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Current Perspectives on Food Oral Processing

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food oral processing, food texture, food flavor, bolus swallowing, eating behavior, food sensory, oral physiology

Abstract

Food oral processing (FOP) is a fast-emerging research area in the food science discipline. Since its first introduction about a decade ago, a large amount of literature has been published in this area, forming new frontiers and leading to new research opportunities. This review aims to summarize FOP research progress from current perspectives. Food texture, food flavor (aroma and taste), bolus swallowing, and eating behavior are covered in this review. The discussion of each topic is organized into three parts: a short background introduction, reflections on current research findings and achievements, and future directions and implications on food design. Physical, physiological, and psychological principles are the main concerns of discussion for each topic. The last part of the review shares views on the research challenges and outlooks of future FOP research. It is hoped that the review not only helps readers comprehend what has been achieved in the past decade but also, more importantly, identify where the knowledge gaps are and in which direction the FOP research will go.

1. INTRODUCTION

It has been more than a decade since the publication of the first review on food oral processing (FOP) (Chen 2009). In that review, the concept of FOP was introduced for the first time and the underpinning physical, oral physiological, and sensory psychological principles of eating and sensory perception were discussed in detail. Thanks to that review, FOP is now widely accepted as an emerging research area in the food science discipline, and the importance of applying an integrated approach to the research of food sensory and consumer preference is widely recognized.

Figure 1 provides highlights of oral dynamics and various interfaces and interplays for eating and sensory perception. Food and food particles, saliva, aroma and taste compounds, receptors, the tongue, oral muscles, and many other aspects all play a role in FOP. The physics, physiology, and psychology of food oral destruction and reconstruction (i.e., bolus formation), oral lubrication, food–saliva interactions, release and diffusion of flavor compounds, stimulation and perception, and function of the human tongue and teeth are the dominating mechanisms acting either alone or, more often, in combinations. It is not easy to comprehend all the achievements and progress of FOP research made in the past decade, but the following claims can be made based on our current understanding:

- Eating experience and sensory appreciation combine all perceivable sensory attributes, specifically texture, aroma, and taste. Sensory attributes are intercorrelated and exhibit a dynamic nature that is closely influenced by the oral breakdown of food structure (Çakır et al. 2012, Foegeding et al. 2017).
- The rheology–tribology (the study of the friction, lubrication, and wear between interacting surfaces that are in relative motion) transition reflects the changing of the dominating physical principles during oral processing. This transition is now widely accepted as an underpinning mechanism of food texture perception, or the so-called mouthfeel (Chen & Stokes 2012, Sarkar et al. 2021, Stokes et al. 2013).

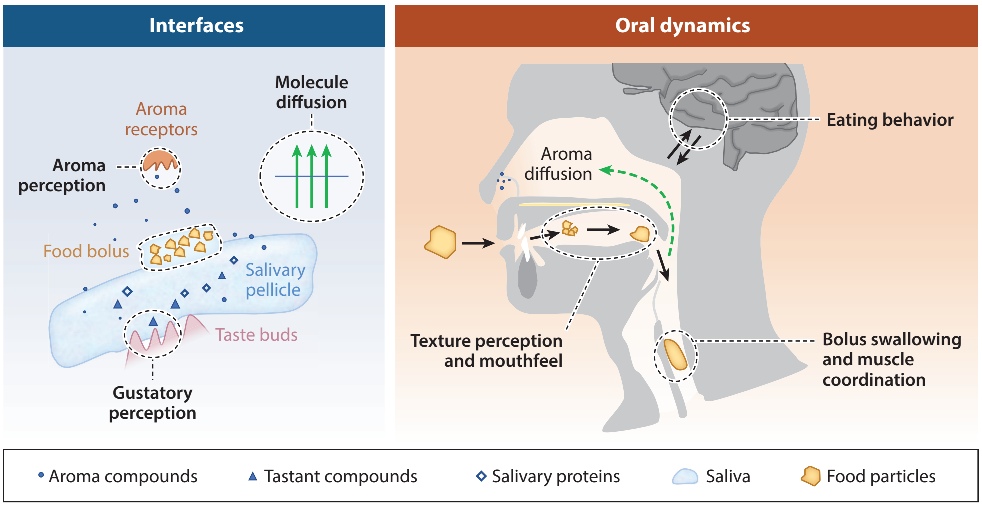

Figure 1

Active research areas of food oral processing. On the left side, all possible interfaces are highlighted involving food and taste and aroma compounds, as are the saliva, tongue, and receptors. On the right side, the dynamic aspects of eating and sensory perception are highlighted.

- As an indispensable ingredient, saliva plays a hugely important role in FOP and sensory perception. People once believed that what we perceive during oral processing comes from the stimuli of food, but our perception actually comes from the stimuli of the bolus, a mixture of food and saliva, which is completely different from the ingested food because of complicated interactions between food components and saliva (Mosca & Chen 2017).
- Although instrumental measurements are always desirable for texture and flavor assessment, it is important to acknowledge that instruments can measure only material properties, not the real sensory properties. Material properties are different in nature from sensory, i.e., perceived by humans, properties (Chen 2020, Nishinari et al. 2019a).
- The controlling of bolus movement and the initiation of swallowing are still too complicated to comprehend. However, it is generally accepted that good flowability and appropriate cohesiveness are critical in triggering swallowing and regulating bolus flow from the oral cavity to the pharynx and then to the esophagus (Hadde & Chen 2021).

This review aims to further depict fundamental principles of eating and sensory perception from the current perspectives of FOP research, focusing on a few topics of immediate concern to food scientists, consumers, and manufacturers: texture perception, flavor (aroma and taste) perception, bolus swallowing, and eating behavior. Research progress discussion is largely on that made in the past decade. We hope that the discussions and retrospectives presented here provide young researchers useful guidance in establishing research in this area and may also provide useful information to industry in the design of quality food. We also hope that this review not only helps readers comprehend what has been achieved in this area in the past decade but, more importantly, identify the knowledge gaps and future direction of FOP research. Readers are reminded that, despite strong industrial interest in the eating behavior of animals (in particular pets) and animal food, only human oral processing is covered in this review. Oral processing of animals and texture modification for animal food are of growing interest and could be a topic for another comprehensive review.

2. TEXTURE PERCEPTION

2.1. Introduction

Food texture (or sometimes mouthfeel) is a sensory reflection of the structural, mechanical, and surface properties of the food. However, texture perception is, in principle, influenced by two main factors: the properties of the food and the individual's oral physiology. Any small variation in both can lead to delicate differences in texture perception. Consumers' texture concerns could be very different for food in different physical statuses, specifically solid, soft-solid (or semisolid), and liquid food (e.g., drinks and beverages), because of their very different oral behavior and very different governing physical principles.

