD and sensory sensitivity remains unclear in view of these contradicting results between studies. The link between PROP taster status and various sensory sensitivities has been investigated across different sensory properties with several studies finding relationships (de Wijk et al., 2007; Essick et al., 2003; Hayes & Duffy, 2007) while other studies did not find relationships (Bakke & Vickers, 2008; Nachtsheim & Schlich, 2013; Yackinous & Guinard, 2001). Green and colleagues suggested that caution should be taken when predicting sensory sensitivity with PROP sensitivity (Green et al., 2005). We conclude that the link between sensory sensitivity and consumer characteristics is still unclear and needs to be researched further. Previously, dietary habits have been related to taste sensitivity (Rolls, 1999; Rozin et al., 1981; Schiffman, 1993). Since the current study did not find taste (sweetness) and texture (thickness, firmness) sensitivity differences between ethnicities, this suggests that differences in dietary habits between ethnicities or consumer living in different countries and cultures cannot be explained solely by taste and texture sensitivities. Cultural factors might play a considerably larger role than taste and texture sensitivity determining dietary habits of consumers belonging to different ethnicities.

6.5 Conclusions

The aim of this study was to quantify texture and taste sensitivity in relation to consumer characteristics in consumers differing in ethnicity and gender. We conclude that texture (thickness, firmness) and taste (sweetness) sensitivity do not differ between Dutch, Caucasian and Chinese, Asian adults. Gender affected only firmness sensitivity and FPD, whereas thickness and sweetness sensitivity and saliva flow rate, lingual tactile threshold and PROP taste status were not different between genders. Saliva flow rate, fungiform papillae density, lingual tactile threshold and PROP taster status do not explain inter-individual variation in these sensory sensitivities between consumers. Previous research found similar grittiness sensitivity between ethnicities, while the current study found similar results for thickness and firmness sensitivity. This suggests that texture sensitivity in general does not differ between ethnicities. Dietary intake is suggested to influence sensory sensitivity and could also be culturally determined. These relationships should be taken into account when investigating sensory sensitivities between ethnicities in future studies.

Acknowledgements

The authors have declared that no competing interests exist. The project is funded by TiFN, a public - private partnership on precompetitive research in food and nutrition. The public partners are responsible for the study design, data collection and analysis, decision to publish, and preparation of the manuscript. The private partners have contributed to the project through regular discussion. The private partners are Royal FrieslandCampina, Fromageries Bel and Unilever. This research was performed with additional funding from the Top Consortia for Knowledge and Innovation of the Dutch Ministry of Economic Affairs.

CHAPTER 7

General Discussion

This thesis aimed to understand which food properties and consumer characteristics (oral physiology, anatomy, sensory sensitivity and consumer phenotype) determine food oral processing behavior. Relationships between consumer characteristics and food oral behavior of consumers varying in age, gender and ethnicity were investigated. The main results of this thesis are summarized in section 7.1. The influence of food properties and consumer characteristics on food oral processing behavior is discussed in section 7.2. A conceptual framework of food oral processing behavior based on these factors is proposed and discussed in section 7.3. Methodological considerations and directions for future research (section 7.4) and practical implications and conclusions (section 7.5) are discussed.

7.1 Main findings

In chapter 2, it was found that both mechanical and rheological properties have a strong effect on the oral processing parameters of liquid, semi-solid and solid foods. Solid foods with increasing fracture stress resulted in increased consumption time and decreased bite size. Semi-solid and liquid foods with increasing consistency resulted in increased consumption time and decreased bite size.

Chapter 3, 4 and 5 investigated oral processing behavior differences for consumers varying in age, gender and ethnicity. During ageing, consumption time and chews per bite increase and eating rate decreases. These effects of ageing on oral processing behavior were found in all food categories, liquid, semi-solid and solid foods, and in both Dutch (chapter 3 & 4) and Chinese consumers (chapter 5). In chapter 3 and 4 gender was found to have a clear effect on oral processing behavior, with males having a larger bite size and higher eating rate compared to females. These effects of gender on oral processing behavior were found in all food categories, and in both Dutch (chapter 3 & 4), and Chinese consumers (not reported). Chapter 3 and 4 found that Chinese, Asian consumers had a smaller bite size and lower eating rate compared to Dutch, Caucasian consumers. In chapter 5 an opposite effect was found on oral processing behavior, due to differences in consumption instructions. The Chinese, Asian consumers in chapter 5 were instructed to chew and spit out the food at the moment of swallowing, compared to the instructions of chew and swallow in chapter 3 and 4. Therefore, we conclude that ethnicity does have an influence on oral processing behavior with a lower eating rate for Chinese, Asian consumers compared to Dutch, Caucasian consumers. In chapter 3, the effect of eating capability was investigated in healthy participants and was not found to affect oral processing.

Ageing was found to have a clear effect on oral physiology, with a decrease in dental status and volume of oral cavity with age. Chinese, Asian older adults had a lower saliva flow rate compared to Chinese, Asian adults, while this effect was not found in Dutch, Caucasian older adults compared to Dutch, Caucasian adults. We believe this is due to relatively healthy Dutch older adults. Males were found to have a larger volume of oral cavity and larger head dimensions compared to females. These effects were not investigated in previous research. Saliva flow rate seems to be lower for females compared to males, however differences in the current thesis were not statically different. Ethnicity was found to have an effect on oral physiology, while not all effects were found for both adult and older adult groups. Several physiological parameter, including mastication performance, saliva flow, number of teeth, are influenced by an interaction effect of ethnicity and age. Therefore extra caution should be taken when interpreting ethnicity effect while including consumers with large age range.

Chapter 4 and 5 found that oral physiological and anatomical parameters partially explain the variation in oral processing behavior. Number of teeth and body weight were found to have the highest beta-values, indicating to have the strongest relationship with oral processing behavior. Consumers with a low number of teeth and low body weight are found to have smaller bite size. However, consistency between products and oral processing parameters was lacking.

Chapter 6 found that thickness, firmness and sweetness sensitivity did not differ for consumer varying in ethnicity. Firmness sensitivity did differ for gender, however no effect was found for the other sensory properties. Phenotyping consumers based on saliva flow rate, fungiform papillae density, lingual tactile threshold and PROP taster status, does not seem to be linked to sensory sensitivity.

Table 7.1: Summary of the main findings of the studies described in this thesis

Chapter	Aim	Methods	Outcome measures	Main findings
2	To determine the influence of rheological and mechanical properties of foods on oral processing behavior of liquid, semi-solid and solid foods.	Video-recordings of 18 liquid, semi-solid and solid foods. Uniaxial compression test and flow curves assessed by rheology.	Oral processing behavior: Consumption time, chews per bite, bite size, eating rate, chewing rate. Food properties: Rheological and mechanical properties: apparent shear viscosity, stress at 15% strain, Young's modulus.	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. 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. Liking, familiarity, and consumption frequency impacted oral processing behavior to a considerable lower degree than rheological and mechanical properties.
3	To investigate the influence of age, gender, ethnicity and eating capability on oral processing behavior of liquid, semi-solid and solid foods.	Video-recordings of 18 liquid, semi-solid and solid foods.	Oral processing behavior: Consumption time, chews per bite, bite size, eating rate, chewing rate.	Age, gender and ethnicity impact oral processing behavior differently. Effects are very consistent for all three food groups. Consumption time increases and eating rate decreases with age. Males consume solid foods with larger bite size and higher eating rate than females. Chinese, Asians consume liquid, semi-solid and solid foods with smaller bite size and lower eating rate than Dutch, Caucasians.

4 & 5	To quantify oral processing behavior and oral physiology and anatomy of consumers varying in age, gender and ethnicity. To link parameters describing oral physiology and anatomy to food oral processing of consumers varying in age, gender and ethnicity.	Video-recordings of three solid foods. Quantification of oral physiology and anatomy.	Oral processing behavior: Consumption time, chews per bite, bite size, eating rate. Oral physiology and anatomy: Saliva flow rate, mastication performance, dental status, volume of oral cavity, head anatomy	Dutch older adults have smaller volume of oral cavity and lower number of teeth and consumed solid foods with higher eating rate than Dutch adults. Males have larger volume of oral cavity and larger head size than females. Chinese, Asian adults show minor differences in oral physiology compared to Dutch, Caucasian adults. Chinese, Asian older adults show large differences with Dutch, Caucasian older adults. Only few oral physiological and anatomical parameters are related to food oral processing behavior. Body weight and number of teeth have the strongest relationship with oral processing behavior.
6	To quantify texture and taste sensitivity and phenotype of consumers varying in gender and ethnicity. To investigate the link between sensory sensitivity and consumer phenotype.	Ascending staircase method: 2-AFC tests. Phenotyping of consumer characteristics.	Sensory sensitivity: Thickness, firmness and sweetness. Phenotype parameters: PROP taster status, Fungiform Papillae Density (FPD), Oral tactile threshold, Salivary flow rate.	Gender does not affect sweetness and thickness sensitivity but has a small effect on firmness sensitivity and FPD. Ethnicity has no effect on thickness, firmness and sweetness sensitivity and on any of the phenotype parameters. PROP taster status, FPD, oral tactile threshold and salivary flow rate are not linked to sensory sensitivity.

7

7.2 Determinants of food oral processing behavior

Figure 7.1 provides a comparative overview of the effects of product properties, consumer characteristics, oral physiology and anatomy on food oral processing behavior.

7.2.1 Effects of product properties on food oral processing behavior

The model of Hutchings and Lillford propose that every food has their own breakdown pathway, depending on their product properties and lubrication (Hutchings & Lillford, 1988). Rheological and mechanical food properties of liquid, semi-solid and solid foods have a large impact on oral processing behavior. Food texture has previously been found to influence oral processing behavior of single foods (Forde et al., 2017; Van den Boer et al., 2017). For liquid and semi-solid foods, there seems to be consensus that food viscosity (consistency and shear thinning behavior index) is the main driver of oral processing behavior (Aguayo-Mendoza et al., 2019; Chen & Lolivret, 2011). For solid foods, the current thesis found stress at 15% strain and Young's modulus to be main drivers of oral processing behavior. A previous study found significant correlations between oral processing behavior and texture properties (springiness, cohesiveness, chewiness and resilience) obtained by Textural Profile Analysis (TPA) (Wee et al., 2018). This demonstrates clearly that for solid foods mechanical and texture properties determine food oral processing behavior. Which mechanical and texture properties affect oral processing behavior might depend on the type of solid food. The model of Hutchings and Lillford also suggests lubrication is a key factor in the formation of a smooth bolus. Lubrication as fluids released from the food in combination with saliva can therefore influence of oral processing behavior. Investigation of lubrication during oral processing behavior was outside the scope of this thesis. Hall and colleagues have found an increased food intake for ultra-processed foods compared to unprocessed foods (Hall et al., 2019), an effect suggested to be mediated via eating rate, energy density and palatability (Forde et al., 2020; Rolls et al., 2020). These insights are useful for the modification of eating rate by changing the product properties. Eating rate can be modified to either (1) increase eating rate for vulnerable elderly and consequently increase food intake, or (2) decrease eating rate for overweight consumers and consequently decrease food intake (Bolhuis et al., 2014; McCrickerd et al., 2017). For example, consumption time is found to decrease with decreasing viscosity in yogurt (Mosca et al., 2019). Another study found that that peach gel particles with increasing hardness resulted in increased consumption time and decreased eating rate (Aguayo-Mendoza et al., 2020). These studies indicate oral processing behavior can be influenced by the modification of product properties.

7.2.2 Effects of consumer characteristics on food oral processing behavior

While rheological and mechanical food properties have a large impact on food oral processing behavior, consumer characteristics are a major factor contributing to inter-individual variation in food oral processing behavior.

During ageing, consumption time increases and eating rate decreases. Decreased eating rate in older adults is known to be a factor contributing to decreased food energy intake which adds to the risk of malnutrition. Previous research has suggested that chewing effort is related to oral processing behavior (Westenhoefer et al., 1994). Most consumers experience little problems with chewing effort, however during ageing dental status and strength of oral muscles decline so that chewing effort becomes more relevant and could therefore interfere with efficient oral processing behavior. It is important to note that the older adult consumers form a very heterogeneous group (den Uijl et al., 2016; Laguna et al., 2015a; van der Zanden et al., 2014). Older adults show a high variation in health status, nutritional needs and wants. These variations could potentially influence oral processing behavior. It should be noted that food habits play a large role in the eating behavior and potentially oral processing behavior (Wansink, 2004). Changing food habits during ageing could moderate effects on oral processing behavior.

Males consumed foods with higher eating rate compared to females. Males have a higher energy need and basal metabolic rate compared to females (Henry et al., 2018). A positive association was found between eating rate (g/s) and basal metabolic rate (BMR), indicating that differences in energy requirements between genders might impact eating behavior. This could explain the observed differences in eating rate between genders. Body size has been similarly discussed to be a mediating factor in food oral processing behavior (Hill & McCutcheon, 1984). Since males have larger body size, this could also contribute to larger bite size and higher eating rate. Differences in mealtime etiquette and food habits can also potentially affect oral processing behavior. Females have been taught to take small bites and pay attention to food intake more than males which could further add to the observed differences in oral processing behavior between genders (Hill & McCutcheon, 1984; Rolls et al., 1991).

		Oral processing behavior					
		Consumption time	Chews per bite	Number of swallows	Bite size	Eating rate	Chewing rate
Product properties	Stress (σ15)	-	↑	-	↓↓	↓↓	-
	Young's modulus	-	↑	-	↓↓	↓↓	-
	Consistency	↑↑	-	↑↑	↓↓	↓↓	-
	Flow behavior index n	↓↓	-	↓↓	↑↑	↑↑	-
Chapter 2	Product liking	-	-		↑	↑	-
	Product familiarity	↑	↑		-	-	-
	Frequency of consumption	-	↑		-	↑	-
Consumer characteristics	Age (older adults vs. adults)	↑↑	↑↑	-	↑↓	↓↓	-
	Gender (male vs. female)	-	-	-	↑↑	↑↑	-
	Ethnicity (Chinese vs. Dutch)	↑	-	-	↓↓	↓↓	-
Chapter 3, 4, 5	Eating capability (high vs. low)	-	-	-	-	-	-
Oral physiology	Saliva flow rate	-	-		↑	-	
Chapter 4, 5	Mastication performance	↓	↓		-	-	
	Dental status	↓	↓		↓	↑	
	Volume of oral cavity	-	-		↑	-	
	Head size	-	-		↑	-	
Anatomy	Head shape (rectangular vs square)	-	↑		↑	-	
	Tongue size	-	-		↑	↑	
Chapter 4, 5	Body weight	-	-		↑	-	
	Body height	-	-		-	-	

Figure 7.1: Comparative overview of the effects of product properties, consumer characteristics, oral physiology and anatomy on food oral processing behavior. Increased effects, decreased effects and no effects are illustrated with '↑', '↓' and '-', respectively. Single arrows indicate small effects and two arrows indicate large effects. Gray boxes represent parameters that were not studied.

