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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.

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, Mulvihill, & Auty, 2011; Chanasattru, Corradini, & Peleg, 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, 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.,

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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 and 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, 2017; 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 et al. (2017) and Bellisle and 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., 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.

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 × 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 ($\sigma_{15\%}$) 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 < 3.5 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/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