Figure 2 provides a highlight of the interplay between food physics and oral physiology in texture perception during oral processing. Sensory texture is obtained when a food is masticated, destructured, mixed, and interacted with saliva, all simultaneously inside the oral cavity. Although some example texture terms are listed in the figure, consumer sensory terms are much more comprehensive. Instrumental approaches, specifically fracture test, rheology, and tribology analysis, are widely applied in research laboratories. Proper understanding of the cross-disciplinary interplay between food physics and oral physiology and the correlation between instrumental measurement and sensory perception have always been the top priorities of food texture research.

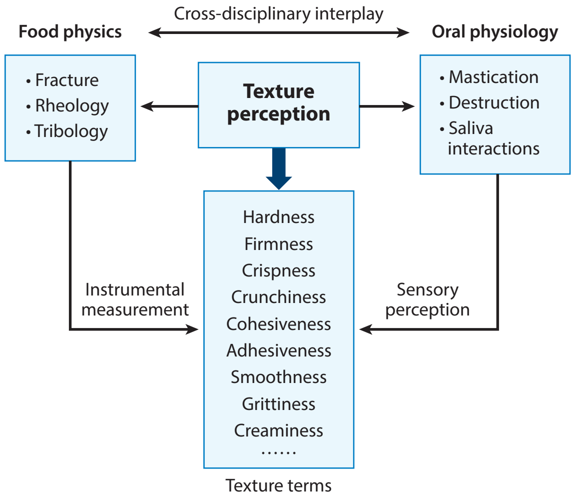

Figure 2

Food texture perception during oral processing. The cross-disciplinary interplay between food physics and oral physiology and the correlation between instrumental measurement and sensory perception are fundamentally important in influencing food texture perception during oral processing.

2.2. Mastication and Chewing Behavior

Mastication is a process of primary digestion, when food is reduced to smaller particle sizes and mixed with saliva. Food particles (of various sizes) are manipulated by the tongue and are compressed and sheared between molar teeth for continuous size reduction. The process is controlled and regulated by two factors: the selection function (referring to the chance of a food particle being selected for size reduction) and the breakage function (referring to the extent of size reduction of a food particle after being chewed once). The two functions represent very well the dynamic process of mastication and have been discussed in detail in a previous review (Chen 2009). Also, in relation to mastication and chewing behavior, several parameters, including chewing efficiency, chewing capability, and chewing performance, have been used in the literature to describe and differentiate the oral behavior of human individuals. Definitions and assessments of these terms were once widely varied, but a consensus has been recently reached (Gonçalves et al. 2021).

Although mastication mainly serves the purpose of digestion, its implications for texture (and probably flavor) sensation are often the main focus of research. How a food particle is selected for chewing by an individual could be the main reason for population variation in texture perception and has become an interesting question in recent years (Liu et al. 2018, 2020; van der Glas et al. 2020). Although the number of paired teeth and the chewing force are considered the main factors determining chewing efficiency, it was recently confirmed that appropriate locking (or fixing) of food particles is also hugely important and for which the tongue plays a key role (Zhang et al. 2019).

For oral behavior assessment, model food gels made of proteins and polysaccharides have been used because of their easy manipulation with respect to size, structure, texture, calorie level, and even flavor, and precise investigations could be conducted to study the dynamic correlation between chewing behavior and texture and, particularly, the reduction of particle sizes. TDS (temporal dominance of sensations) and TCATA (temporal-check-all-that-apply) are feasible sensory tools to link dynamic texture perception with food structure change (Fiszman & Tarrega 2018, Sharma & Duizer 2019). However, because of the effect of attention diversion, these methods often involve a slight compromise on the ongoing chewing behavior. Therefore, how perception can be evaluated in time without compromising/interrupting natural chewing behavior is worth further investigation (Koç et al. 2019, Kohyama et al. 2017).

Close correlations between food texture and oral physiology have been well documented. For solid and soft-solid foods, their texture perception is better reflected by the adaptation of chewing behavior than mechanical properties alone because of the particularly complicated oral physiology that an instrumental test cannot mimic (Koç et al. 2014). In situ or in vivo studies prefer noninvasive techniques, and electromyography (EMG), jaw tracking (JT), and video recording are often applied to monitor orofacial muscle activity (Vinyard & Fiszman 2016). Masseter and anterior temporalis muscles, which are responsible for jaw closing and power stroke, are highly correlated with firmness perception (Çakır et al. 2012, Koç et al. 2014, Kohyama et al. 2017), and EMG variables have been reported in close association with the true fracture stress of food products (Kohyama et al. 2017). Temperature is a very important influencing factor for food texture, and, therefore, how food changes its temperature during oral processing is a hugely interesting problem to investigate, in particular for thermal-sensitive foods such as ice cream, chocolate, hot soup, and butter spread. A recent work demonstrated the feasibility of using thermal imaging techniques for in situ oral temperature measurement (Lv et al. 2019). The dynamic trend during FOP can be monitored in situ in a semicontinuous manner; an example is the wide application of model foods in which repeated chew-and-spit procedures are included to acquire a full picture of the entire FOP process (Foegeding et al. 2017; Ishihara et al. 2013, 2014; Kohyama 2015; Kohyama et al. 2016, 2017).

Evidence now shows that oral physiology plays an equally important role in influencing eating behavior (Boehm et al. 2020, Foegeding et al. 2017) and therefore oral physiological properties must be taken into consideration in the design of food, especially food for special consumers (e.g., infant babies, school children, elderly people, patients, athletes, etc.). For more on eating behavior, the book *Gulp* by Mary Roach (2014) explains the complicated science of eating in simple language and a humorous manner.

2.3. Fracture and Rheology

The physical base of chewing and size reduction in the mouth is the deformation and flow of food material. It has been long accepted that how a food is deformed and/or fractured under an external force/stress determines its texture perception. Therefore, fracture and rheology studies were adopted almost as soon as food texture became a subdiscipline of food science in the first half of the past century (Matz 1962). For a solid food (either dry or wet), the fracture mechanism is the core factor of texture sensation, in particular the sensation of hardness, crispness, crunchiness, etc. For a soft-solid food (such as gels), how it deforms and breaks determines its texture sensation, in particular the sensation of firmness, cohesiveness, stickiness, etc. Fracture tests and rheological analyses remained the main research tools for food texture study until late in the twentieth century, but research interest in food rheology has shrunk in the past two decades. There are two possible reasons for this: The availability of commercial texture analyzers, which are easier and cheaper to operate, attracts many researchers' attention away from the rheometer, and the theoretical complexity of rheology is often beyond the comprehension of food researchers, even more so when combined rheological parameters are used for texture interpretation. For more information regarding the progress in fracture and rheology of foods, *Rheology and Fracture Mechanics of Foods* by Ton van Vliet (2013) is a great reference that discusses the theories and fundamentals of deformation, experimental techniques, and applications to various food systems in depth.

