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

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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.

Key words: Food oral processing, food consistency, bite size, consumption time, eating rate, liking

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 (Hiiemae, 2004; Chanasattru, Corradini, & Peleg, 2002; Abhyankar, Mulvihill, & Auty, 2011; Chen & Stokes, 2012). 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, Vingerhoeds, & de Hoog, 2007; van Vliet, van Aken, de Jongh, & Hamer, 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, Leong, Chia-Ming, & McCrickerd, 2017; Forde, van Kuijk, Thaler, de Graaf, & Martin, 2013; 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., 2013). 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, Zijlstra, Mars, de Graaf, & Prinz, 2008; Steele & Lieshout, 2004). 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. (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 & 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, Wagoner, & Foegeding, n.d.; Woda, Foster, Mishellany, & Peyron, 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, 2013). Forde (2017) and Bellisle (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., 2013) showed no relationship between liking and oral processing behavior. Yet, the relationship between liking and familiarity for liquid and semi-solid foods and oral processing behavior remains unclear.

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

2 Material and Methods

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 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 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 Instrumental analyses

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 1). Though the food temperature may vary during oral processing, it was assumed that the temperature of liquid and semi-solid foods changed only to a small extent during consumption. Thus, under this assumption the serving temperature was chosen as the relevant temperature for the rheological testing. The Ostwald-de Waele model ($\eta = K\,\dot{\gamma}^{n-1}$) was used to fit the flow curves to quantify consistency K and flow behavior index n. In the Ostwald-de Waele model η represents viscosity (Pas), $\dot{\gamma}$ (s^{-1}) shear rate, K consistency which corresponds to viscosity at a shear rate of 1 s^{-1}($\eta_{1s\text{-}1}$), 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, Wolfgang & Kretzschmar, Hans-Joachim, 2008), and used for water and tea. Viscosity of sparkling water was assumed to be the same as viscosity of still water.

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 75 mm diameter was used to perform uniaxial compression tests on all chewable foods with the exception of noodles. Samples were cylinders with 15 mm height and 18 mm diameter. Processed cheese (Kiri) was used in its original shape, a block of 37 x 37 x 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 ($\sigma_{15\%}$) were calculated by averaging over the replicate measurements.

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, van der Bilt, Abbink, & Bosman, 2004; Sánchez-Ayala, Vilanova, Costa, & Farias-Neto, 2014) and only subjects considered with good mastication efficiency, defined as subjects with a median particle size <3.5mm, 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/m^2, 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).

2.4 Experimental procedure

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

Before starting video recording, the researcher placed four round stickers on the participant's face: two on the forehead spaced horizontally 5 cm, one on the tip of the nose, and one on the center of the chin. These stickers were used for video analysis.

Participants were seated in a chair in front of a table with a video camera (Canon IXUS-500HS), approximately 50 cm from the participant's face. This distance was close enough to take a complete picture of the face without distracting or discomforting the participants. Participants were instructed to hold their head straight and not to block their mouth or face while eating.

Drinkable products were served in 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.

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

Table 2. Parameters describing oral processing behavior of 18 foods belonging to three categories.

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

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.

2.7 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 (η_p^2) was calculated to estimate effect sizes. Post hoc pairwise comparisons were performed using Bonferroni's adjustment. Additionally, an analysis of variance within each product category was conducted to compare products liking, familiarity and frequency of consumption.

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

3 Results

3.1 Rheological and mechanical properties of foods

Consistency *K* corresponding to viscosity at a shear rate of 1 s^{-1} and flow behavior index *n* indicating the magnitude of shear thinning behavior ($0 < n < 1$) of drinkable and spoonable foods are shown in Table 3. 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 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
Semi-solid Spoonable	Drinking yogurt	1.312	0.45
	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 ($\sigma_{15\%}$) for solid, chewable foods are shown in Table 4. Young's modulus ranged from 0.28 kPa for tofu to 50.31 kPa for carrot. $\sigma_{15\%}$ ranged from 4.42 kPa for tofu to 661.25 kPa for chocolate.

Table 4. Mean and standard error of Young's modulus and stress at 15% strain ($\sigma_{15\%}$) of solid, chewable foods.