Ethnicity influences food oral processing behavior. Chinese, Asians consumed food with lower eating rate compared to Dutch, Caucasians. Since eating rate is known to affect food intake and BMI, extra caution should be taken when developing food for consumers varying in ethnicity. Oral physiology and anatomy (dental occlusion status, tongue length and width, head height:width ratio and BMI) differed only slightly between Chinese, Asians and Dutch, Caucasians. It is therefore wondered which other factors moderate the oral processing behavior. The food environment differs largely for consumers varying in ethnicity or living in different countries, including many different factors such as attitude towards food consumption, cutlery use, eating atmosphere and distractions during consumption (Ma, 2015; Sun et al., 2015; Wansink, 2004). Consumption of a meal is considered an important family activity in Asian cultures (Ma, 2015). Since consumption with others is known to increase food intake (Herman et al., 2003), this could influence oral processing behavior in Asian cultures. Cutlery use is also known to affect consumption behavior. Eating with chopsticks results in smaller bite sizes compared to eating with cutlery (Sun et al., 2015). It should be noted that in our studies cutlery was only used for a few solid foods and no chopsticks were used. Therefore, it is wondered whether this difference habitual utensil use could lead to development of preferred or common bite size. Secondly, food habits differ between consumer groups belonging to different ethnicities. Habits could potentially affect oral processing behavior. Many habits and rituals are present during food consumption (Askegaard & Madsen, 1998; van't Riet et al., 2011), mainly driven by religion, culture and family (Ratcliffe et al., 1985). Food rituals can positively influence product perception (Vohs et al., 2013).

Differences in oral physiology and anatomy were hypothesized to moderate changes in oral processing behavior. However, oral physiological and anatomical parameters only partially explained the variation in oral processing behavior observed between different consumer groups. Other physiological parameters, food environment and food habits might play a larger role contributing to variation in food oral processing behavior between consumer groups. Previous research has investigated maximum bite force and tongue pressure in consumer groups differing in age and gender. As discussed in chapter 4, these parameters quantify maximum oral forces and are not relevant for oral processing behavior of healthy consumer. The forces needed to fracture hard solid foods such as nuts, carrots are considerably smaller than the maximum bite force of healthy adults. Salivary mucins lubricate and bind food particles into a coherent, smooth bolus (Nagler, 2004; Pedersen et al., 2002). Salivary mucins are known to decrease with age (Denny et al., 1991). Consequently, a low amount of mucins could inhibit smooth oral processing behavior. However, salivary mucins might only play a small role in oral processing behavior. Mastication is known to be affected by occlusion surface and contact area of the canines and molars (Bourdiol & Mioche, 2000). Males are known to have a larger surface and contact area, which could assist in oral processing behavior (Julien et al., 1996). Assessing occlusion surface and contact area require dental expertise and was therefore not assessed in the current thesis. Lip sealing has been suggested to be relevant for proper oral processing behavior (Laguna & Chen, 2016). Lip sealing is expected to be difficult in unhealthy older adults and stroke patients, we believe this parameter might not be relevant for healthy consumers and have a limited effect on older adults.

7.2.3 Effects of sensory sensitivity on food oral processing behavior

Sensory sensitivity has been suggested to be linked to sensory perception and could affect oral processing behavior (Nachtsheim & Schlich, 2013). Ethnicity does not impact thickness, firmness and sweetness sensitivity. Gender does not affect sweetness and thickness sensitivity, but has a small effect on firmness sensitivity. The results of this thesis indicate that sensory sensitivity is rather stable for Dutch and Chinese consumers.

However, oral processing behavior of these consumer groups differed (chapter 3, 4, 5). This suggests that sweetness, firmness and thickness sensitivity are not closely linked to oral processing behavior. It is speculated that texture and taste sensitivity in general are not strongly linked to oral processing behavior. Differences in dietary habits of consumers as a result of culture can contribute to differences in taste sensitivity and perception (Rozin et al., 1981). Therefore, we believe that differences in sensory perception is partially explained by sensory sensitivity and partially by environmental factors, such as exposure and culture.

Several studies found links between consumer phenotype and sensory sensitivity (de Wijk et al., 2007; Essick et al., 2003; Hayes et al., 2008; Hayes & Duffy, 2007; Nachtsheim & Schlich, 2013), while other studies did not find any links between consumer phenotype and sensitivity (Bakke & Vickers, 2008, 2011; Nachtsheim & Schlich, 2013; Yackinous & Guinard, 2001). This thesis found no strong and consistent links between consumer phenotype and sweetness, thickness and firmness sensitivity. Previously, doubts have been raised about the links between sensory sensitivity and consumer phenotype (Dinnella et al., 2018; Garneau et al., 2014; Webb et al., 2015). These studies suggest sensory sensitivity and food perception is a complex process that can't be measured with a single measurements. Webb and colleagues propose future research should include innovative methods to assess taste and texture function in details (Webb et al., 2015). Furthermore, a large set of stimuli should be included to fully understand sensory sensitivity. We conclude that the link between sensory sensitivity and consumer characteristics is still unclear and needs to be researched further.

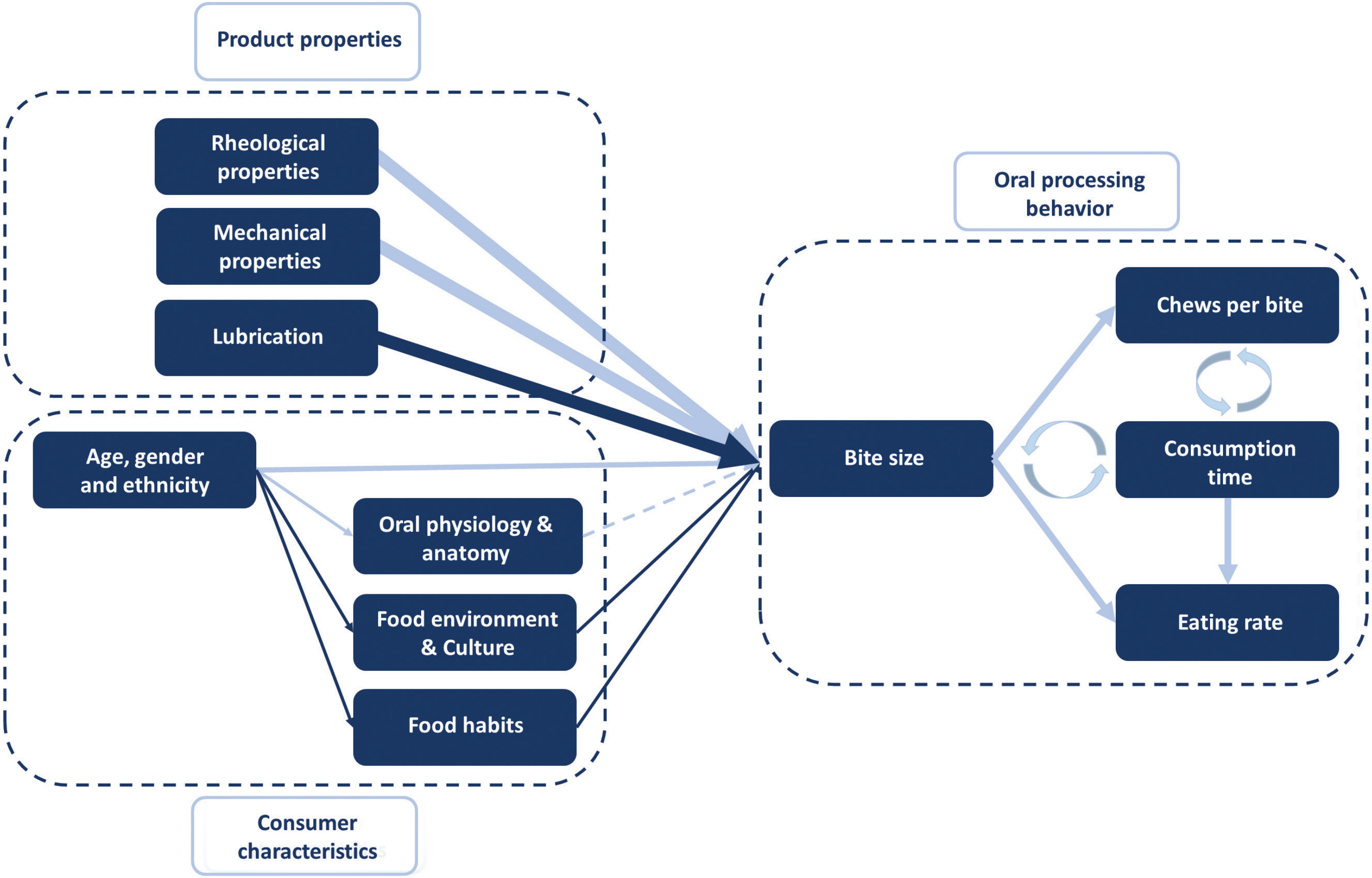

Figure 7.2: Conceptual framework of oral processing behavior and its determinants. Arrow size indicates the strength of relationships. Light blue arrows indicate investigated relationships, dark blue arrows indicate proposed relationships based on literature.

7.3 Conceptual framework of food oral processing behavior

Based on this thesis and previous research on oral processing behavior, a conceptual framework of food oral processing behavior is proposed (Figure 7.2). It is assumed that consumers orally process foods until the bolus is ready for swallowing. The properties of the bolus need to correspond to certain criteria with respect to lubrication, particle size and probably also bolus hardness. Food properties, mainly rheological and mechanical properties, and consumer characteristics such as age, gender and ethnicity moderated by oral physiology and anatomy influence bite size of foods. Bite size determines consumption time and chews per bite that is needed until the bolus reaches the individual criteria for a safe swallow. Consumers might have a preferred maximum consumption time of a single bite. Therefore, consumption time also influences bite size. Both bite size and consumption time determine eating rate.

In this conceptual framework product properties play a large role in determining oral processing behavior. Consumer characteristics have a secondary role in determining inter-individual variation in food oral processing behavior. Oral physiology and anatomy seem to moderate the effect of consumer characteristics on food oral processing behavior to a limited extend only. Culture and food habits are proposed to play a larger role in determining food oral processing behavior.

7.4 Methodological considerations and directions for future research

7.4.1 Selection of consumer groups

This thesis investigated the effect of age by comparing adults (18-30 years) and older adults (60-85 years). Recently, there has been a lot of discussion about the heterogeneity of older adults (den Uijl et al., 2016; Laguna et al., 2015a; van der Zanden et al., 2014). When are older adults considered 'old'? Several studies exploring the effect of age on oral processing behavior investigated older adults from the age of 55 years and older (Kohyama et al., 2003; Kohyama et al., 2002; Kossioni & Bellou, 2011), while other studies set the minimum age at 65 (Laguna et al., 2016; Mioche et al., 2004a) and several studies included older adults from the age of 80, often named 'the very old'. 'The very old' consumers are known for having a very low number of teeth and consequently resulting in a low nutrient intake (Marshall et al., 2002; Mojon et al., 1999; Nordström, 1990). We expect that the 'very old' consumers have are larger change in physiology and slower eating behavior compared to the older adults in this thesis. The slower eating behavior in the 'very old' consumers could be one of the factors resulting in a low nutrient intake. Chapter 4 and 5 discuss the large variation in oral processing behavior of older adults, indicating the highly heterogeneity of this consumer group. The older adults were selected based on several strict criteria, including dental status and general health, therefore reducing the heterogeneity of this group. It is wondered which other factors has resulted in the heterogeneous results in oral processing behavior. Since the older adults in this thesis were relatively healthy and had a maximum of four missing teeth, they are not representative for older adults. Future studies could investigate oral processing behavior of sub-groups of older adults, based on health status and age. It is suggested that the health status of older adults is highly dependent on national health care, physical activity and nutrient intake (Bautmans et al., 2004; Sweeney et al., 2007; van Lancker et al., 2012).

During ageing the prevalence of dysphagia, a combination of swallowing problems, increases due to neurological disorder, including stroke, Alzheimer's disease and Parkinson's (Humbert & Robbins, 2007). Dysphagia patients are known to avoid meal consumption with others, experience a high anxiety during food consumption and consequently have an increasing risk of dehydration and malnutrition (Ekberg et al., 2002). Future research could investigate oral processing behavior oral physiology and anatomy of dysphagia patients.

The effect of ethnicity on oral processing behavior was investigated by comparing Dutch, Caucasian and Chinese, Asian consumers. Chinese, Asian consumers were selected since this is a rapidly growing population and growing market for European food producers (McKay, 2007). Since the results of this thesis indicate clear differences in oral processing behavior between Dutch and Chinese consumers, it is wondered whether similar differences can be found for other ethnic groups, e.g. Afro-Americans, Latin-Americans. Extending the current research by investigating other ethnic groups would give more insights in oral processing behavior for consumers across the globe. Cultural factors driving oral processing behavior have not been investigated in the current research, but have been suggested to play a role in oral processing behavior. The effect of culture could be investigated by studying oral processing behavior of newly arrived Asian consumers and already integrated Asian consumers.

The consumer groups in the current thesis have a rather small sample size of typically around n=30. The groups are too small to represent parts of the population. Especially in highly heterogeneous consumer groups, such as older adults, larger sample size is needed. This could give more insights in the variation in consumers and make the results more generalizable to the specific populations. To reduce the time load of research, a selection of foods (see section 7.2.2) can be used to study oral processing behavior or only the most relevant physiological parameters can be selected (see section 7.2.3).

To fully understand the development of oral processing behavior, future research could investigate the development of oral processing behavior in children. Multiple studies found food fussiness to decline over time and texture preference change depending on exposure to different foods (Carruth & Skinner, 2000; Nicklaus & Schwartz, 2019; Schwartz et al., 2011). Investigation of children's oral processing behavior indicate a strong link between eating rate and food intake (Fogel et al., 2017a, 2017b). Oral processing behavior of monozygotic (identical) and dizygotic twins was assessed to understand the influence of genetic variation in oral processing behavior (Llewellyn et al., 2008). Correlations between eating rate and BMI were higher for monozygotic twins compared to monozygotic twins. Heritability was found to significantly estimate eating rate.