The introduction of the texture analyzer was a big event in the history of texture research. One great advantage of a texture analyzer is that, through a combination of force and distance (and sometimes time) and a wide range of available measurement geometries and probes, it can assess texture properties of a food in a rather simple manner. However, the seemingly quantitative analysis of a texture analyzer could be misleading if data are not treated with care. Results obtained from a texture analyzer are mostly not comparable and are highly case-dependent. The most obvious example is the so-called texture profile analysis, a double compression test first proposed by Friedman et al. (1963) and then further solidified by Bourne (2002). Although the thinking behind the method is logical, the application and feasibility of the method have been stretched far beyond its suitability. Serious cautions must be taken when implementing this method for oral texture interpretation (Nishinari et al. 2019b, Peleg 2019).

2.4. Oral Tribology

Oral tribology is an emerging area and especially refers to the friction and lubrication inside the oral cavity, between the surfaces of food, tongue, teeth, and hard palate (Sarkar & Krop 2019, Sarkar et al. 2021). The approach has attracted growing attention in the past few years in the hope that it can throw new light on the scientific insights of oral texture sensation. Unlike rheology, which concerns a material's bulk properties, tribology concerns properties of the system, with two interacting surfaces in relative motion and a fluid layer between the two surfaces closely mimicking the oral cavity, where the tongue moves against the hard palate with a thin layer of saliva between. Theoretically, shear and normal forces at the tongue surface are produced by tongue movements and pressing, picked up by the tactile receptors on the tongue surface, and finally translated into thin film–related textural information such as creaminess, smoothness, slipperiness, and greasiness. Hence, the in vitro oral tribology measurements are promising for (at least partially) quantifying these perceptions. Using food emulsions as model systems, several studies demonstrated that the friction coefficient was strongly correlated with creaminess perception, which was also strongly correlated with oil droplet clustering (Fuhrmann et al. 2019), emulsion coalescence (Dresselhuis et al. 2008), and emulsion structure creation (Oppermann et al. 2016, 2017). Despite these promising findings, we are not yet at a stage where creaminess can be assessed simply by a friction coefficient measurement (Upadhyay et al. 2020). Similarly, although a high correlation ($R^2 = 0.93$) was found between the astringency of red wine and the friction coefficient at a sliding speed of 0.075 mm/s (Brossard et al. 2016), its physical mechanism is still under debate. Vague definitions of thin film–related texture attributes, undefined substrates, and the varied settings of tribometers, and the complexity of saliva and tongue topography are the major obstacles in applying in vitro tribology data to understanding texture perception and mouthfeel.

Although tribological study can typically be easily conducted in vitro with commercial devices, the setting of such assessments is mostly in contrast with oral conditions and applications are limited (Krop et al. 2019, 2020; Nishinari et al. 2019a). Recently, a texture analyzer with a novel attachment (a tribometer) was successfully developed in the authors' lab, offering a reliable and affordable alternative in tribology study (Chen et al. 2014, Mo et al. 2019, Wang et al. 2020). This technique has been applied successfully in assessments of wine astringency (Brossard et al. 2016), smoothness in toothpaste (Cai et al. 2017), creaminess and smoothness in protein-added yogurt (Morell et al. 2017), the stick-slip phenomenon (Sanahuja et al. 2017), and smoothness in oil-in-water (o/w) emulsions (Upadhyay & Chen 2019). This tribometer was further improved

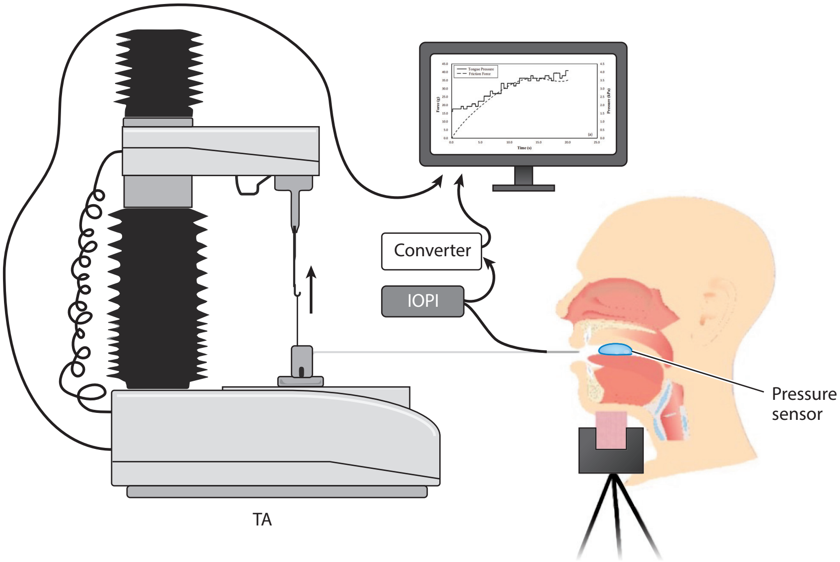

Figure 3

An illustration of an experimental setup for in situ oral lubrication measurement. An IOPI (Iowa oral performance instrument) pressure sensor is synchronized with a texture analyzer (TA). The pressure sensor (shown as blue inside the oral cavity) is used as a probe for the normal load detector and is under the control of the TA for sliding movement. The friction force sensed by the load cell can be recorded live as a function of time or distance. Figure adapted with permission from Mo et al. (2019); copyright 2019 Elsevier.

by replacing substrates with PDMS (polydimethylsiloxan) to become a soft oral tribometer (Q. Wang et al. 2020, 2021). Moreover, the synchronization of the device with an IOPI (Iowa oral performance instrument), a commercial intraoral pressure measurement setup, has enabled the first in situ oral tribological measurements (**Figure 3**) (Mo et al. 2019, X. Wang et al. 2022).