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

3.2 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 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, η_p^2 = .13], spoonable [F (3, 238) = 4.44, p = .005, η_p^2 = .05], and chewable [F (7, 478) = 11.94, p < .001, η_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.

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).

Table 5. Means of parameters describing oral processing behavior, liking, familiarity and frequency of consumption for all drinkable, spoonable, and chewable foods. Values are reported as mean ± SE. Superscripts indicate significant differences between means within each column within a product category (p<0.05).

		Bite size (g)	**Consumption time (s)**	**Number of swallows**	**Eating rate (g/s)**	**Number of chews**	**Chewing rate (chews/s)**	**Cycle duration (s)**	**Liking**	**Familiarity**	**Frequency of consumption**
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 ± 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

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 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, η_p^2 = .02], spoonable [F (1,238) = 36.42, p < .001, η_p^2 = .13] and chewable foods [F (1,478) = 23.80, p < .001, η_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, η_p^2 = .06] and chewable foods [F (1,478) = 20.69, p < .001, η_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, η_p^2 = .01] and number of chews [F (1,477) = 10.94, p < .001, η_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, η_p^2 = .03] and number of chews of solids products [F (1,477) = 5.06, p = .025, η_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.

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 6).

Table 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<0.05 level and **correlation is significant at p<0.01 level. [a] Variables were transformed into logaritmic scale.

Bite size of liquid and semi-solid foods was negatively correlated with product consistency *K* (r = -.880, n = 10, p < .001) (Figure 1a and Table 6) and positively correlated with flow behavior index *n* (r = .891, n = 10, p < .001). Bite size of chewable foods was negatively correlated with stress ($\sigma_{15\%}$) (r = -.912, n = 7, p = .004) and Young's modulus (r = -.899, n = 7, p = .006) (Figure 2a and Table 6).

Consumption time was positively correlated with consistency (r = .750, n = 10, p = .012) and negatively with flow behavior index (r = -.762, n = 10, p = .010) (Figure 1b and Table 6). Figure 2b shows that for chewable foods, with increasing $\sigma_{15\%}$ or Young's modulus consumption time tended to increase. However, this correlation was not significant since beef deviates from the trend line. When beef is removed from the data analysis, the correlation between consumption time and Young's modulus becomes significant (r =.846, n = 6, p = .034) (Figure 2d). Likewise, a trend was observed with regards to number of chews and $\sigma_{15\%}$. With increasing $\sigma_{15\%}$or Young's modulus, the number of chews increased. However, this trend was not significant unless beef is removed from data, then the correlation is r =.815, n = 6, p = .048.

Eating rate was negatively correlated with product consistency for liquid and semi-solid foods and $\sigma_{15\%}$ for solid foods (r = -.915, n = 10, p < .001; r = - .774, n = 7, p = .041 respectively). It can be observed that when consistency or stress increased eating rate decreased (Figure 1c and 2c and Table 6). The number of swallows positively correlated with consistency (r = .853, n = 10, p = .002), therefore products that had a higher consistency *K* needed more swallows than foods with lower consistency *K*. Other oral processing parameters such as number of chews, chewing rate, and cycle duration did not significantly correlate with the rheological and mechanical properties of solid, chewable foods.