7.4.2 Selection of food products

The selected 18 food products in chapter 2 and 3 were chosen to represent a large range of textures, including liquid, semi-solid and solid foods. Naturally the 18 foods do not cover the standard food products consumed on a daily basis. Daily food consumption consists of single foods, a combination of two or more food products or a whole meal. Therefore, the results in chapter 2 and 3 give a first glance on the generalizability of the effect of rheological and mechanical properties on oral processing behavior. The selected foods in chapter 4 and 5 were chosen to represent a small range of solid textures, including firm textures (raw and cooked carrots) and softer textures (sausage, cheese and tofu-gan). While the carrots and sausage were included in both studies to ensure comparison between the two studies, this was not the case for the cheese and tofu-gan. Due to unfamiliarity of cheese in the Chinese population, it was decided to not include cheese in the Chinese study (chapter 5). Selecting another food product that is both familiar in the Dutch and Chinese culture would have ensured a better comparison between ethnicities. The results from chapter 3, 4 and 5 indicate that the effect of age, gender and ethnicity seem to be similar to all three food categories. Therefore, we propose solid foods can be used to investigate oral processing behavior to represent oral processing behavior of different food categories. Chapter 4 and 5 indicate that a smaller set of foods is appropriate to assess oral processing behavior of different consumers compared to including a larger set of foods as done in chapter 2 and 3. Future studies aiming to understand consumer differences in oral processing behavior, could therefore decide to select a relative small set of foods. However, it is advised to include more than one food to confirm differences in oral processing behavior in at least one other food.

Chapter 6 included a set of sucrose solutions to assess the sweetness threshold. The sucrose concentrations were too high to obtain an accurate Best Estimate Threshold (BET) for sweetness threshold. Ideally 50% of consumers would be able to correctly select half of the samples. In the case of sweetness sensitivity more than 90% of the participants were able to correctly select half of the samples. Future studies should include a sucrose concentration of 0.00125 g/mL and consider including an even lower concentration of 0.000625 g/mL.

7.4.3 Selection of methodologies

The current thesis investigated oral physiology and anatomy by determining mastication performance, saliva flow, dental status, volume of oral cavity, tongue dimensions and head dimensions. Mastication efficiency was measured with Optosil, an artificial rubber. This material can be easily modified in any food shape and size and is not affected by saliva during mastication. Broken down particles can easily be separated and subjected to image analysis. Therefore, the material is ideal to assess mastication efficiency of subjects. However, the material does not represent an actual food with regards to color (yellow cubes were used in the current thesis) and texture (the cube are very hard and brittle). Therefore, the material might be experienced as unnatural. Only during the first few chewing cycles mastication might be slightly different compared to mastication of normal foods. However, mastication is very automated process, therefore standard mastication might be continued afterwards. Therefore, using an artificial rubber will only minimally influence the mastication process.

Assessment of volume of oral cavity and tongue dimensions were both highly dependable on the willingness of participants to perform the task in the appropriate manner. During the water holding methodology, used to quantify volume of oral cavity, participants had to keep as much water as possible in their oral cavity. For the tongue dimensions, participants had to stick out their tongue. Therefore, these two methodologies are highly influenced by the participants execution of the method and are hard to standardize. An alternative methodology is ultrasonography and has been suggested to be a be an objective measurement of the oral cavity. However, this methodology is relatively expensive and need specific expertise (Law et al., 2011). In primate research, molar size has been suggested to be a proxy for volume of oral cavity and could therefore be useful in human research (Smith et al., 2017). Future research should therefore aim to include objective measurements of the volume of oral cavity and tongue dimensions.

Besides the selected methodologies in the current thesis, other methodologies have been previously discussed to be related to oral processing behavior. The tongue plays an important role in the movement of the food before, during and after mastication. The tongue facilitates the swallowing process (Matsuo & Palmer, 2009; Pereira & van der Bilt, 2016). However, limited research has investigated how tongue mobility and movement facilitate oral processing behavior. Measuring the tongue and its movements is rather expensive and difficult to quantify. This thesis assessed tongue dimensions as an anatomical measurement. However, including measurements of tongue movements is less common. Maximum tongue pressure and bite force were not included in the current thesis, since it was hypothesized that these measurements are not representative for actual oral processing behavior. Other physiological and anatomical parameters that could be linked to oral processing behavior include salivary mucins, occlusion surface and contact area and lip sealing. However, these parameters might play a very small role in oral processing behavior. Therefore, the measured physiological and anatomical parameters in this thesis might be the most relevant parameters of oral processing behavior. However, the result of chapter 4 and 5 indicate that oral physiology and anatomy only partially explain the variation in oral processing behavior.

It is suggested that culture and food habits might play a larger role in oral processing behavior. Future studies could investigate measurements of culture and food habits related to oral processing behavior. Several cultural factors are discussed to determine oral processing behavior, including the use of utensils and consumption context. Consumption with chopsticks is known to result in lower eating rates compared to consumption with a spoon (Sun et al., 2015). The consumption context, e.g. family meals and traditions, has also been suggested to influence oral processing behavior. Consumption with others is known to influence eating behavior and increases food intake (Herman et al., 2003).

7.5 Practical implications and conclusions

The results of the current research give more insights into the variation of food oral processing behavior and oral physiology and anatomy of consumers differing in age, gender and ethnicity. This information can be used to segment consumers and target food design towards specific consumer groups. Based on the results of this thesis and previous research, a segmentation based on demographic information such as age, gender and ethnicity is proposed, and secondly a segmentation based on specific physiological parameters: dental status, body weight and overall health status. These measures are the most relevant to understand inter-individual variation in oral processing behavior. The other measured parameters, including several anatomical and physiological parameters and consumer phenotype, were not closely linked to oral processing behavior. Several specific consumer segments do need specific attention. For example, the older adults have an increased consumption time and decreased eating rate compared to adults and could therefore be at risk for malnutrition. Older adults have a decrease in the number of teeth and lower saliva flow rate. Therefore, for this consumer segment saliva flow rate is a relevant physiological parameter. Food industry could therefore develop product for older adults that are nutritious and easy and quick to consume. To fulfill these criteria, foods should have a relatively low hardness to avoid mastication problems by older adults and have a relatively low dryness to avoid problems with lubrication of the bolus. Secondly, Dutch, Caucasian consumers, were found to have a relatively high eating rate and are therefore at risk to have an increased food intake and develop an unhealthy BMI. Food industry could therefore modify product properties to reduce eating rate. Different approaches have been investigated to modify eating rate, including softening foods during food preparation, including contrasting mechanical properties (Aguayo-Mendoza et al., 2020; Devezeaux de Lavergne et al., 2016) or by combining dry foods with lubricating toppings (van Eck et al., 2019) and ultra-processing of foods (Hall et al., 2019).

This thesis showed clear differences in oral processing behavior, oral physiology and anatomy between consumers varying in age, gender and ethnicity. Consumer phenotyping and sensory sensitivity remained similar for consumers varying in ethnicity and minor differences were found for gender differences. Sensory sensitivity does not seem to be useful in understanding differences in food sensory perception between Chinese and Dutch consumers. Future research could investigate other consumer groups with a large set of stimuli. Oral physiology seems to partially explain the variation in oral processing behavior. Other cultural and food habits need to be further investigated.

References

A

Abhyankar, A. R., Mulvihill, D. M., & Auty, M. A. E. (2011). Combined microscopic and dynamic rheological methods for studying the structural breakdown properties of whey protein gels and emulsion filled gels. *Food Hydrocolloids, 25*(3), 275-282.

Affoo, R. H., Foley, N., Garrick, R., Siqueira, W. L., & Martin, R. E. (2015). Meta-analysis of salivary flow rates in young and older adults. *Journal of the American Geriatrics Society, 63*(10), 2142-2151.

Agrawal, K. R., Lucas, P. W., & Bruce, I. C. (2000). The effects of food fragmentation index on mandibular closing angle in human mastication. *Arch Oral Biol, 45*(7), 577-584.

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.

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.

Ahne, G., Erras, A., Hummel, T., & Kobal, G. (2000). Assessment of gustatory function by means of tasting tablets. *The Laryngoscope, 110*(8), 1396-1401.

Aktar, T., Chen, J., Ettelaie, R., & Holmes, M. (2015a). Evaluation of the sensory correlation between touch sensitivity and the capacity to discriminate viscosity. *Journal of sensory studies, 30*(2), 98-107.

Aktar, T., Chen, J., Ettelaie, R., & Holmes, M. (2015b). Tactile sensitivity and capability of soft-solid texture discrimination. *Journal of Texture Studies, 46*(6), 429-439.

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

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

Angle, E. H. (1899). Classification of malocclusion. *Dental cosmos, 41*, 248-264,350-357.

Askegaard, S., & Madsen, T. K. (1998). The local and the global: exploring traits of homogeneity and heterogeneity in European food cultures. *International Business Review, 7*(6), 549-568.

Assad-Bustillos, M., Tournier, C., Septier, C., Della Valle, G., & Feron, G. (2019). Relationships of oral comfort perception and bolus properties in the elderly with salivary flow rate and oral health status for two soft cereal foods. *Food Research International, 118*, 13-21.

B

Baharuddin, A., & Sharifudin, M. (2015). The impact of geographical location on taste sensitivity and preference. *International Food Research Journal, 22*(2), 731.

Bakke, A., & Vickers, Z. (2008). Relationships between fungiform papillae density, PROP sensitivity and bread roughness perception. *Journal of Texture Studies, 39*(5), 569-581.

Bakke, A., & Vickers, Z. (2011). Effects of bitterness, roughness, PROP taster status, and fungiform papillae density on bread acceptance. *Food Quality and Preference, 22*(4), 317-325.

Bakke, M., Holm, B., Jensen, B. L., Michler, L., & Møller, E. (1990). Unilateral, isometric bite force in 8-68-year-old women and men related to occlusal factors. *European Journal of Oral Sciences, 98*(2), 149-158.

Baranowski, J. C., Baranowski, T., Beltran, A., Watson, K. B., Jago, R., Callie, M., . . . Tepper, B. J. (2010). 6-n-Propylthiouracil sensitivity and obesity status among ethnically diverse children. *Public health nutrition, 13*(10), 1587-1592.

Bartoshuk, L. M., Duffy, V. B., & Miller, I. J. (1994). PTC/PROP tasting: anatomy, psychophysics, and sex effects. *Physiology & Behavior, 56*(6), 1165-1171.
Bautmans, I., Lambert, M., & Mets, T. (2004). The six-minute walk test in community dwelling elderly: influence of health status. *BMC geriatrics, 4*(1), 6.
Beghini, M., Pereira, T. L., Montes, J. M. C., De Moura, D. V., & Dezem, T. U. (2017). Morphometric Analysis of Tongue in Individuals of European and African Ancestry. *Journal of Forensic Investigation, 5*(1), 5.
Belafsky, P. C., Mouadeb, D. A., Rees, C. J., Pryor, J. C., Postma, G. N., Allen, J., & Leonard, R. J. (2008). Validity and Reliability of the Eating Assessment Tool (EAT-10). *Annals of Otology, Rhinology & Laryngology, 117*(12), 919-924.
Bellisle, F., Guy-Grand, B., & Le Magnen, J. (2000). Chewing and swallowing as indices of the stimulation to eat during meals in humans: effects revealed by the edogram method and video recordings. *Neuroscience & Biobehavioral Reviews, 24*(2), 223-228.
Bellisle, F., & Le Magnen, J. (1980). The analysis of human feeding patterns: the edogram. *Appetite, 1*(2), 141-150.
Bertino, M., Beauchamp, G. K., & Jen, K.-l. C. (1983). Rated taste perception in two cultural groups. *Chemical senses, 8*(1), 3-15.
Birch, D., & Lawley, M. (2014). The role of habit, childhood consumption, familiarity, and attitudes across seafood consumption segments in Australia. *Journal of food products marketing, 20*(1), 98-113.
Blancher, G., Lê, S., Sieffermann, J.-M., & Chollet, S. (2008). Comparison of visual appearance and texture profiles of jellies in France and Vietnam and validation of attribute transfer between the two countries. *Food Quality and Preference, 19*(2), 185-196.
Bolhuis, D. P., Forde, C. G., Cheng, Y., Xu, H., Martin, N., & de Graaf, C. (2014). Slow food: sustained impact of harder foods on the reduction in energy intake over the course of the day. *PloS one, 9*(4), e93370.
Bourdiol, P., & Mioche, L. (2000). Correlations between functional and occlusal tooth-surface areas and food texture during natural chewing sequences in humans. *Arch Oral Biol, 45*(8), 691-699.
Breen, S. P., Etter, N. M., Ziegler, G. R., & Hayes, J. E. (2019). Oral somatosensatory acuity is related to particle size perception in chocolate. *Scientific reports, 9*(1), 1-10.

C

Campbell, C. L., Wagoner, T. B., & Foegeding, E. A. (2017). Designing foods for satiety: The roles of food structure and oral processing in satiation and satiety. *Food Structure, 13*, 1-12.
Carpenter, G. (2012). Role of Saliva in the Oral Processing of Food. In *Food Oral Processing* (pp. 45-60): Wiley-Blackwell.
Carruth, B. R., & Skinner, J. D. (2000). Revisiting the picky eater phenomenon: neophobic behaviors of young children. *Journal of the American College of Nutrition, 19*(6), 771-780.
Cattaneo, C., Liu, J., Bech, A. C., Pagliarini, E., & Bredie, W. L. (2020). Cross-cultural differences in lingual tactile acuity, taste sensitivity phenotypical markers, and preferred oral processing behaviors. *Food Quality and Preference, 80*, 103803.
Chanasattru, W., Corradini, M. G., & Peleg, M. (2002). Determination of practically significant differences in the sensorily perceived consistency of semiliquid foods. *Journal of Texture Studies, 33*(5), 445-460.
Chang, W.-I., Chung, J.-W., Kim, Y.-K., Chung, S.-C., & Kho, H.-S. (2006). The relationship between phenylthiocarbamide (PTC) and 6-n-propylthiouracil (PROP) taster status and taste thresholds for sucrose and quinine. *Arch Oral Biol, 51*(5), 427-432.
Chen, J. (2009). Food oral processing—A review. *Food Hydrocolloids, 23*(1), 1-25.