Interactions between food and saliva have attracted much attention in recent years because of their roles in changing the structural status and physicochemical properties of food during oral processing. The importance of saliva in eating and sensory perception can be seen in saliva's functional roles: wetting and lubricating oral surfaces, wetting and aggregating food particles to form a bolus suitable for swallowing, interacting with food and food components, and altering structural and textural properties of the food (Mosca et al. 2019a). Food–saliva interactions occur in various forms and mechanisms, including surface coating, particle clustering, colloidal interactions, complexation, and enzymatic interactions (Mosca & Chen 2017), which are all reported to alter oral rheology and tribology (Chong et al. 2019, Morell et al. 2017, Wang et al. 2020). For example, a higher emulsion viscosity with lower friction usually leads to a stronger creaminess perception. However, such a correlation becomes less clear once saliva is presented (X. Wang et al. 2022) and a different sensation (e.g., graininess and fattiness) might be perceived (Fuhrmann et al. 2019). Under existing experimental settings, it is not easy to make a general rule about saliva and oral tribology because of large inter- and intra-individual differences in saliva secretion and composition. Experimental settings and the current understanding of the role of saliva in oral tribology were discussed in a recent review by Laguna et al. (2021).

Most interestingly, it was recently found that saliva could behave as an emulsifier, and oral emulsification is an immediate consequence of oral processing of oil/fat (Glumac et al. 2019a,b). This finding demonstrated that oil/fat is immediately dispersed once mixed with saliva and is not in bulk status inside the oral cavity. The finding challenges the lipase degradation theory of oil/fat sensation (Mattes 2009) and the theory of oral lubrication for oral sensation of oil/fat (Rolls et al. 2003). The sensation mechanism of oil/fat remains a mystery and requires further investigation. However, oral emulsification has a profound implication for the oral behavior of oil/fat as well as its sensation. Early results from the authors' lab indicated that individuals have very different capabilities of oral emulsification, and capability of oral emulsification could be a decisive factor for the transition from creaminess sensation to greasiness sensation (results to be published).

2.5. Research Directions and Implications in Food Design

Establishing a correlation between food composition/structure and texture properties is a must to understand consumer texture perception. During FOP, oral physiological properties (tongue topography, density and sensibility of oral tactile sensors, dental conditions, oral/orofacial muscles) (Andablo-Reyes et al. 2020; X. Wang et al. 2019, 2022), in addition to saliva composition and properties (Mosca et al. 2019a), play irreplaceable roles in food breakdown, bolus formation, and in-mouth perception. Whether to use human saliva or artificial saliva for food–saliva interaction studies and in vitro eating and sensory studies is still under debate. The low stability and property variation of collected human saliva are clearly disadvantageous. However, although several artificial salivas have been reported in the literature (Cai et al. 2017, Krop et al. 2019, Laguna et al. 2017, Upadhyay & Chen 2019, Wang et al. 2020), no consensus has been reached by the scientific community on the formulation of artificial saliva and conditions for its applications. In vitro tribology studies to investigate texture perception are heavily dependent on the tested fitting's/accessory's resemblance to human oral cavity tissues and organs; substrates should share comparable hardness and viscoelasticity, roughness, mucosal-film coating, and hydrophobicity with oral surfaces. In vivo studies on tactile sensitivity, particularly under different experimental settings (such as thermal shock and trigeminal stimulation), are also worth further investigation to better understand the delicate differences in texture perception among different individuals (Shupe et al. 2018, 2019).

Optimizing sensory appreciation and oral experience through food design has always been a challenge for the food industry. From an FOP perspective, texture design must carefully consider the oral physiological properties of target consumers. Consumer groups of different ages (e.g., infants/toddlers, children, adults, elderly), genders, health conditions, regions, and cultures differ in oral physiological features and FOP capability as well as dietary preferences (Ketel et al. 2021, Zhang et al. 2020). This variation in oral physiology could be built into in vitro oral simulators to gain insights into food structure breakdown (Panda et al. 2020, Peyron et al. 2019) and, with the assistance of computational simulation and mathematical modeling, the temporal and spatial movement/transport of food particles and bolus in the oral cavity. Designing desirable food structure and texture, such as microstructure alteration and emulsion/gel formation, could also facilitate flavor perception (Hu et al. 2019, 2021; Kupirovič et al. 2017; van Eck et al. 2019), nutrient delivery (Fuhrmann et al. 2019; Mao & McClements 2012, 2013; Oppermann et al. 2015, 2016, 2017), and weight management (discussed further in the following sections).

3. FLAVOR PERCEPTION

3.1. Introduction

Flavor is a collective term of sensory attributes originating from taste and aroma compounds and perceived by specific receptors. Flavor consists of two very different categories of sensory features: aroma and taste. The former is associated with volatile compounds and perceived by the olfactory epithelium on the roof of the nasal cavity, whereas the latter is associated with nonvolatile tastant components and perceived by taste receptors on the tongue surface.

The sensation of flavor is chemistry dominant and highly dynamic. During oral processing, the release of aroma and taste compounds barely reaches equilibrium in terms of its release and distribution between the three phases (the food material, the saliva, and the air inside the oral cavity), making it very difficult to use in vitro instrumental analysis of aroma and taste components for smell and taste prediction. To some extent, the sensation and perception of aroma and taste are more complicated than those of texture because of the high mobility and sensitivity of the taste and aroma compounds whose release and diffusion are easily influenced by many factors. Any factor that could alter the release and distribution of flavor compounds exerts influence on their final perception (Wagoner et al. 2019). The perception of aroma and taste never occurs as a single sensory attribute but mostly in a complicated combination. On the one hand, saliva components chemically and enzymatically interact with tastants and aroma molecules (Lamy et al. 2021), and, on the other hand, the physical and physiological properties of saliva affect the transport dynamics because of differences in, e.g., viscosities (Aubert et al. 2016) and flow rates (Yang et al. 2021). As indicated by a recent study, the topographic features of the oral surface could also affect flavor perception (X. Wang et al. 2022).

For flavor aspects of FOP, the release of target flavor components and the physiological functioning of (olfactory and gustatory) receptors are core concerns. For the former, distribution, diffusion, and interactions with saliva components are the main factors for consideration; for the latter, the physiology and sensing mechanisms of sensory receptors are of particular interest to sensory scientists. Although sensory physiology seems to be beyond the traditional food science discipline, exploratory research has already begun in this area by food scientists.