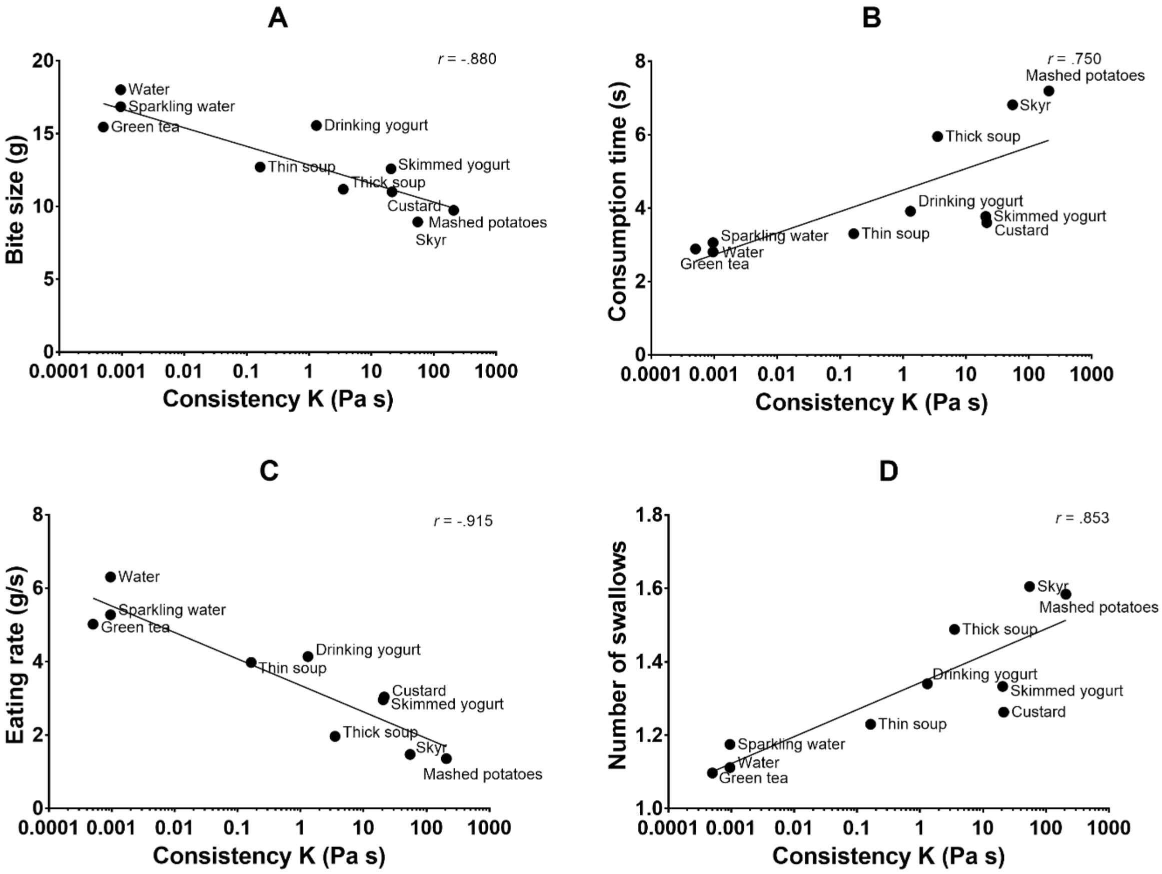

Figure 1. Correlations between consistency K and (A) bite size, (B) consumption time, (C) eating rate and (D) number of swallows of liquid and semi-solid foods.