Chen, J. (2012). Bolus Formation and Swallowing. In *Food Oral Processing* (pp. 139-156): Wiley-Blackwell.
Chen, J. (2014). Food oral processing: Some important underpinning principles of eating and sensory perception. *Food Structure, 1*(2), 91-105.
Chen, J. (2016). Food for Elderly: Challenges and Opportunities. *Journal of Texture Studies, 47*(4), 255-256. doi:10.1111/jtxs.12203
Chen, J., & Lolivret, L. (2011). The determining role of bolus rheology in triggering a swallowing. *Food Hydrocolloids, 25*(3), 325-332.
Chen, J., & Stokes, J. R. (2012). Rheology and tribology: Two distinctive regimes of food texture sensation. *Trends in Food Science & Technology, 25*(1), 4-12.
Clark, H. M., & Solomon, N. P. (2012). Age and Sex Differences in Orofacial Strength. *Dysphagia, 27*(1), 2-9.
Collaboration, N. R. F. (2016). A century of trends in adult human height. *Elife, 5*, e13410.
Cowart, B. J., Yokomukai, Y., & Beauchamp, G. K. (1994). Bitter taste in aging: compound-specific decline in sensitivity. *Physiology & Behavior, 56*(6), 1237-1241.
Crow, H. C., & Ship, J. A. (1996). Tongue Strength and Endurance in Different Aged Individuals. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 51A*(5), M247-M250.

D

de Abreu, R. A. M., Pereira, M. D., Furtado, F., Prado, G. P. R., Mestriner, W., & Ferreira, L. M. (2014). Masticatory efficiency and bite force in individuals with normal occlusion. *Arch Oral Biol, 59*(10), 1065-1074.
de Castro, J. M., Bellisle, F., & Dalix, A.-M. (2000a). Palatability and intake relationships in free-living humans: measurement and characterization in the French. *Physiology & Behavior, 68*(3), 271-277.
de Castro, J. M., Bellisle, F., Dalix, A.-M., & Pearcey, S. M. (2000b). Palatability and intake relationships in free-living humans: characterization and independence of influence in North Americans. *Physiology & Behavior, 70*(3-4), 343-350.
de Jong, N., Mulder, I., de Graaf, C., & van Staveren, W. A. (1999). Impaired sensory functioning in elders: the relation with its potential determinants and nutritional intake. *Journals of Gerontology Series A: Biomedical Sciences and Medical Sciences, 54*(8), B324-B331.
de Wijk, R. A., Dijksterhuis, G., Vereijken, P., Prinz, J. F., & Weenen, H. (2007). PROP sensitivity reflects sensory discrimination between custard desserts. *Food Quality and Preference, 18*(4), 597-604.
de Wijk, R. A., Zijlstra, N., Mars, M., de Graaf, C., & Prinz, J. F. (2008). The effects of food viscosity on bite size, bite effort and food intake. *Physiology & Behavior, 95*(3), 527-532.
den Uijl, L. C., Jager, G., de Graaf, C., & Kremer, S. (2016). Exploring the functional mealtime associations of older adults through consumer segmentation and a means-end chain approach. *Appetite, 107*, 613-622.
Denny, P., Denny, P., Klauser, D., Hong, S., Navazesh, M., & Tabak, L. (1991). Age-related changes in mucins from human whole saliva. *Journal of Dental Research, 70*(10), 1320-1327.
Derks, J. A. M., de Wijk, R. A., de Graaf, C., & Stieger, M. (2016). Influence of Stimulus Properties and Sensory Task Instructions on Oral Processing Behavior of Liquid Stimuli. *Journal of Texture Studies, 47*(1), 49-57. doi:10.1111/jtxs.12159
Devezeaux de Lavergne, M., Derks, J. A. M., Ketel, E. C., de Wijk, R. A., & Stieger, M. (2015). Eating behaviour explains differences between individuals in dynamic texture perception of sausages. *Food Quality and Preference, 41*, 189-200.
Devezeaux de Lavergne, M., Tournier, C., Bertrand, D., Salles, C., van de Velde, F., & Stieger, M. (2016). Dynamic texture perception, oral processing behaviour and

bolus properties of emulsion-filled gels with and without contrasting mechanical properties. *Food Hydrocolloids, 52*, 648-660.
Dinnella, C., Monteleone, E., Piochi, M., Spinelli, S., Prescott, J., Pierguidi, L., . . . Predieri, S. (2018). Individual variation in PROP status, fungiform papillae density, and responsiveness to taste stimuli in a large population sample. *Chemical senses, 43*(9), 697-710.
Duffy, V. B., & Bartoshuk, L. M. (2000). Food acceptance and genetic variation in taste. *Journal of the American Dietetic Association, 100*(6), 647-655.

E

Ekberg, O., Hamdy, S., Woisard, V., Wuttge–Hannig, A., & Ortega, P. (2002). Social and psychological burden of dysphagia: its impact on diagnosis and treatment. *Dysphagia, 17*(2), 139-146.
Engelen, L., de Wijk, R. A., Prinz, J. F., Janssen, A. M., van der Bilt, A., Weenen, H., & Bosman, F. (2003). A comparison of the effects of added saliva, α-amylase and water on texture perception in semisolids. *Physiology & Behavior, 78*(4-5), 805-811.
Engelen, L., Fontijn-Tekamp, A., & van der Bilt, A. (2005). The influence of product and oral characteristics on swallowing. *Arch Oral Biol, 50*(8), 739-746. doi:1
Engelen, L., van den Keybus, P. A. M., de Wijk, R. A., Veerman, E. C. I., Nieuw Amerongen, A. V., Bosman, F., . . . van der Bilt, A. (2007). The effect of saliva composition on texture perception of semi-solids. *Arch Oral Biol, 52*(6), 518-525.
Engelen, L., & van Der Bilt, A. (2008). Oral physiology and texture perception of semisolids. *Journal of Texture Studies, 39*(1), 83-113.
Essick, G. K., Chopra, A., Guest, S., & McGlone, F. (2003). Lingual tactile acuity, taste perception, and the density and diameter of fungiform papillae in female subjects. *Physiology & Behavior, 80*(2-3), 289-302.
Etter, N. M., Miller, O. M., & Ballard, K. J. (2017). Clinically available assessment measures for lingual and labial somatosensation in healthy adults: Normative data and test reliability. *American Journal of Speech-Language Pathology, 26*(3), 982-990.

F

Farooq, M., & Sazonov, E. (2016). Automatic measurement of chew count and chewing rate during food intake. *Electronics, 5*(4), 62.
Feeney, E. L., O'Brien, S. A., Scannell, A. G., Markey, A., & Gibney, E. R. (2014). Genetic and environmental influences on liking and reported intakes of vegetables in Irish children. *Food Quality and Preference, 32*, 253-263.
Fei, T., Polacco, R. C., Hori, S. E., Molfenter, S. M., Peladeau-Pigeon, M., Tsang, C., & Steele, C. M. (2013). Age-related differences in tongue-palate pressures for strength and swallowing tasks. *Dysphagia, 28*(4), 575-581.
Ferriday, D., Bosworth, M. L., Godinot, N., Martin, N., Forde, C. G., Van Den Heuvel, E., . . . Brunstrom, J. M. (2016). Variation in the oral processing of everyday meals is associated with fullness and meal size; a potential nudge to reduce energy intake? *Nutrients, 8*(5), 315.
Fischer, M. E., Cruickshanks, K. J., Schubert, C. R., Pinto, A., Klein, R., Pankratz, N., . . . Huang, G.-H. (2013). Factors related to fungiform papillae density: the beaver dam offspring study. *Chemical senses, 38*(8), 669-677.
Foegeding, A. (2007). Rheology and sensory texture of biopolymer gels. *Current opinion in colloid & interface science, 12*(4-5), 242-250.
Fogel, A., Goh, A. T., Fries, L. R., Sadananthan, S. A., Velan, S. S., Michael, N., . . . Toh, J. Y. (2017a). 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. *Physiology & Behavior, 176*, 107-116.
Fogel, A., Goh, A. T., Fries, L. R., Sadananthan, S. A., Velan, S. S., Michael, N., . . . Toh, J. Y. (2017b). 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 growing up in Singapore towards healthy outcomes (GUSTO) cohort. *British Journal of Nutrition, 117*(7), 1042-1051.
Fontijn-Tekamp, F. A., Slagter, A. P., van Der Bilt, A., Van 'T Hof, M. A., Witter, D. J., Kalk, W., & Jansen, J. A. (2000). Biting and Chewing in Overdentures, Full Dentures, and Natural Dentitions. *Journal of Dental Research, 79*(7), 1519-1524.
Fontijn-Tekamp, F. A., van der Bilt, A., Abbink, J. H., & Bosman, F. (2004). Swallowing threshold and masticatory performance in dentate adults. *Physiology & Behavior, 83*(3), 431-436.
Forde, C. G., Leong, C., Chia-Ming, E., & McCrickerd, K. (2017). Fast or slow-foods? Describing natural variations in oral processing characteristics across a wide range of Asian foods. *Food & function, 8*(2), 595-606.
Forde, C. G., Mars, M., & de Graaf, K. (2020). Ultra-Processing or Oral Processing? A Role for Energy Density and Eating Rate in Moderating Energy Intake from Processed Foods. *Current Developments in Nutrition, 4*(3), nzaa019.
Forde, C. G., van Kuijk, N., Thaler, T., de Graaf, C., & Martin, N. (2013a). Oral processing characteristics of solid savoury meal components, and relationship with food composition, sensory attributes and expected satiation. *Appetite, 60*, 208-219.
Forde, C. G., Van Kuijk, N., Thaler, T., de Graaf, C., & Martin, N. (2013b). Texture and savoury taste influences on food intake in a realistic hot lunch time meal. *Appetite, 60*, 180-186.

G

Garneau, N. L., Nuessle, T. M., Sloan, M. M., Santorico, S. A., Coughlin, B. C., & Hayes, J. E. (2014). Crowdsourcing taste research: genetic and phenotypic predictors of bitter taste perception as a model. *Frontiers in integrative neuroscience, 8*, 33.
Genick, U. K., Kutalik, Z., Ledda, M., Destito, M. C. S., Souza, M. M., Cirillo, C. A., . . . Sameshima, K. (2011). Sensitivity of genome-wide-association signals to phenotyping strategy: the PROP-TAS2R38 taste association as a benchmark. *PloS one, 6*(11).
Gerritsen, A. E., Allen, P. F., Witter, D. J., Bronkhorst, E. M., & Creugers, N. H. J. (2010). Tooth loss and oral health-related quality of life: a systematic review and meta-analysis. *Health and Quality of Life outcomes, 8*(1), 126.
Gray-Stuart, E. M., Jones, J. R., & Bronlund, J. E. (2017). Defining the end-point of mastication: A conceptual model. *Journal of Texture Studies, 48*(5), 345-356.
Green, B. G., Alvarez-Reeves, M., George, P., & Akirav, C. (2005). Chemesthesis and taste: evidence of independent processing of sensation intensity. *Physiology & Behavior, 86*(4), 526-537.
Gudziol, H., & Hummel, T. (2007). Normative values for the assessment of gustatory function using liquid tastants. *Acta oto-laryngologica, 127*(6), 658-661.
Guinard, J.-X., Zoumas-Morse, C., Walchak, C., & Simpson, H. (1997). Relation between saliva flow and flavor release from chewing gum. *Physiology & Behavior, 61*(4), 591-596.

H

Hall, K. D., Ayuketah, A., Brychta, R., Cai, H., Cassimatis, T., Chen, K. Y., . . . Darcey, V. (2019). Ultra-processed diets cause excess calorie intake and weight gain: an inpatient randomized controlled trial of ad libitum food intake. *Cell metabolism, 30*(1), 67-77. e63.

Hayes, J. E., Bartoshuk, L. M., Kidd, J. R., & Duffy, V. B. (2008). Supertasting and PROP bitterness depends on more than the TAS2R38 gene. *Chemical senses, 33*(3), 255-265.

Hayes, J. E., & Duffy, V. B. (2007). Revisiting sugar–fat mixtures: sweetness and creaminess vary with phenotypic markers of oral sensation. *Chemical senses, 32*(3), 225-236.

Henry, C. J., Ponnalagu, S., Bi, X., & Forde, C. G. (2018). Does basal metabolic rate drive eating rate? *Physiology & Behavior, 189*, 74-77.

Herman, C. P., Roth, D. A., & Polivy, J. (2003). Effects of the presence of others on food intake: a normative interpretation. *Psychological bulletin, 129*(6), 873.

Hiiemae, K. (2004). Mechanisms of food reduction, transport and deglutition: how the texture of food affects feeding behavior. *Journal of Texture Studies, 35*(2), 171-200.

Hiiemae, K., Heath, M. R., Heath, G., Kazazoglu, E., Murray, J., Sapper, D., & Hamblett, K. (1996). Natural bites, food consistency and feeding behaviour in man. *Arch Oral Biol, 41*(2), 175-189.

Hiiemae, K. M., & Palmer, J. B. (2003). Tongue movements in feeding and speech. *Critical Reviews in Oral Biology & Medicine, 14*(6), 413-429.

Hill, S. W., & McCutcheon, N. B. (1984). Contributions of obesity, gender, hunger, food preference, and body size to bite size, bite speed, and rate of eating. *Appetite, 5*(2), 73-83.

Hong, J.-H., Chung, J.-W., Kim, Y.-K., Chung, S.-C., Lee, S.-W., & Kho, H.-S. (2005). The relationship between PTC taster status and taste thresholds in young adults. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontology, 99*(6), 711-715.

Humbert, I. A., & Robbins, J. (2007). Normal swallowing and functional magnetic resonance imaging: a systematic review. *Dysphagia, 22*(3), 266-275.

Humbert, I. A., & Robbins, J. (2008). Dysphagia in the Elderly. *Physical Medicine and Rehabilitation Clinics of North America, 19*(4), 853-866.

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

Hyde, R. J., & Feller, R. P. (1981). Age and sex effects on taste of sucrose, NaCl, citric acid and caffeine. *Neurobiology of aging, 2*(4), 315-318.

I

Ikebe, K., Matsuda, K.-i., Kagawa, R., Enoki, K., Yoshida, M., Maeda, Y., & Nokubi, T. (2011). Association of masticatory performance with age, gender, number of teeth, occlusal force and salivary flow in Japanese older adults: is ageing a risk factor for masticatory dysfunction? *Arch Oral Biol, 56*(10), 991-996.

Inoue, H., Ono, K., Masuda, W., Morimoto, Y., Tanaka, T., Yokota, M., & Inenaga, K. (2006). Gender difference in unstimulated whole saliva flow rate and salivary gland sizes. *Arch Oral Biol, 51*(12), 1055-1060.

J

Jacobsson, C., Axelsson, K., Österlind, P. O., & Norberg, A. (2000). How people with stroke and healthy older people experience the eating process. *Journal of clinical nursing, 9*(2), 255-264.

James, C. E., Laing, D. G., & Oram, N. (1997). A comparison of the ability of 8–9-year-old children and adults to detect taste stimuli. *Physiology & Behavior, 62*(1), 193-197.