The application of chewing simulators/artificial mouths to reproduce the compression and shear forces of human jaws provides direct correlations between chewing behavior and flavor release (Panda et al. 2020, Tarrega et al. 2019), but in vivo studies are becoming a trend in flavor research, integrating food physics and oral physiology at various interfaces, as highlighted in **Figure 1**. Consumption of food matrices, such as an ice cube (Yang et al. 2020, 2021), complex coacervate (Li et al. 2020), layered gel (Mosca et al. 2010, 2015), or gel-in-gel system (Funami et al. 2016), coupled with real-time aroma detection equipment (e.g., atmospheric pressure chemical ionization–mass spectroscopy, proton transfer reaction–mass spectrometry, and selected ion flow tube–mass spectrometry) and the subject's dynamic sensory evaluation often works well to reveal the dynamic nature of food flavor release and its perception (Feron et al. 2014; Guichard et al. 2017; Ruijschop et al. 2009; Tarrega et al. 2019; Yang et al. 2020, 2021). Compared to solid and semisolid foods, fluid foods are less studied, probably because of the misperception that a short oral residence time in the oral cavity makes aroma and taste release less relevant (Markey et al. 2015). We speculate that aroma and taste could play a more important role in influencing consumers' preference and liking of a fluid food, simply because of a relatively simple texture variation among fluid products.

3.2. Aroma Release and Perception

The chemical properties of aroma compounds, along with the physicochemical and structural properties of the food matrix, are considered as the two main factors affecting aroma release (Ployon et al. 2017), but the interplay between food and oral physiology greatly affects how aroma compounds are released and then perceived during oral processing. In vivo measurements revealed that higher fragmentation of foods, which typically comes along with higher mastication performance and/or muscle activities of the subject, were positively correlated with aroma release

(Okawa et al. 2021; Repoux et al. 2012; Tarrega et al. 2008, 2011). Studies based on the chewing simulators also showed a greater release of less hydrophobic aroma compounds from food breakdown (Tarrega et al. 2019). Other physiological properties, such as oral volume, tongue pressure, and number of teeth, exert little effect on aroma release and perception; however, saliva flow rate (or the rate of saliva secretion) has a major effect. A possible dilution and retention effect due to high salivary flow influences aroma release, as has been repeatedly demonstrated in in vitro studies using a lipoprotein matrix (Tarrega et al. 2019) and in vivo studies using aroma-contained ice cubes (Yang et al. 2020), gummy jellies (Okawa et al. 2021), and model cheeses (Feron et al. 2014).

There is also a chemical and enzymatic role that saliva plays in aroma release and perception. Saliva is capable of either binding to or reacting with aroma compounds, in addition to assisting enzymatic degradation of the food matrix (Ployon et al. 2017). By simply mixing saliva with test samples in vitro, saliva is able to retain the aroma compounds in coffee (Genovese et al. 2014) and wine/alcohol (Muñoz-González et al. 2014, 2018); wine intake in turn leads to alterations in the subject's salivary biochemical property and then aroma perception (such as esterase activity). The release rate and amount of aroma are dependent on the partition between air and saliva in the oral cavity and greatly affected by the composition of saliva, such as the presence of α-amylase and mucins (Pagès-Hélary et al. 2014).

Aroma compounds can reach the olfactory epithelium through two pathways: via the nose, during sniffing (referred to as ortho-nasal olfaction), and via the mouth, during food consumption (referred to as retro-nasal olfaction). Retro-nasal olfaction has been generally seen as the main mechanism for olfactory sensation during oral processing. It has been suggested that aroma compounds released inside the oral cavity during food manipulation are diffused and transported into the nasal cavity through breaths (Bojanowski & Hummel 2013). Although the hypothesis is feasible and has been confirmed by much experimental evidence (Özay et al. 2019), the kinetics of molecular movement from oral to nasal cavity, which is relevant to olfactory sensation, remains to be explored.

3.3. Gustatory Perception

Compared to nearly hundreds or even thousands of aroma compounds identified for olfactory perception, gustatory perception is simpler to a certain extent, with only five basic tastes being identified so far. Understanding the underpinning mechanisms and improving structural design for enhanced taste perception have been the main research focuses in recent years (Luo et al. 2019, 2020; Mosca et al. 2012, 2015). The recognition of the taste of saliva as a taste reference, or a baseline of taste perception, is a major achievement in FOP study. Tastants in normal saliva constantly stimulate taste receptors in the oral environment and humans perceive it as tasteless due to the phenomena of self-adaptation (Feron 2019). Therefore, taste perception occurs only when concentrations of tastants become different in the vicinity of taste receptors. This perception baseline, the salivary tastant concentration, might partially explain perception variations in different subjects to the same food. Recent findings (Ma et al. 2021, Zhang et al. 2020) from the authors' group also showed significant differences in saliva (physical and biochemical) properties among populations of different ethnic groups and their possible associations with dietary preferences.

With much emphasis on sugar and salt reduction, extensive efforts have been made to manipulate tastant delivery processes and rates. It has been found that, by altering mechanical strength and structure complexity, a food that creates a larger total surface area during oral processing renders a higher amount of available tastants and enhances taste perception (Mosca et al. 2012, 2015). It has also been shown that the uneven/inhomogeneous spatial distribution of tastants in model foods leads to a pulsed delivery pattern (Busch et al. 2009; Konitzer et al. 2013; Mosca et al. 2013, 2010; Noort et al. 2010), increasing taste perception. A recent study using complex coacervates fabricated from oppositely charged polyelectrolytes of soy protein and gum arabic showed a promising 30% reduction in salt content without impacting the salty taste perception and textural properties (Li et al. 2020). A 3D-printed cube-in-cube chocolate confectionery, which delivers contained sucrose at different concentrations at varying time-points, also showed an increase in sweetness perception of more than 30% (Kistler et al. 2021). Attempts to reduce sugar and salt by manipulating binary taste perception using other basic tastes such as sour (Veldhuizen et al. 2017) and umami (Onuma et al. 2018, Y. Wang et al. 2021) have also been made.