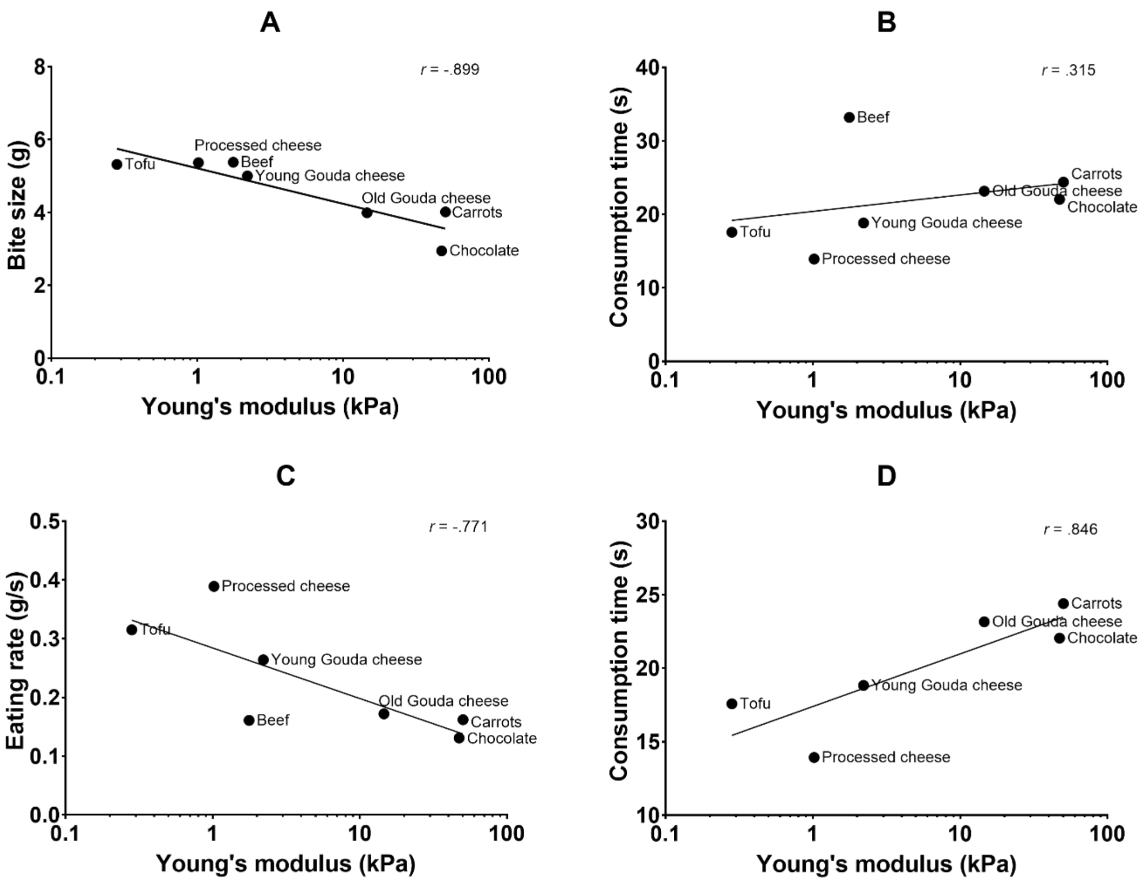

Figure 2. Correlations between Young's modulus and (A) bite size, (B) consumption time of all products, (C) Eating rate and (D) consumption time excluding beef meat.

4 Discussion

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

The present study showed that bite size has an inverse relationship with consistency *K* for drinkable and spoonable foods and with stress needed to compress to 15% strain ($\sigma_{15\%}$) for chewable foods. In line with our results are the results of de Wijk

(2008) who investigated the effect of viscosity on bite size of one liquid (milk) and one semi-solid food (custard). de Wijk (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 ($\sigma_{15\%}$) although bite size decreases. 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 $\sigma_{15\%}$ of solid foods consumption time increases although bite size decreases. This suggests that consumption time of liquid, semi-solid and solid foods seems to be determined by rheological and mechanical food properties.

The number of chews per bite were significantly different between solid foods. The correlation between number of chews and mechanical properties of solid foods was not significant. We observed that beef is a product that differed from the other foods tested, probably due to its fibrous, anisotropic structure which strongly influences mechanical properties. In our study, this effect has been neglected during the characterization of the mechanical properties of beef. In order to form a bolus suitable to swallow, the beef meat needs to be well mashed by teeth, and even in the swallowing point some intact fibers can be observed in the bolus (Mioche, Bourdiol, Monier, & Martin, 2002). 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 (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, 2013; van den Boer et al., 2017; Viskaal-van Dongen, Kok, & de Graaf, 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, Lim, Leong, Chia, &

Forde, 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 $\sigma_{15\%}$ are mechanical properties which are determined under conditions mimicking oral processing behavior. It is therefore surprising that these measures yielded such strong correlations with oral processing behaviors, given they do not accurately reflect the kind of mechanical stress and deformation food structure undergoes during mastication. Since mastication of solid foods involves large deformations it would be interesting to quantify the relationships between parameters describing oral processing behavior and mechanical properties of solid foods determined under large deformation or under repetitive compression such as Texture Profile Analysis (TPA).

Cycle duration and chewing rate remained considerably stable across chewable foods, with an average of 0.7 s and 1.4 chews/s, respectively. These values are in line with previously reported results (Bellisle, Guy-Grand, & Le Magnen, 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, Lucas, & Bruce, 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, Honma, Nomura, & Yamada, 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 (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.

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.

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Figure 1. Correlations between consistency and (A) bite size, (B) consumption time, (C) eating rate and (D) number of swallows of liquid and semi-solid foods.

Figure 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.