Jean, A. (2001). Brain stem control of swallowing: neuronal network and cellular mechanisms. *Physiological reviews, 81*(2), 929-969.
Jeltema, M., Beckley, J., & Vahalik, J. (2015). Model for understanding consumer textural food choice. *Food science & nutrition, 3*(3), 202-212.
Julien, K. C., Buschang, P. H., Throckmorton, G. S., & Dechow, P. C. (1996). Normal masticatory performance in young adults and children. *Arch Oral Biol, 41*(1), 69-75.

K

Kamegai, T., Tatsuki, T., Nagano, H., Mitsuhashi, H., Kumeta, J., Tatsuki, Y., . . . Inaba, D. (2005). A determination of bite force in northern Japanese children. *The European Journal of Orthodontics, 27*(1), 53-57.
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 behaviour of liquid, semi-solid and solid foods differently. *Food Research International*, 143-151.
Ketel, E. C., de Wijk, R. A., de Graaf, C., & Stieger, M. (2020). Relating oral physiology and anatomy of consumers varying in age, gender and ethnicity to food oral processing behavior.
Kim, E. H., Jakobsen, V. B., Wilson, A. J., Waters, I. R., Motoi, L., Hedderley, D. I., & Morgenstern, M. P. (2015). Oral Processing of Mixtures of Food Particles. *Journal of Texture Studies, 46*(6), 487-498.
Kim, S., & Vickers, Z. (2020). Liking of food textures and its relationship with oral physiological parameters and mouth-behavior groups. *Journal of Texture Studies, 51*(3), 412-425. doi:10.1111/jtxs.12504
Kim, Y.-K., Jombart, L., Valentin, D., & Kim, K.-O. (2015). Familiarity and liking playing a role on the perception of trained panelists: A cross-cultural study on teas. *Food Research International, 71*, 155-164.
Koç, H., Çakir, E., Vinyard, C. J., Essick, G., Daubert, C. R., Drake, M. A., . . . Foegeding, E. A. (2014). Adaptation of oral processing to the fracture properties of soft solids. *Journal of Texture Studies, 45*(1), 47-61.
Koç, H., Vinyard, C. J., Essick, G. K., & Foegeding, E. A. (2013). Food Oral Processing: Conversion of Food Structure to Textural Perception. *Annual Review of Food Science and Technology, 4*(1), 237-266.
Kohyama, K., Mioche, L., & Bourdio, P. (2003). Influence of age and dental status on chewing behaviour studied by EMG recordings during consumption of various food samples. *Gerodontology, 20*(1), 15-23.
Kohyama, K., Mioche, L., & Martin, J. (2002). Chewing patterns of various texture foods studied by electromyography in young and elderly populations. *Journal of Texture Studies, 33*(4), 269-283.
Koliandris, A., Lee, A., Ferry, A.-L., Hill, S., & Mitchell, J. (2008). Relationship between structure of hydrocolloid gels and solutions and flavour release. *Food Hydrocolloids, 22*(4), 623-630.
Komiyama, O., & De Laat, A. (2005). Tactile and pain thresholds in the intra-and extra-oral regions of symptom-free subjects. *Pain, 115*(3), 308-315.
Komiyama, O., Kawara, M., & De Laat, A. (2007). Ethnic differences regarding tactile and pain thresholds in the trigeminal region. *The Journal of Pain, 8*(4), 363-369.
Kossioni, A., & Bellou, O. (2011). Eating habits in older people in Greece: The role of age, dental status and chewing difficulties. *Archives of gerontology and geriatrics, 52*(2), 197-201.
Kremer, S., Bult, J. H., Mojet, J., & Kroeze, J. H. (2007). Food perception with age and its relationship to pleasantness. *Chemical senses, 32*(6), 591-602.
Krop, E. M., Hetherington, M. M., Nekitsing, C., Miquel, S., Postelnicu, L., & Sarkar, A. (2018). Influence of oral processing on appetite and food intake–A systematic review and meta-analysis. *Appetite, 125*, 253-269.

L

Laguna, L., & Chen, J. (2016). The eating capability: Constituents and assessments. *Food Quality and Preference, 48, Part B*, 345-358.
Laguna, L., Hetherington, M. M., Chen, J., Artigas, G., & Sarkar, A. (2016). Measuring eating capability, liking and difficulty perception of older adults: A textural consideration. *Food Quality and Preference, 53*, 47-56.
Laguna, L., Sarkar, A., Artigas, G., & Chen, J. (2015a). A quantitative assessment of the eating capability in the elderly individuals. *Physiology & Behavior, 147*, 274-281.
Laguna, L., Sarkar, A., & Chen, J. (2015b). Assessment of eating capability of elderly subjects in UK: a quantitative evaluation. *Proceedings of the Nutrition Society, 74*(OCE2).
Landis, B. N., Welge-Luessen, A., Brämerson, A., Bende, M., Mueller, C. A., Nordin, S., & Hummel, T. (2009). "Taste Strips"–a rapid, lateralized, gustatory bedside identification test based on impregnated filter papers. *Journal of neurology, 256*(2), 242.
Law, C. P., Chandra, R., Hoang, J., & Phal, P. M. (2011). Imaging the oral cavity: key concepts for the radiologist. *The British journal of radiology, 84*(1006), 944-957.
Lawless, H. T., & Heymann, H. (2013). *Sensory evaluation of food: principles and practices*: Springer Science & Business Media.
Leong, S. L., Madden, C., Gray, A., Waters, D. A., & Horwath, C. (2011). Faster self-reported speed of eating is related to higher body mass index in a nationwide survey of middle-aged women. *Journal of the American Dietetic Association, 111*(8), 1192-1197.
Levin, S., Pearsall, G., & Ruderman, R. J. (1978). Von Frey's method of measuring pressure sensibility in the hand: an engineering analysis of the Weinstein-Semmes pressure aesthesiometer. *Journal of hand surgery, 3*(3), 211-216.
Liu, H., Qin, L., Wu, Y., van der Glas, H. W., Chen, J., & Wang, X. (2019). Oral physiological characteristics among Chinese subjects in the eastern region of China. *Arch Oral Biol, 108*, 104539.
Llewellyn, C. H., Van Jaarsveld, C. H., Boniface, D., Carnell, S., & Wardle, J. (2008). Eating rate is a heritable phenotype related to weight in children. *The American journal of clinical nutrition, 88*(6), 1560-1566.
Lundgren, B., Pangborn, R.-M., Daget, N., Yoshida, M., Laing, D. G., McBride, R., . . . Paulus, K. (1986). An interlaboratory study of firmness, aroma, and taste of pectin gels. *Lebensm Wiss Technol, 19*(1), 66-76.

M

Ma, G. (2015). Food, eating behavior, and culture in Chinese society. *Journal of Ethnic Foods, 2*(4), 195-199.
Mackie, D., & Pangborn, R. (1990). Mastication and its influence on human salivary flow and alpha-amylase secretion. *Physiology & Behavior, 47*(3), 593-595.
Mahar, A., & Duizer, L. (2007). The effect of frequency of consumption of artificial sweeteners on sweetness liking by women. *Journal of Food Science, 72*(9), S714-S718.
Marshall, T. A., Warren, J. J., Hand, J. S., Xie, X.-J., & Stumbo, P. J. (2002). Oral health, nutrient intake and dietary quality in the very old. *The Journal of the American Dental Association, 133*(10), 1369-1379.
Masi, C., Dinnella, C., Monteleone, E., & Prescott, J. (2015). The impact of individual variations in taste sensitivity on coffee perceptions and preferences. *Physiology & Behavior, 138*, 219-226.
Matsuo, K., & Palmer, J. B. (2009). Coordination of mastication, swallowing and breathing. *Japanese Dental Science Review, 45*(1), 31-40.

McCrickerd, K., & Forde, C. G. (2017). Consistency of eating rate, oral processing behaviours and energy intake across meals. *Nutrients, 9*(8), 891.

McCrickerd, K., Lim, C. M. H., Leong, C., Chia, E. M., & Forde, C. G. (2017). Texture-Based Differences in Eating Rate Reduce the Impact of Increased Energy Density and Large Portions on Meal Size in Adults–3. *The Journal of nutrition, 147*(6), 1208-1217.

McKay, J. (2007). Food industry & economic development in the Asia Pacific. *Asia Pacific journal of clinical nutrition, 16*, 80.

Methven, L., Allen, V. J., Withers, C. A., & Gosney, M. A. (2012). Ageing and taste. *Proceedings of the Nutrition Society, 71*(4), 556-565.

Michon, C., O'Sullivan, M., Delahunty, C., & Kerry, J. (2009). The investigation of gender-related sensitivity differences in food perception. *Journal of sensory studies, 24*(6), 922-937.

Michon, C., O'Sullivan, M., Sheehan, E., Delahunty, C., & Kerry, J. (2010). Investigation of the influence of age, gender and consumption habits on the liking of jam-filled cakes. *Food Quality and Preference, 21*(5), 553-561.

Miller Jr, I. J. (1986). Variation in human fungiform taste bud densities among regions and subjects. *The Anatomical Record, 216*(4), 474-482.

Miller Jr, I. J., & Reedy Jr, F. E. (1990a). Quantification of fungiform papillae and taste pores in living human subjects. *Chemical senses, 15*(3), 281-294.

Miller Jr, I. J., & Reedy Jr, F. E. (1990b). Variations in human taste bud density and taste intensity perception. *Physiology & Behavior, 47*(6), 1213-1219.

Mioche, L., Bourdiol, P., & Monier, S. (2003). Chewing behaviour and bolus formation during mastication of meat with different textures. *Arch Oral Biol, 48*(3), 193-200.

Mioche, L., Bourdiol, P., Monier, S., & Martin, J. (2002). The relationship between chewing activity and food bolus properties obtained from different meat textures. *Food Quality and Preference, 13*(7-8), 583-588.

Mioche, L., Bourdiol, P., Monier, S., Martin, J., & Cormier, D. (2004a). Changes in jaw muscles activity with age: effects on food bolus properties. *Physiology & Behavior, 82*(4), 621-627.

Mioche, L., Bourdiol, P., & Peyron, M. (2004b). Influence of age on mastication: effects on eating behaviour. *Nutrition Research Reviews, 17*(01), 43-54.

Mioche, L., Hiiemae, K. M., & Palmer, J. B. (2002). A postero-anterior videofluorographic study of the intra-oral management of food in man. *Arch Oral Biol, 47*(4), 267-280.

Mojet, J., Christ-Hazelhof, E., & Heidema, J. (2001). Taste perception with age: generic or specific losses in threshold sensitivity to the five basic tastes? *Chemical senses, 26*(7), 845-860.

Mojon, P., Budtz-Jørgensen, E., & Rapin, C.-H. (1999). Relationship between oral health and nutrition in very old people. *Age and ageing, 28*(5), 463-468.

Mosca, A. C., Stieger, M., Neyraud, E., Brignot, H., van de Wiel, A., & Chen, J. (2018). How are macronutrient intake, BMI, ethnicity, age and gender related to the composition of unstimulated saliva? A case study. *Journal of Texture Studies*.

Mosca, A. C., Torres, A. P., Slob, E., de Graaf, K., McEwan, J. A., & Stieger, M. (2019). Small food texture modifications can be used to change oral processing behaviour and to control ad libitum food intake. *Appetite, 142*, 104375.

Mosca, A. C., van de Velde, F., Bult, J. H., van Boekel, M. A., & Stieger, M. (2015). Taste enhancement in food gels: Effect of fracture properties on oral breakdown, bolus formation and sweetness intensity. *Food Hydrocolloids, 43*, 794-802.

N

N'Gom, P. I., & Woda, A. (2002). Influence of impaired mastication on nutrition. *The Journal of Prosthetic Dentistry, 87*(6), 667-673.

Nachtsheim, R., & Schlich, E. (2013). The influence of 6-n-propylthiouracil bitterness, fungiform papilla count and saliva flow on the perception of pressure and fat. *Food Quality and Preference, 29*(2), 137-145.

Nagasawa, T., Yanbin, X. U., Tsuga, K., & Abe, Y. (1997). Sex difference of electromyogram of masticatory muscles and mandibular movement during chewing of food. *Journal of Oral Rehabilitation, 24*(8), 605-609.

Nagler, R. (2004). Salivary glands and the aging process: mechanistic aspects, health-status and medicinal-efficacy monitoring. *Biogerontology, 5*(4), 223-233.

Neyraud, E., Palicki, O., Schwartz, C., Nicklaus, S., & Feron, G. (2012). Variability of human saliva composition: possible relationships with fat perception and liking. *Arch Oral Biol, 57*(5), 556-566.

Nicklaus, S., & Schwartz, C. (2019). Early influencing factors on the development of sensory and food preferences. *Current Opinion in Clinical Nutrition & Metabolic Care, 22*(3), 230-235.

Nordström, G. (1990). The impact of socio-medical factors and oral status on dietary intake in the eighth decade of life. *Aging Clinical and Experimental Research, 2*(4), 371-385.

Nuessle, T. M., Garneau, N. L., Sloan, M. M., & Santorico, S. A. (2015). Denver papillae protocol for objective analysis of fungiform papillae. *JoVE (Journal of Visualized Experiments)*(100), e52860.

O

Ohkuma, T., Hirakawa, Y., Nakamura, U., Kiyohara, Y., Kitazono, T., & Ninomiya, T. (2015). Association between eating rate and obesity: a systematic review and meta-analysis. *International journal of obesity, 39*(11), 1589.

Okada, A., Honma, M., Nomura, S., & Yamada, Y. (2007). Oral behavior from food intake until terminal swallow. *Physiology & Behavior, 90*(1), 172-179.

P

Palinkas, M., Nassar, M. S. P., Cecílio, F. A., Siéssere, S., Semprini, M., Machado-de-Sousa, J. P., . . . Regalo, S. C. H. (2010). Age and gender influence on maximal bite force and masticatory muscles thickness. *Arch Oral Biol, 55*(10), 797-802.

Park, S., & Shin, W. (2015). Differences in eating behaviors and masticatory performances by gender and obesity status. *Physiology & Behavior, 138*, 69-74.

Pedersen, A., Bardow, A., Jensen, S. B., & Nauntofte, B. (2002). Saliva and gastrointestinal functions of taste, mastication, swallowing and digestion. *Oral diseases, 8*(3), 117-129.

Pedrotti, M., Spaccasassi, A., Biasioli, F., & Fogliano, V. (2019). Ethnicity, gender and physiological parameters: Their effect on in vivo flavour release and perception during chewing gum consumption. *Food Research International, 116*, 57-70.

Percival, R. S., Challacombe, S. J., & Marsh, P. D. (1994). Flow rates of resting whole and stimulated parotid saliva in relation to age and gender. *Journal of Dental Research, 73*(8), 1416-1420.