3.4. Research Directions and Implications in Food Design

Aroma and taste perception are intertwined with all other sensory attributes, including texture. The duality of smell, i.e., the ortho-nasal and retro-nasal pathways, incorporates what is happening in both the nasal and oral cavities. It is interesting that aroma released inside the oral cavity during oral processing is detected only inside the nasal cavity. This makes the retro-nasal mechanism fascinating to study. For a better understanding, two fundamental questions should be asked: (*a*) What is the transportation mechanism of aroma molecules from the oral cavity to the nasal cavity, molecular diffusion or via the breath, and (*b*) is the retronasal perception release limited (controlled by how fast aroma compounds release from the food matrix) or diffusion limited (controlled by the speed of oral-nasal transportation of aroma compounds)? In release-limited perception, the concentrations inside the nasal cavity and oral cavity are very close, i.e., $C_{a,o} \approx C_{a,n}$; in diffusion-limited perception, the oral concentration is much higher than nasal concentration, i.e., $C_{a,o} > C_{a,n}$. **Figure 4** provides an illustration of the release of aroma molecules inside the oral cavity and their diffusion to the nasal cavity, where they were perceived by the olfactory receptors. Breath

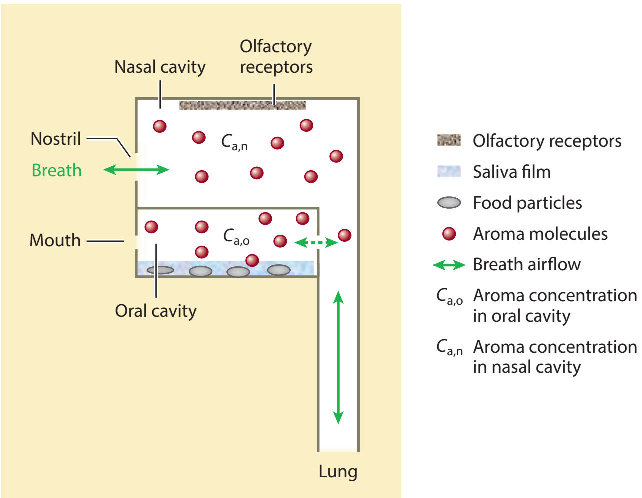

Figure 4

Retro-nasal perception during oral processing. Aroma compounds are released into the air (via saliva) during oral processing. These small molecules are highly mobile and brought to the nasal cavity by the airflow as a result of breath. Olfactory perception is then received by the receptors on the roof of the nasal cavity.

appears to be a driving force for retronasal sensation. However, it is puzzling that retronasal aroma sensation never shows any sign of on-and-off, as would be expected given that air is breathed in and out in a rhythmic pattern. Does this suggest that nasal receptors have delayed effect in detecting aroma molecules? Or does the strong surface adsorption of aroma molecules make the on/off of airflow less relevant? These questions are important to understanding the controlling mechanisms of retronasal sensation. However, to answer these questions, we have to wait for more experimental evidence.

Similar research questions could also be asked about taste perception. Is tastant release a bulk-dominated or a pellicle-dominated process? How do the interfaces shown in **Figure 1** function in tastant diffusion? Furthermore, what are the mechanisms of other senses affecting taste perception? Studies have shown a significant microbiota difference in bulk saliva and saliva pellicle (Feng et al. 2018), which correlates to variations in taste sensitivity and responsiveness. An increase in mucosa protein could be observed after drinking protein-enriched milk products; this might also alter interactions with tastants and affect their release. We now know that aroma can stimulate saliva secretion and alter salivary biochemical compositions, and, therefore, manipulate taste perception. Possible effects of other senses on taste perception, such as sight, sound, and touch [both trigeminal (Houghton et al. 2020, Yang et al. 2021) and tactile (Carpenter et al. 2019, Taladrid et al. 2019)] have also been reported. Whether oil/fat perception is taste-based or texture-based has been controversial for a long time. The oral mechanism of oil/fat sensation is important to scientific understanding but more so to the food industry in seeking alternatives of oil/fat for healthy food design. For these reasons, further investigation into its physical, physiological, biochemical, and neurological origins and its correlation with aroma and taste perceptions during oral processing is urgently needed.

Flavor modulation, as in the enhancement of desirable aromas and tastes and the masking of undesirable ones, is key to the design of healthy and tasty food. Food structure manipulation at various length scales (manufacturing and oral stage breakdown/degradation) is undoubtedly a universal choice, but an understanding of interactions between interested food (and components) and saliva provides useful insights into the release of target aroma/tastant compounds and potentially their perception by target consumers who vary in saliva physical and biochemical characteristics and sensory sensitives. This calls for a reliable database(s) of consumer profiles, developed from a wide-ranging population survey and, perhaps, mathematical computation. An understanding of saliva–aroma/tastant interactions could also be preliminarily achieved by cellular/molecular approaches, and the search for aroma/tastant analogs with health benefits and affordable costs could be conducted via computational simulations and chemical synthesis. However, both of which are beyond the scope of this review.

4. SWALLOWING

4.1. Introduction

Swallowing is simply a transport process that transfers the food bolus from the oral cavity to the stomach. The whole process has to be well controlled by all relevant muscles operating in a highly coordinated manner (Chen 2012). A swallowing process can be briefly described in a few sequential steps: the oral phase, when food is masticated and mixed with saliva to become an appropriate bolus; the oropharyngeal phase, when the bolus is transported to the pharynx by the tongue extruding pressure; and the esophageal phase, when the bolus is squeezed into the esophagus by oropharyngeal pressure. During this process, the entrance of the esophagus is enlarged by the relaxation of the cricopharyngeal muscles, which accompanies the larynx's elevation to close the airway with the help of the epiglottis. At the same time, the soft palate is elevated to seal off the nasal cavity.

Safety is the top priority for swallow control. It is generally agreed that certain conditions must be reached before swallow initiation; however, the criteria are still unclear, although there is a strong belief that bolus rheology is the key control (Gallegos et al. 2021). However, one thing is certain: an inappropriate swallow, or swallowing a poorly prepared bolus, can lead to the risk of food particles entering the trachea and lung and causing coughing or even choking. This may be very unusual among normal healthy adults but is a common risk to some special population groups, such as the elderly, dysphagia patients, infants/toddlers, and children. A proper match of bolus properties with an individual's swallowing capability is believed to be key to safe swallowing (Hadde & Chen 2021).

Different approaches have been applied in investigating bolus swallowing for two main purposes: to identify critical bolus properties of safe swallowing (the material aspect) and to establish the individual physiology of safe swallowing (the physiological aspect) (Cichero 2020). The former reveals the critical rheological and flow properties of a food bolus and influencing factors such as particle size and shape, saliva incorporation, etc. The latter clarifies the oral physiological function of individuals in bolus manipulation and transportation.

To study the material influences of bolus flow, a ready-made bolus in the form of thickened fluid is commonly used for swallow analysis. In this way, direct correlations can be acquired between bolus properties and safe swallowing (Hadde et al. 2019, Nishinari et al. 2019b). Swallowing behavior is usually assessed by medical diagnosis methodologies like videofluoroscopy, ultrasound (Doppler), and nasoendoscopy (Steele 2015). Videofluoroscopy has been considered the gold standard for examining swallowing difficulties. However, because of the complex structure of the pharynx, videofluoroscopy cannot differentiate the rheological properties of bolus flow. Ultrasound as a noninvasive technique can measure flow speed and bolus distribution in the pharynx (Gao & Kohyama 2014) but with a relatively low precision because of the limited quality of the images it produces.

No single instrument is so far capable of collecting high-resolution spatial and temporal information about swallowing (Steele 2015). Computer simulation, which is based on data derived from medical images, seems to provide a promising alternative (Kamiya et al. 2019; Kikuchi et al. 2015, 2017; Michiwaki et al. 2019, 2020a,b). Both the organs and bolus flows can be modeled, and the flow behavior of the bolus is analyzed using fluid simulation and modeling. Computer modeling can be used to calculate bolus trajectory and predict the risk of aspiration. Currently, it is still time-consuming to build a reliable model and the computation fluid dynamics of bolus flow is confined by the power-law model (Michiwaki et al. 2020b), which clearly needs further improvement.

4.2. Bolus Formation and Swallowing Initiation

The Hutchings and Lillford breakdown path model (Lillford 2011, 2018) was proposed to describe the process of eating and bolus formation using a three-dimensional graph (structure, lubrication, and time) to qualitatively describe the degree of food breakdown. The model is still widely referred to in the literature because of its conceptual simplicity, but scant direct experimental evidence is available to prove its validity. Recently, a modified model using only two dimensions was proposed (Boehm et al. 2020): One dimension displays the structure parameter against time, and the other dimension displays the lubrication parameter against time. The structure and lubrication parameters in the modified model are defined with measurable parameters (see **Figure 5**): A dimensionless particle area (particle area/initial food area) is proposed to represent structure properties,

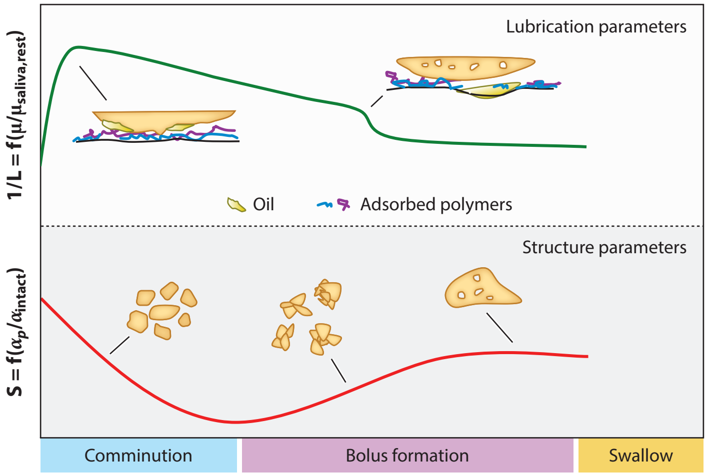

Figure 5

Hypothetical curve of lubrication and structure parameters of potato chips during oral processing. Measurable parameters μ, $\mu_{saliva,\ rest}$, α_p, and α_{intact} refer to the friction coefficient at any given time, the friction coefficient of saliva at rest, areas of food particles, and initial areas of intact food, respectively. The top graph shows oral lubrication and the lower graph shows structure change. Figure adapted with permission from Boehm et al. (2020); Copyright 2020 John Wiley and Sons.

and a dimensionless friction parameter (friction coefficient) is used to represent lubrication properties. Gray-Stuart et al. (2017) also proposed a very different conceptual model incorporating the decision-making process of swallowing initiation based on principles of chemical engineering. Again, the model is still in its early stages and waiting for experimental validation.

As described in these models, food turns into a swallowable bolus when it has reached a certain particle size, good lubrication status, and appropriate cohesiveness. However, as demonstrated by many studies, the initiation of swallowing is probably an integrative process combining the perception of bolus properties, eating environment, and personal preference. The dominant perception of the bolus at the end of mastication differs among foods: stickiness was reported to be the dominant perception at the swallowing point of a cereal bolus (Peyron et al. 2011), but for other products (cracker, boiled rice, hard and soft gelatin gel for instance), hardness becomes the most dominating perception (Wada et al. 2017). Not surprisingly, individual differences also play important roles in the initiation of swallowing, such as the oral manipulation capability and salivary flow during mastication of food (Maeda et al. 2020); this intrinsic variation in turn results in a wide variation of bolus properties.

4.3. Swallowing Safety

Bolus properties required for safe swallowing undoubtedly receive the most attention in swallowing research. Thickened fluid, as suggested by the International Dysphagia Diet Standardization Initiative (IDDSI) (Cichero et al. 2017), has been widely accepted as an ideal solution in addressing these issues (Hadde & Chen 2021), especially for consumers who are suffering from swallowing difficulties, i.e., dysphagia patients and elderly populations. Shear viscosity has long been seen as the most important controlling parameter for safe swallowing and has been used in some countries as a parameter for texture grading for dysphagia management (Steele et al. 2015). One very important recent progress is the recognition of the importance of cohesiveness for safe swallowing (preventing fracturing and splashing during swallow). How the cohesiveness is precisely assessed is still an issue for further investigation, but Hadde et al. (2019) showed that an appropriate extensional viscosity could be a useful indicator for thickened fluids in retaining bolus wholeness when it is elongated through the pharyngeal area. However, the threshold values for these properties are not yet certain.

Although the physiological study of bolus swallowing is still in its early research stages, great interest has been shown by food scientists in engaging in such investigations. For example, Funami et al. (2017) noticed that, compared with the parameters obtained from rheometers or texture analyzers, ease of swallowing had a better correlation with thyroid cartilage movement; Matsuyama et al. (2021) found a good correlation with laryngeal movement, suprahyoid musculature activity, and tongue pressure during swallowing. We believe that, because swallowing is individual dependent, future attention should be guided toward the matching of food texture with the individual's physiological capability of swallowing. For this reason, the concept of texture complexity was even proposed to reflect the ease of food manipulation inside the oral cavity (Larsen et al. 2016a,b; Tang et al. 2017). Food contains multiple phases; bones, thermal-sensitive materials, and high amounts of fibrous materials and fiber orientation all increase the complexity and difficulty of oral processing.

4.4. Research Directions and Implications in Food Design

Even though it is only recently that food scientists started studying bolus texture in relation to safe swallowing, the impacts have been huge, particularly to the food industry in the manufacturing and provision of food for special populations who have compromised eating and swallowing capabilities. Food for dysphagia management is seen as an area of huge potential for growth. An extensive range of food products, including thickening agents, are now available for dysphagia patients and elderly to assist safe swallowing, following the publication of the IDDSI framework, an international standard of the terms and classifications of food for dysphagia management (Brewsaugh et al. 2021, Cichero et al. 2017).