Pereira, L., & van der Bilt, A. (2016). The influence of oral processing, food perception and social aspects on food consumption: a review. *Journal of Oral Rehabilitation, 43*(8), 630-648.

Pereira, L. J. (2012). Oral Cavity. In *Food Oral Processing* (pp. 1-14): Wiley-Blackwell.

Pereira, L. J., Duarte Gaviao, M. B., & van der Bilt, A. (2006). Influence of oral characteristics and food products on masticatory function. *Acta Odontologica Scandinavica, 64*(4), 193-201.

Peyron, M., Blanc, O., Lund, J. P., & Woda, A. (2004). Influence of age on adaptability of human mastication. *Journal of neurophysiology, 92*(2), 773-779.

Pingel, J., Ostwald, J., Pau, H. W., Hummel, T., & Just, T. (2010). Normative data for a solution-based taste test. *European Archives of Oto-Rhino-Laryngology, 267*(12), 1911-1917.

Prescott, J., & Bell, G. (1995). Cross-cultural determinants of food acceptability: Recent research on sensory perceptions and preferences. *Trends in Food Science & Technology, 6*(6), 201-205.

Prinz, J., & Lucas, P. (2000). Saliva tannin interactions. *Journal of Oral Rehabilitation, 27*(11), 991-994.

Prinz, J. F., & Lucas, P. W. (1997). An optimization model for mastication and swallowing in mammals. *Proceedings of the Royal Society of London B: Biological Sciences, 264*(1389), 1715-1721.

Prutkin, J., Duffy, V., Etter, L., Fast, K., Gardner, E., Lucchina, L., . . . Bartoshuk, L. (2000). Genetic variation and inferences about perceived taste intensity in mice and men. *Physiology & Behavior, 69*(1-2), 161-173.

R

Ratcliffe, E., Baxter, W. L., & Martin, N. (2019). Consumption rituals relating to food and drink: A review and research agenda. *Appetite, 134*, 86-93.

Robinson, E., Almiron-Roig, E., Rutters, F., de Graaf, C., Forde, C. G., Tudur Smith, C., . . . Jebb, S. A. (2014). A systematic review and meta-analysis examining the effect of eating rate on energy intake and hunger–. *The American journal of clinical nutrition, 100*(1), 123-151.

Rolls, B. J. (1999). Do chemosensory changes influence food intake in the elderly? *Physiology & Behavior, 66*(2), 193-197.

Rolls, B. J., Cunningham, P. M., & Diktas, H. E. (2020). Properties of Ultraprocessed Foods That Can Drive Excess Intake. *Nutrition Today, 55*(3), 109-115.

Rolls, B. J., Fedoroff, I. C., & Guthrie, J. F. (1991). Gender differences in eating behavior and body weight regulation. *Health Psychology, 10*(2), 133.

Rook, D. W. (1985). The ritual dimension of consumer behavior. *Journal of consumer research, 12*(3), 251-264.

Ross, C. F., & Hoye, C. L. (2012). Breaking and Mastication of Solid Foods. In *Food Oral Processing* (pp. 95-109): Wiley-Blackwell.

Rozin, P., Mark, M., & Schiller, D. (1981). The role of desensitization to capsaicin in chili pepper ingestion and preference. *Chemical senses, 6*(1), 23-31.

S

Sala, G., & Stieger, M. (2013). Time to first fracture affects sweetness of gels. *Food Hydrocolloids, 30*(1), 73-81.

Salvy, S.-J., Howard, M., Read, M., & Mele, E. (2009). The presence of friends increases food intake in youth. *The American journal of clinical nutrition, 90*(2), 282-287.

Sánchez-Ayala, A., Vilanova, L. S. R., Costa, M. A., & Farias-Neto, A. (2014). Reproducibility of a silicone-based test food to masticatory performance evaluation by different sieve methods. *Brazilian oral research, 28*(1), 1-8.

Santagiuliana, M., Marigómez, I. S., Broers, L., Hayes, J. E., Piqueras-Fiszman, B., Scholten, E., & Stieger, M. (2019). Exploring variability in detection thresholds of microparticles through participant characteristics. *Food & function, 10*(9), 5386-5397.

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

Schiffman, S. S. (1993). Perception of taste and smell in elderly persons. *Critical Reviews in Food Science and Nutrition, 33*(1), 17-26.

Schwartz, C., Scholtens, P. A., Lalanne, A., Weenen, H., & Nicklaus, S. (2011). Development of healthy eating habits early in life. Review of recent evidence and selected guidelines. *Appetite, 57*(3), 796-807.
Seo, Y., Cruz, A. G. B., & Fam, K.-S. (2015). Food consumption and marketing: turning toward Asia. *Journal of Consumer Marketing*.
Shen, Y., Kennedy, O. B., & Methven, L. (2016). Exploring the effects of genotypical and phenotypical variations in bitter taste sensitivity on perception, liking and intake of brassica vegetables in the UK. *Food Quality and Preference, 50*, 71-81.
Shiga, H., Kobayashi, Y., Katsuyama, H., Yokoyama, M., & Arakawa, I. (2012). Gender difference in masticatory performance in dentate adults. *Journal of prosthodontic research, 56*(3), 166-169.
Shiozawa, K., Mototani, Y., Suita, K., Ito, A., Kawamura, N., Yagisawa, Y., . . . Umeki, D. (2019). Relationship between bite size per mouthful and dental arch size in healthy subjects. *The Journal of Physiological Sciences, 69*(1), 159-163.
Simpson, E. E., Rae, G., Parr, H., O'Connor, J. M., Bonham, M., Polito, A., . . . Coudray, C. (2012). Predictors of taste acuity in healthy older Europeans. *Appetite, 58*(1), 188-195.
Smith, T. D., Muchlinski, M. N., Bucher, W. R., Vinyard, C. J., Bonar, C. J., Evans, S., . . . DeLeon, V. B. (2017). Relative tooth size at birth in primates: Life history correlates. *American journal of physical anthropology, 164*(3), 623-634.
Sorkin, J. D., Muller, D. C., & Andres, R. (1999). Longitudinal change in height of men and women: implications for interpretation of the body mass index: the Baltimore Longitudinal Study of Aging. *American journal of epidemiology, 150*(9), 969-977.
Steele, C. M., & Van Lieshout, P. H. H. M. (2004). Influence of bolus consistency on lingual behaviors in sequential swallowing. *Dysphagia, 19*(3), 192-206.
Steen, B. (1988). Body composition and aging. *Nutrition Reviews, 46*(2), 45-51.
Stevens, J. C., Cruz, L. A., Marks, L. E., & Lakatos, S. (1998). A multimodal assessment of sensory thresholds in aging. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences, 53*(4), P263-P272.
Stieger, M., & van de Velde, F. (2013). Microstructure, texture and oral processing: new ways to reduce sugar and salt in foods. *Current opinion in colloid & interface science, 18*(4), 334-348.
Sun, L., Ranawana, D. V., Tan, W. J. K., Quek, Y. C. R., & Henry, C. J. (2015). The impact of eating methods on eating rate and glycemic response in healthy adults. *Physiology & Behavior, 139*, 505-510.
Sweeney, M., Williams, C., Kennedy, C., Macpherson, L., Turner, S., & Bagg, J. (2007). Oral health care and status of elderly care home residents in Glasgow. *Community dental health, 24*(1), 37.

T

Tada, A., & Miura, H. (2014). Systematic review of the association of mastication with food and nutrient intake in the independent elderly. *Archives of gerontology and geriatrics, 59*(3), 497-505.
Takaki, P., Vieira, M., & Bommarito, S. (2014). Maximum bite force analysis in different age groups. *International archives of otorhinolaryngology, 18*(3), 272-276.
Tamura, F., Kikutani, T., Tohara, T., Yoshida, M., & Yaegaki, K. (2012). Tongue thickness relates to nutritional status in the elderly. *Dysphagia, 27*(4), 556-561.
Taniguchi, H., Tsukada, T., Ootaki, S., Yamada, Y., & Inoue, M. (2008). Correspondence between food consistency and suprahyoid muscle activity, tongue pressure, and bolus transit times during the oropharyngeal phase of swallowing. *Journal of Applied Physiology, 105*(3), 791-799.
Teo, P. S., van Langeveld, A. W., Pol, K., Siebelink, E., de Graaf, C., Martin, C., . . . Mars, M. (2018). Training of a Dutch and Malaysian sensory panel to assess intensities of basic tastes and fat sensation of commonly consumed foods. *Food Quality and Preference, 65*, 49-59.

Tepper, B. J. (2008). Nutritional implications of genetic taste variation: the role of PROP sensitivity and other taste phenotypes. *Annu. Rev. Nutr., 28*, 367-388.
Tepper, B. J., Christensen, C. M., & Cao, J. (2001). Development of brief methods to classify individuals by PROP taster status. *Physiology & Behavior, 73*(4), 571-577.
Triandis, H. C. (1989). The self and social behavior in differing cultural contexts. *Psychological review, 96*(3), 506.

V

van Aken, G. A., Vingerhoeds, M. H., & de Hoog, E. H. A. (2007). Food colloids under oral conditions. *Current opinion in colloid & interface science, 12*(4-5), 251-262.
van den Boer, J., Werts, M., Siebelink, E., de Graaf, C., & Mars, M. (2017). The availability of slow and fast calories in the Dutch diet: The current situation and opportunities for interventions. *Foods, 6*(10), 87.
van den Boer, J. H. W., Kranendonk, J., van de Wiel, A., Feskens, E. J. M., Geelen, A., & Mars, M. (2017). Self-reported eating rate is associated with weight status in a Dutch population: a validation study and a cross-sectional study. *International Journal of Behavioral Nutrition and Physical Activity, 14*(1), 121.
van der Bilt, A., Abbink, J., Mowlana, F., & Heath, M. (1993). A comparison between data analysis methods concerning particle size distributions obtained by mastication in man. *Arch Oral Biol, 38*(2), 163-167.
van der Bilt, A., Olthoff, L., Bosman, F., & Oosterhaven, S. (1993). The effect of missing postcanine teeth on chewing performance in man. *Arch Oral Biol, 38*(5), 423-429.
van der Zanden, L. D., van Kleef, E., de Wijk, R. A., & van Trijp, H. C. (2014). Understanding heterogeneity among elderly consumers: an evaluation of segmentation approaches in the functional food market. *Nutrition Research Reviews, 27*(1), 159-171.
van Eck, A., Hardeman, N., Karatza, N., Fogliano, V., Scholten, E., & Stieger, M. (2019). Oral processing behavior and dynamic sensory perception of composite foods: Toppings assist saliva in bolus formation. *Food Quality and Preference, 71*, 497-509.
van Lancker, A., Verhaeghe, S., Van Hecke, A., Vanderwee, K., Goossens, J., & Beeckman, D. (2012). The association between malnutrition and oral health status in elderly in long-term care facilities: a systematic review. *International journal of nursing studies, 49*(12), 1568-1581.
van Ruth, S. M., Roozen, J. P., Nahon, D. F., Cozijnsen, J. L., & Posthumus, M. A. (1996). Flavour release from rehydrated french beans (Phaseolus vulgaris) influenced by composition and volume of artificial saliva. *Zeitschrift fuer Lebensmittel-Untersuchung und Forschung, 203*(1), 1-6.
van Vliet, T., van Aken, G. A., de Jongh, H. H. J., & Hamer, R. J. (2009). Colloidal aspects of texture perception. *Advances in Colloid and Interface Science, 150*(1), 27-40.
van't Riet, J., Sijtsema, S. J., Dagevos, H., & De Bruijn, G.-J. (2011). The importance of habits in eating behaviour. An overview and recommendations for future research. *Appetite, 57*(3), 585-596.
Vandenberghe-Descamps, M., Labouré, H., Prot, A., Septier, C., Tournier, C., Feron, G., & Sulmont-Rossé, C. (2016). Salivary flow decreases in healthy elderly people independently of dental status and drug intake. *Journal of Texture Studies, 47*(4), 353-360.
Varela, P., Salvador, A., & Fiszman, S. (2007). Changes in apple tissue with storage time: Rheological, textural and microstructural analyses. *Journal of Food Engineering, 78*(2), 622-629.
Varga, S., Spalj, S., Lapter Varga, M., Anic Milosevic, S., Mestrovic, S., & Slaj, M. (2010). Maximum voluntary molar bite force in subjects with normal occlusion. *The European Journal of Orthodontics, 33*(4), 427-433.

Viskaal-van Dongen, M., Kok, F. J., & de Graaf, C. (2011). Eating rate of commonly consumed foods promotes food and energy intake. *Appetite, 56*(1), 25-31.
Vohs, K. D., Wang, Y., Gino, F., & Norton, M. I. (2013). Rituals enhance consumption. *Psychological Science, 24*(9), 1714-1721.

W

Wagner, W., & Kretzschmar, H. (2007). *International Steam Tables-Properties of Water and Steam based on the Industrial Formulation IAPWS-IF97*: Springer Science & Business Media.
Walls, A. W. G., & Steele, J. G. (2004). The relationship between oral health and nutrition in older people. *Mechanisms of ageing and development, 125*(12), 853-857.
Wansink, B. (2004). Environmental factors that increase the food intake and consumption volume of unknowing consumers. *Annu. Rev. Nutr., 24*, 455-479.
Webb, J., Bolhuis, D. P., Cicerale, S., Hayes, J. E., & Keast, R. (2015). The relationships between common measurements of taste function. *Chemosensory perception, 8*(1), 11-18.
Wee, M. S. M., Goh, A. T., Stieger, M., & Forde, C. G. (2018). Correlation of Mechanical Properties from Textural Profile Analysis (TPA) with Eating Behaviours and Macronutrient Composition for a Wide Range of Solid Foods. *Food & function*.
Westenhoefer, J., Broeckmann, P., Münch, A.-K., & Pudel, V. (1994). Cognitive control of eating behavior and the disinhibition effect. *Appetite, 23*(1), 27-41.
Wiriyawattana, P., Suwonsichon, S., & Suwonsichon, T. (2018). Effects of aging on taste thresholds: A case of Asian people. *Journal of sensory studies*, e12436.
Witt, T., & Stokes, J. R. (2015). Physics of food structure breakdown and bolus formation during oral processing of hard and soft solids. *Current Opinion in Food Science, 3*, 110-117.
Wium, H., Qvist, K. B., & Gross, M. (1997). Uniaxial compression of UF-Feta cheese related to sensory texture analysis. *Journal of Texture Studies, 28*(4), 455-476.
Woda, A., Foster, K., Mishellany, A., & Peyron, M. (2006). Adaptation of healthy mastication to factors pertaining to the individual or to the food. *Physiology & Behavior, 89*(1), 28-35.

X

Xue, S. A., & Hao, J. G. (2006). Normative Standards for Vocal Tract Dimensions by Race as Measured by Acoustic Pharyngometry. *Journal of Voice, 20*(3), 391-400.

Y

Yackinous, C., & Guinard, J.-X. (2001). Relation between PROP taster status and fat perception, touch, and olfaction. *Physiology & Behavior, 72*(3), 427-437.
Yeh, C. K., Johnson, D. A., & Dodds, M. W. J. (1998). Impact of aging on human salivary gland function: a community-based study. *Aging Clinical and Experimental Research, 10*(5), 421-428.
Yeomans, M. R. (1996). Palatability and the micro-structure of feeding in humans: the appetizer effect. *Appetite, 27*(2), 119-133.
Yeomans, M. R., Gray, R. W., Mitchell, C. J., & True, S. (1997). Independent effects of palatability and within-meal pauses on intake and appetite ratings in human volunteers. *Appetite, 29*(1), 61-76.
Youmans, S. R., Youmans, G. L., & Stierwalt, J. A. G. (2009). Differences in tongue strength across age and gender: is there a diminished strength reserve? *Dysphagia, 24*(1), 57-65.

Youssef, R. E., Throckmorton, G. S., Ellis, E., & Sinn, D. P. (1997). Comparison of habitual masticatory patterns in men and women using a custom computer program. *The Journal of Prosthetic Dentistry, 78*(2), 179-186.

Yven, C., Patarin, J., Magnin, A., Labouré, H., Repoux, M., Guichard, E., & Feron, G. (2012). Consequences of individual chewing strategies on bolus rheological properties at the swallowing threshold. *Journal of Texture Studies, 43*(4), 309-318.

Z

Zhuang, Z., Landsittel, D., Benson, S., Roberge, R., & Shaffer, R. (2010). Facial anthropometric differences among gender, ethnicity, and age groups. *Annals of occupational hygiene, 54*(4), 391-402.

Zijlstra, N., de Wijk, R. A., Mars, M., Stafleu, A., & de Graaf, C. (2009). Effect of bite size and oral processing time of a semisolid food on satiation. *The American journal of clinical nutrition, 90*(2), 269-275.

English summary

Oral processing behavior is the start of food digestion, with the breakdown of food into smaller particles and the formation of a smooth bolus. This process consist of multiple physiological parameters and product properties all contributing to a smooth oral processing. Physiological parameters are driven by differences in consumer characteristics. Oral processing behavior is known to affect our food intake and it is therefore important to understand the variation and underlying mechanism of oral processing behavior. The research described in this thesis aimed to better understand food oral processing behavior of consumers varying in age, gender and ethnicity based on oral physiology, anatomy and sensory sensitivity. Secondly, this thesis systematically investigates the relationship of oral processing behavior with oral physiology and anatomy.

In the first chapters of this thesis the influence of product properties (chapter 2) and consumer characteristics (chapter 3) on the oral processing behavior was investigated. In both chapters oral processing behavior was assessed with video recordings of the consumption behavior of 18 liquid, semi-solid and solid foods. In chapter 2 mechanical and rheological properties were assessed with uniaxial compression and with the use of a rheometer. Product liking, familiarity and frequency of consumption were assessed with the use of questionnaire. Rheological and mechanical properties of all food categories had a large effect on bite size, consumption time and eating rate. Liking, familiarity, and consumption frequency showed to have a relatively smaller impact on oral processing behavior.

In chapter 3 oral processing behavior was compared between Dutch, Caucasian adults (18-30 yrs), Chinese, Asian adults (18-30 yrs), Dutch, Caucasian older adults (60-80 yrs), and consumers with mild swallowing problems and/or low mastication efficiency (18-80 yrs). Age, gender and ethnicity influenced oral processing behavior of liquid, semi-solid and solid foods differently. Age, gender and ethnicity had a strong effect on oral processing behavior. Older adults had an increased consumption and lower eating rate compared to adults. Females had smaller bite size and therefore a lower eating rate compared to males. Chinese, Asian consumers had a smaller bite size and lower eating rate compared to Dutch, Caucasian consumers. 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.

To understand the underlying mechanisms of the oral processing behavior, oral physiology and anatomy were quantified of Dutch adults and older adults (chapter 4) and Chinese adults and older adults (chapter 4 & 5). Mastication performance, salivary flow rate (stimulated and unstimulated) and dental status were quantified to characterize oral physiology. Volume of oral cavity, tongue dimensions, facial anthropometry, height and weight were quantified to characterize anatomy. Oral processing behavior of three solid foods (carrot, cheese and sausage) was quantified by video recordings. Age, gender and ethnicity were found to affect oral physiology and anatomy. During ageing, dental status decrease, volume of oral cavity was smaller, head dimensions become smaller. Males had a larger volume of oral cavity and larger head dimensions compared to females. Chinese, Asian consumers were shorter, weigh less, had a lower height:width ratio of the head; had a lower percentage of normal occlusion compared to Dutch, Caucasian consumers. Certain effects of ethnicity on physiology were mediated by age, including saliva flow rate, number of teeth and molars. Several relationships were found between oral processing behavior and oral physiology and anatomy. Body weight and number of teeth had the strongest relationships with oral processing behavior. The results of chapter 4 and 5 suggest oral physiology and anatomy partially explain the variation in oral processing behavior. Other factors, including food habits and culture are suggested to have a stronger influence on oral processing behavior.

Chapter 6 investigated texture and taste sensitivity and consumer phenotype in consumers varying in gender and ethnicity. Texture and taste sensitivity were assessed by a 2-AFC ascending staircase method for thickness (maltodextrin solutions differing in viscosity), firmness (agar gels differing in fracture stress) and sweetness (sucrose solutions differing in concentration) sensitivity. Consumer phenotype was quantified by saliva flow rate, fungiform papillae density (FPD), lingual tactile threshold and PROP taster status. No significant differences were found between Chinese, Asian and Dutch, Caucasian adults in thickness, firmness and sweetness sensitivity and consumer’s phenotyping. Minor differences were found in firmness sensitivity and FPD between gender. Only one out of 15 relationships between sensory sensitivity (thickness, firmness, sweetness) and consumer characteristics (saliva flow rate, FPD, lingual tactile threshold, PROP taster status) was significantly and weakly related suggesting that inter-individual variation in these consumer characteristics was almost unrelated to sensory sensitivity. The results of this chapter indicate that texture (thickness, firmness) and taste (sweetness) sensitivity do not differ between Dutch, Caucasian and Chinese, Asian adults. Saliva flow rate, fungiform papillae density, lingual tactile threshold and PROP taster status do not explain inter-individual variation in sensory sensitivity between these consumers.

To conclude, oral processing behavior has been found to be influenced by product properties and consumers characteristics, age, gender and ethnicity. While rheological and mechanical food properties have a large impact on food oral processing behavior, consumer characteristics are a major factor contributing to inter-individual variation in food oral processing behavior. Age, gender and ethnicity had an impact on oral physiology and anatomy. These factors should be taken into account when investigating oral processing behavior and oral physiology and anatomy. Since oral physiology and anatomy only partially explain the variation in oral processing behavior, we suggest other factors such as food habits and culture show a stronger influence on oral processing behavior.

Nederlandse samenvatting

Het eetproces in de mond is het begin van de voedselvertering, met de afbraak van voedsel in kleinere deeltjes en de vorming van een gladde bolus. Bij dit proces dragen meerdere fysiologische parameters en producteigenschappen bij aan het soepel verlopen van het eetproces. Fysiologische parameters worden bepaald door verschillen tussen consumenten. Het is bekend dat het eetproces invloed heeft op onze voedselinname en het is daarom belangrijk om de variatie en het onderliggende mechanisme van het eetproces te begrijpen. Het onderzoek dat in dit proefschrift wordt beschreven is gericht op het beter begrijpen van het eetproces van consumenten die variëren in leeftijd, geslacht en etniciteit op basis van orale fysiologie, anatomie en sensorische gevoeligheid. Ten tweede onderzoekt dit proefschrift systematisch de relatie tussen het eetproces en de orale fysiologie en anatomie.

In de eerste hoofdstukken van dit proefschrift is de invloed van producteigenschappen (hoofdstuk 2) en consumentenkenmerken (hoofdstuk 3) op het eetproces onderzocht. In beide hoofdstukken werd het eetproces vastgelegd met video-opnames tijdens het eten van 18 vloeibare, half-vaste en vaste voedingsmiddelen. In hoofdstuk 2 werden de mechanische en rheologische eigenschappen onderzocht met behulp van uni-axiale compressie en een rheometer. De voorkeur voor het product, de bekendheid, en de frequentie van de consumptie werden gemeten met behulp van een vragenlijst. De rheologische en mechanische eigenschappen van alle voedselproducten hadden een groot effect op de hap grootte, consumptietijd en eetsnelheid. De voorkeur, bekendheid en consumptiefrequentie bleken een relatief kleinere invloed te hebben op het eetproces.

In hoofdstuk 3 werd het eetproces vergeleken van Nederlandse, Kaukasische volwassenen (18-30 jaar), Chinese, Aziatische volwassenen (18-30 jaar), Nederlandse, Kaukasische ouderen (60-80 jaar), en consumenten met milde slikproblemen en/of lage kauwefficiëntie (18-80 jaar). Leeftijd, geslacht en etniciteit hebben het eetproces van vloeibare, half-vaste en vaste voedingsmiddelen verschillend beïnvloed. Ouderen hadden een langere consumptietijd en een lagere eetsnelheid in vergelijking met volwassenen. Vrouwen hadden een kleinere hapgrootte en daardoor een lagere eetsnelheid in vergelijking met mannen. Chinese, Aziatische consumenten hadden een kleinere hapgrootte en een lagere eetsnelheid in vergelijking met Nederlandse, Kaukasische consumenten. Consumenten met verminderde kauwefficiëntie of milde slikproblemen vertoonden een vergelijkbaar eetproces als gezonde consumenten, waarschijnlijk omdat de vermindering van het kauwvermogen in de groep beperkt was.

Om inzicht te krijgen in de onderliggende mechanismen van het eetproces, werden de orale fysiologie en de anatomie onderzocht van Nederlandse volwassenen en ouderen (hoofdstuk 4) en Chinese volwassenen en ouderen (hoofdstuk 4 & 5). Kauw efficiëntie, speekselproductie en tandheelkundige status werden gekwantificeerd om de mondfysiologie te karakteriseren. Het volume van de mondholte, afmetingen van de tong, antropometrie van het gezicht, en lengte en gewicht werden gekwantificeerd om de anatomie te karakteriseren. Het eetproces van drie voedingsmiddelen (wortel, kaas en worst) werd gekwantificeerd met behulp van video-opnamen. Leeftijd, geslacht en etniciteit hadden een invloed op de orale fysiologie en anatomie. Tijdens het ouder worden neemt de tandheelkundige status af, wordt het volume van de mondholte kleiner, en wordt het hoofd kleiner. Mannen hadden een groter volume van de mondholte en grotere hoofddimensies dan vrouwen. Chinese, Aziatische consumenten waren korter, wogen minder, hadden een lagere hoogte-breedte verhouding van het hoofd, en hadden een lager percentage normale occlusie (contact tussen bovenkaak en onderkaak) in vergelijking met Nederlandse, Kaukasische consumenten. Speekselproductie en het aantal tanden en kiezen werden beïnvloed door een interactie van etniciteit en leeftijd. Er werden verschillende relaties gevonden tussen het eetproces, orale fysiologie en anatomie. Het lichaamsgewicht en het aantal tanden waren het meest bepalend voor het eetproces. De resultaten van hoofdstuk 4 en 5 suggereren dat de fysiologie en anatomie van de mond in mindere mate bepalend waren voor het eetproces. Andere factoren, waaronder de voedingsgewoonten en cultuur, hebben mogelijk een sterkere invloed op het eetproces.

In hoofdstuk 6 werd de textuur- en smaakgevoeligheid en verschillende fenotype eigenschappen van consumenten die variëren in geslacht en etniciteit onderzocht. Textuur- en smaakgevoeligheid werden beoordeeld met een 2-AFC oplopende trap-methode voor viscositeit (maltodextrine oplossingen die verschillen in viscositeit), stevigheid (agar gels die verschillen in hardheid) en zoetheid (suiker oplossingen die verschillen in concentratie) gevoeligheid. Het fenotype van de consument werd gekwantificeerd aan de hand van de speekselproductie, dichtheid van papillen op de tong (FPD), tactiele gevoeligheid van de tong en gevoeligheid voor bitter. Er werden geen significante verschillen gevonden tussen Chinese, Aziatische en Nederlandse, Kaukasische volwassenen in gevoeligheid voor viscositeit, stevigheid en zoetheid en de fenotypering van de consument. Kleine verschillen werden gevonden in stevigheidsgevoeligheid en FPD tussen de geslachten. Slechts één van de 15 relaties tussen sensorische gevoeligheid (viscositeit, stevigheid, zoetheid) en consumentenkenmerken (speekselproductie, FPD, tactiele gevoeligheid van de tong, gevoeligheid voor bitter) was significant en zwak gerelateerd, wat suggereert dat interindividuele variatie in deze consumentenkenmerken bijna geen verband hield met sensorische gevoeligheid. De resultaten van dit hoofdstuk geven aan dat textuur (viscositeit, stevigheid) en smaak (zoetheid) gevoeligheid niet verschillen tussen Nederlandse, Kaukasische en Chinese, Aziatische volwassenen. De speekselproductie, FPD, tactiele gevoeligheid van de tong en gevoeligheid voor bitter verklaren niet de interindividuele variatie in sensorische gevoeligheid tussen deze consumenten.

Samenvattend, het is gebleken dat het eetproces wordt beïnvloed door de eigenschappen van het product en de kenmerken van de consument, leeftijd, geslacht en etniciteit. De rheologische en mechanische eigenschappen van voedingsmiddelen hebben een grote invloed op het eetproces van voedingsmiddelen, maar vooral de kenmerken van de consument dragen bij aan de interindividuele variatie in het eetproces. Leeftijd, geslacht en etniciteit hebben een impact op de orale fysiologie en anatomie. Met deze factoren moet rekening worden gehouden bij het onderzoeken van het eetproces en de orale fysiologie en anatomie. Aangezien orale fysiologie en anatomie slechts gedeeltelijk de variatie in het eetproces verklaren, suggereren we dat andere factoren zoals voedingsgewoonten en cultuur een sterkere invloed hebben op het eetproces.

Dankwoord
About the author
List of publications
Overview of completed training activities

Dankwoord

Zo dat was het dan, mijn PhD is klaar! Het waren 4 bijzondere jaren met veel ups en downs. Tijdens mijn PhD heb ik veel hulp gehad van verschillende mensen, die ik hierbij graag wil bedanken.

Als eerste mijn begeleiders, **Markus Stieger, René de Wijk en Kees de Graaf**. Markus, you have been a great supervisor and mentor for me. You have counselled and supported me during every step of my PhD. Whenever I received critical comments from either reviewers or industrial partners, you always had my back. I couldn't have completed my PhD without your support. You were always eager to have a critical look at my papers, posters and presentations and pushing me to take it to the next step. I am very thankful for this. René, bedankt voor de fijne gesprekken of het nu om werk of privé ging, bij jou kon ik het altijd kwijt. Jij was altijd benieuwd hoe het met mij ging. Bedankt voor je input en feedback op mijn thesis. Markus & Rene, the three of us had very interesting meetings which always started with at least 15 minutes of chitchat about the education system, collaborations with industry, the division and many other subjects. I want to thank you for these chats, where I was able to share a critical look on and get to know the academic world in another way. Kees, ondanks dat we niet veel meetings samen hebben gehad, heb ik onze samenwerking altijd als erg prettig ervaren. Jij vond het fijn om samen te brainstormen over toekomstige studies en gaf fijne feedback hoe we nog meer uit de onderzoeken konden halen.

I would also like to thank my thesis committee **Prof. Lisette de Groot, Prof Wender Bredie, Prof. Jeff Brunstrom, Prof. Chris Vinyard** for reading my thesis and being present at my defence.

Bij de voorbereiding en uitvoering van mijn studies heb ik veel hulp gehad van verschillende mensen. **Els, Henriette en Ineke**, heel erg bedankt voor de ondersteuning van mijn voedingsstudies. Toen het tegen zat met mijn METC aanvraag, hebben jullie mij veel steun kunnen bieden. Bedankt voor jullie hulp! **Corine**, bedankt voor je hulp met EyeQuestion en de gezellige gesprekjes op de gang. **Esmee Doets** en **Milou Vrijthof** bedankt voor jullie hulp bij het gebruik van het SenTo panel tijdens mijn eerste studie. **Joao Paulo**, thank you for your statistical advice and pleasant meetings. **Dione**, bedankt voor het controleren van de informatiebrochures en flyers voor de deelnemers.

Gea, Jasmijn, Adrienne, Jeanine, Riekie en Cornelia, bedankt voor het regelen van alle administratieve klussen en financiën. Jasmijn ik wil jou in het bijzonder bedanken voor al je harde werk bij het regelen van mijn visum naar China. Ik bewonder je om je no-nonsense mentaliteit waarbij niets in je weg staat.

Tijdens mijn studies heb ik veel hulp gehad van mijn studenten, hiervoor ben ik hun erg dankbaar. **Claudia Briseno Ozumbilla** and **Kysha Kraaijvanger**, thank you for your help during the first study. Claudia, you were very motivated and eager to learn. I enjoyed our Spanish and Dutch 'classes' during the preparations of the study and I hope you will have a successful career. Kysha, als MBO student mailde je mij voor een stageplek bij de FOP studie. Je had erg veel plezier in het contact met deelnemers en je ging er altijd 110% tegen aan. **Liza Kester, Judith Schuijs en Ellen Koedam**, bedankt voor jullie hulp tijdens mijn 2^{e} studie. Liza en Judith, jullie begonnen samen met een thesis (Liza) en stage (Judith), zodat er een hecht team ontstond voor de OrCa studie. Ik vond het erg leuk om samen met jullie te werken en jullie te zien groeien en ontwikkelen. Ellen, bedankt voor je hulp als student assistent zonder jouw hulp zou ik nog veel langer bezig zijn geweest met data verzameling. **Yifan Zhang and Jingke Jia**, thank you for your help during my 4th study in China. Yifan, you were always very motivated and had a critical look on the study design. Jingke, you always wanted to help with translations of Chinese documents, it was a pleasure working with you.

I would also like to thank my colleagues of the Division of Human Nutrition & Health. During my first two years, I got a lot of help and advice from the more experienced PhD candidates, thank you **Jet, Inge, Yfke, Suzanne, Guido, Irene, Janet, Apple, Astrid and Vera**. I also enjoyed discussing work and chatting with the newer generation of PhD candidates, thank you **Korrie, Elbrich, Rachelle, Paulina, Ruoxuan, Maria Salazar, Matjaz, Eva and Pol**. In 2019 heb ik samen met Nicole en Anne de alumni dag georganiseerd. **Nicole en Anne**, bedankt voor de leerzame en leuke tijd, dit was een mooie afwisseling op mijn PhD activiteiten.

I would like to thank my fellow PhD candidates of the Smooth Bite for All project, **Marco, Philipp, Arianne, Monica and Roelien**. Marco, thank you for the interesting talks about the Dutch culture and your help with the preparations of my 3rd study. Philipp, thank you for the honest and open conversations about (PhD) life. Arianne, I admire your enthusiasm and energy, I wish you good luck in your future career. Monica, I enjoyed our collaboration during the first study a lot. I admire your hard work and commitment. I would also like to thank the project partners a lot for their feedback during our meetings, thank you **Amelie, Benoit, Cecile, Marcel, Martijn, Jonathan, Stefanie, Yves, Michel and Veronica**.

My 4th study was a collaboration with the FOP lab in Hangzhou, China. I would like to thank **prof. Jianshe Chen and Xinmiao Wang** for their enthusiasm to collaborate and their input in the study design. Even after my visa was declined, you were still optimistic to continue with the study. Thank you for your support. **Trista** thank you for setting up all the paperwork for the collaboration. **Esther Kim, Hilbert van der Glas and Carol Mosca**, thank you for the interesting conversations about the collaboration and starting a research in China. Without the students, this collaboration would have never worked out, thank you **Sunny, Yifan and Jingke**. I also would like to thank other colleagues in Hangzhou, thank you **Mio, Maryia, Enrico, Macary** and the rest of the lab for my wonderful time in China. Thank you for introducing me to the FOP lab, China and Hangzhou. I enjoyed the nice group dinners we had together and the talks about culture differences.

Hoe anders zou mijn PhD zijn geweest zonder mijn geweldige kamergenootjes, ik kan het me niet voorstellen. Lieve **Roelien, Marlou, Mariëlle, Janneke, Nick, Tesfaye, Erna, Elise, Maria en Yum** bedankt voor de fijne gesprekken, superhandige adviezen en gezellige dagen op het Helix. Roelien, ik ben zo blij dat we gelijk op dag 1 samen op een kamertje in het Biotechnion zaten. Ik voel me helemaal op mijn gemak bij jou en ben erg blij met de fijne gesprekken die we in alle jaren hebben gehad tijdens onze congressen samen en ook op onze reis in China. Met jou als paranimf weet ik dat ik de hele wereld aan kan. Marlou, jij bent het stoere engeltje op mijn schouder die zegt dat ik soms een stapje meer moet nemen. Jij weet altijd hoe je mij kan motiveren, heel erg bedankt hiervoor. Als top Postdoc'er waardeer ik je werk mentaliteit enorm. Samen met Roelien, ben jij mijn ideale paranimf waardoor mijn zelfvertrouwen enorm groeit. Bedankt! Mariëlle, jij bent mijn go-to persoon voor alle handige dingetjes, jij bent zo enorm handig met Excel, Outlook, Word, echt alles. Ik wil je bedanken dat je mij hebt geleerd om niet te ongeduldig te zijn, al lukt dit nog niet altijd. Ik hoop dat we in de toekomst nog regelmatig een rondje gaan fietsen of een spelletje gaan spelen. Janneke, wat een leuke gesprekken hebben we altijd, soms over hardlopen, maar ook vaak over onze guilty pleasure 'Temptation Island'. Ik zal je gezelligheid missen.

Ook al ben ik al eventjes afgestudeerd, ik waardeer heel erg het contact met mijn BSc miepjes (**Celine, Iris, Deborah, Joke**), MSc sensory groep (**Claudia, Elyn, Ineke, Emma**) en borrelclub (**Anne, Marijn, Anouschka, Suus, Elja, Dane, Emiel**).

Ik wil ook graag het thuisfront, of ook wel 'thuisthuis' genoemd, bedanken. Ten eerste, mijn vrienden uit Vlaardingen en Schiedam. Bedankt **Sebas, Maris, Sander, Annemieke en Quintijn** voor jullie support. Ik vond het altijd leuk om uit te leggen waar mijn onderzoek over gaat. Sebas en Maris, bedankt voor de speciale vriendschap met jullie, ik kan echt alles kwijt bij jullie. Nu ik echt student-af ben, zal ik me iets burgerlijker gaan gedragen ;) Daarnaast wil ik mijn vriendengroep uit Etten-Leur graag bedanken voor hun support, bedankt **Anne-Lotte, Mayckel, Annemarie, Jasper, Manon, Peter, Alain, Monica, Rosa, Maurits, Yvette, Eric en Stefanie**. Het is erg fijn om nog steeds zo'n goed contact te hebben met elkaar. Ons jaarlijkse weekendje weg is een hoogtepunt van het jaar. Ik vind het erg leuk om aan jullie te laten zien waar ik al die jaren zo druk mee ben geweest.

Ik wil graag mijn familie & toekomstige schoonfamilie bedanken. **Elma, Mart, Lisenka, Anita**, jullie nieuwsgierigheid naar mijn onderzoek heb ik altijd als erg leuk ervaren. Bedankt voor jullie support. **Papa, mama, Joost, oma**, bedankt voor jullie onverminderde support en dat jullie altijd in mij geloven. Ik hoop dat jullie trots zijn op jullie dochter, zus en kleindochter. Ik geniet enorm van onze gezellige vakanties, weekendjes weg of gewoon even bijkletsen in de tuin. Bedankt!

Lieve **Fedor**, zonder jou had ik hier niet gestaan. Bedankt dat je er altijd voor mij bent, of het nu even een mailtje doorlezen is, of samen brainstormen over stellingen. Ik kan mijn leven niet voorstellen zonder jou. Jij haalt het beste in mij naar boven en vult mij goed aan. Ik kijk uit naar onze toekomst samen.

About the author

Eva Ketel was born on the 28th of February, 1991 in Etten-Leur, the Netherlands. In 2009, she enrolled in the BSc program Human Nutrition and Health at Wageningen University. In 2012, she enrolled in the MSc specialization Sensory Science at Wageningen University. As part of her MSc program, she followed an Erasmus semester at the University of Copenhagen, Denmark. For her MSc thesis, she investigated the influence of eating speed on sensory perception, bolus properties and muscle activity, which has resulted in a scientific publication. Eva did an internship at the Donders Centre for Cognitive Neuroimaging in Nijmegen, the Netherlands. The internship was part of the FOCOM project, investigating implicit and explicit measures of motivational behavior for ketchup products. Eva graduated in 2014. As part of the FOCOM project, Eva worked as a test leader at Essensor and NIZO food research in Ede, the Netherlands. In 2015, she worked as research assistant at the Donders Centre for Cognitive Neuroimaging on the Satisfaction project investigating neurocognitive mechanisms controlling satiation. In 2016, Eva was appointed as a PhD candidate at TIFN and the Division of Human Nutrition and Health at Wageningen University, the Netherlands. Her PhD project was part of the public-private partnership called "Smooth Bite for All". Her research focused on understanding the variation in oral processing behavior of consumers differing in age, gender and ethnicity by investigating oral physiology and sensory sensitivity. During her PhD project, Eva attended various courses and she presented her work at several international conferences (3 oral presentations, 6 poster presentations). She was involved in teaching of BSc and MSc courses and supervising BSc and MSc students. Eva was part of the VLAG PhD council, ensuring the rights and needs of PhD candidates. In 2019, she co-organized the alumni day of the BSc and MSc Nutrition and Health.

Eva can be contacted by email: eva.ketel@gmail.com.

List of publications

Publications in peer-reviewed journals

Ketel, E.C., de Wijk, R.A., de Graaf, C., Stieger, M. (2020). Relating oral physiology and anatomy of consumers varying in age, gender and ethnicity to food oral processing behaviour. *Physiology & Behaviour*, 215, 112766.

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 behaviour of liquid, semi-solid and solid foods differently. *Food Research International*, 119, 143-151.

Aguayo-Mendoza, M.G., **Ketel, E.C.**, van der Linden, E., Forde, C.G., Piqueras-Fiszman, B., Stieger, M. (2019). Oral processing behaviour of drinkable, spoonable and chewable foods is primarily determined by rheological and mechanical food properties. *Food Quality and Preferences*, 71, 87-95.

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

Submitted for publications

Ketel, E.C., Zhang, Y., Jingke, J., Wang, X., de Wijk, R.A., Chen, J., Stieger, M. Comparison of and relationships between oral physiology, anatomy and food oral processing behaviour of Chinese, Asian and Dutch, Caucasian consumers differing in age.

Ketel, E.C., de Wijk, R.A., de Graaf, C., Stieger, M. Thickness, firmness and sweetness sensitivity do not differ between Chinese, Asian and Dutch, Caucasian adults.

Overview of completed training activities

Discipline specific courses

2017	Discussion meeting “Sensory science has to move on” at Vakgroep Sensorisch Onderzoek	Utrecht, NL
	BFDG conference *	Reading, UK
2018	Nudgis conference	Utrecht, NL
	VoedingNederland conference	Utrecht, NL
	Course “Sensory perception & Food preference – The role of context’’ (VLAG)	Wageningen, NL
	Food Oral Processing conference *	Nottingham, UK
	Eurosense conference **	Verona, IT
2019	SSIB conference **	Utrecht, NL
	Pangborn conference **	Edinburgh, UK

* Oral presentation(s) ** Poster presentation(s)

General courses

2016	Multivariate analysis for food data/sciences (VLAG)	Wageningen, NL
	PhD week (VLAG)	Baarlo, NL
2017	Competence assessment (WGS)	Wageningen, NL
2018	Scientific writing (WGS)	Wageningen, NL
	Stress identification & management (WGS)	Wageningen, NL
	Start to teach (WGS)	Wageningen, NL
2019	Career perspective (WGS)	Wageningen, NL
2020	Last stretch of the PhD program (WGS)	Wageningen, NL
	Writing propositions (WGS)	Wageningen, NL

Optional courses

2016	VLAG proposal	Wageningen, NL
	Good Clinical Practice	Wageningen, NL
2017	PhD tour HNH	UK
2016-2020	Tasty talks meetings SSEB	Wageningen, NL
2016-2020	Project meetings TiFN “Smooth Bite for All”	Wageningen, NL
2018-2020	Member of VLAG PhD council	Wageningen, NL

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.

Cover and design by: Proefschriftmaken.nl

Printed by Proefschriftmaken.nl