In developing quality food for swallowing assistance, two major knowledge gaps need to be filled. First is the match between an individual's swallowing capability and the texture of ingested food and its bolus. Although reliable assessments of swallowing difficulty are available in clinical practice and standard classifications of food texture are available, the link between the two seems to be lacking. Another knowledge gap is the reliable assessment of food texture designed for dysphagia management (Hadde & Chen 2021). The IDDSI framework provides a syringe flow test for texture grading of fluid foods. Even though the method is practically feasible for frontline users, it is not the most suitable for food manufacturer quality control because of its subjective manner. Objective assessment methods are in demand by the industry. A ball back extrusion technique, where compression stress is used as a valid parameter for assessment of all fluid food specified by the IDDSI framework, seems to be a possible solution to this problem (Chen et al. 2021).

5. EATING BEHAVIOR

5.1. Introduction

Eating behavior is another active FOP area that aims to reveal consumer behavior and attitude toward food consumption and the impacts of such behavior on health and well-being. Past eating experiences, expectations, food properties, sensory perception, and individual physiology and psychology all influence one's eating behavior. Digestion metabolism (e.g., satiety and satiation) and health impacts are currently the main concerns of eating behavior studies. Emerging evidence shows that the way a food is eaten (e.g., bite size, chews per bite, and eating rate) impacts how much is consumed and the corresponding satisfaction one may perceive during and after consumption (Bolhuis & Forde 2020). A good understanding of eating behavior and influencing factors will assist consumers in developing a healthy eating style via either consciously or unconsciously manipulating oral processing parameters.

Test foods (model or real foods) in various satiation and satiety studies do not share many similarities because of differences in research hypotheses and recruited participants. Experimental studies can either manipulate subjects' chewing behavior when consuming the same foods (e.g., a slower chewing rate or a smaller bite size) or modify food structure to unconsciously change subjects' chewing behavior (e.g., grind, puree, homogenize, add ingredient, or increase volume). In addition to approaches like EMG, JT, and video recording, smarter devices have also been developed to track eating behaviors with minimal interruption; examples include ear hooks integrated with microphones and photoplethysmography sensors (Papapanagiotou et al. 2017, van den Boer et al. 2018) and dining trays with built-in weighing stations (Lasschuijt et al. 2021).

Panelist rating is still the most frequently used method to obtain sensory evaluation on satiety and satiation. This subjective result is more than often correlated with physiological biomarkers (blood glucose, insulin, ghrelin, leptin, cholecystokinin, glucagon-like peptide-1, peptide YY, and gastric inhibitory peptide) and physiological measurements (diet-induced thermogenesis, gastric emptying) (Campbell et al. 2017). It should be made clear that intrinsic biological and physiological variations in panelists can complicate research outcomes, and comparable results across studies could be achieved only with standardized experimental procedures, particularly at the prior-hunger stage.

5.2. Oral Processing with Satiation and Satiety

Satiation is the process that results in meal termination and is modified by cognitive and sensory processes during oral processing. Satiety more often refers to the suppression of hunger between meals and is a consequence of post-ingestive and post-absorptive physiological processes. Although the mechanism of how oral processing parameters and food texture influence the ad libitum intake of foods is not fully understood, it is generally accepted that longer orosensory exposure (OSE), smaller bite size, higher chew numbers per bite, and lower eating rate induce early satiation and enhance the following satiety. Harder (Lasschuijt et al. 2017) and more viscous food led to lower ad libitum intake because of the longer OSE and smaller amount of food per bite (McCrickerd et al. 2017, Tarrega et al. 2016); this is also the case for lower ad libitum food intake with slow eaters (Goh et al. 2021, Lasschuijt et al. 2020, McCrickerd & Forde 2017, Mosca et al. 2019b). Currently, OSE is still a conceptual idea with no definite quantification method, and it cannot be used directly in evaluating the satiation effect of food. Lubricity of food might also affect fullness sensation and reduce calorie intake (Krop et al. 2019, Stribițcaia et al. 2021), but the conclusions are not definite. In addition to an alteration in the textural complexity of food (Larsen et al. 2016a,b), the digestion of food by saliva during oral processing might also have an effect on satiation and satiety as well as dietary-induced hormone levels in saliva.

Currently, studies are still limited and understanding about satiation and satiety is still in its preliminary stages. Many studies did not have experimental conditions properly controlled, making it difficult to make comparisons and draw meaningful conclusions. For example, a recent study (Planes-Muñoz et al. 2021) explored the satiety effects of hummus, ajoblanco, and gazpacho by measuring the ad libitum intakes in the participants' following meal, and showed that gazpacho had the highest satiating scores. However, the differences in composition (macro- and micronutrients) were not sufficient to explain gazpacho's high satiating effects, whereas the physical (viscosity) and physiological (chewing behaviors) properties of these foods were not mentioned at all. The complexity and dynamic nature of oral processing make it a huge challenge for experimental investigation, and developing novel methods and techniques to decouple multiple variables is a promising research direction.

5.3. Research Directions and Implications in Food Design

Designing food structures that increase hardness, thickness, or toughness for a longer OSE would hypothetically increase satiety or satiation (Mosca et al. 2019b), but with vulnerable populations, this might cause a reduction in food intake and lead to malnutrition (Ketel et al. 2020). It is therefore of great importance to balance the health and hedonic values of foods, and taking full advantage of flavor release and perception during oral processing might provide possible solutions that lead to a stronger willingness to shift to healthier oral processing behavior while maintaining sufficient nutrient intake. Plant-based food is receiving more attention in recent years because of advocacy by both environmentalists and food scientists. The nutritional benefits of plant-based food have been heavily emphasized, but its oral processing and possible satiation/satiety effects are largely unknown, providing a great opportunity for both academic and industrial researchers to discover new breakthroughs.

In addition to manipulating the structure and flavor profiles in food products, smart devices that could record eating behavior and provide real-time feedback might also be a possible way to regulate human dietary intakes. For example, a smart fork developed by Hermsen et al. (2016) can provide real-time feedback on eating behavior: If users take a bite too quickly, they feel a gentle vibration in the handle of the fork and see a red indicator light up. Health and well-being are probably the most important driving forces for eating behavior research. How to address the balance between the pleasure of eating and the amount of food intake is a meaningful question to consumers as well as researchers.

6. CHALLENGES AND OUTLOOKS

Since its establishment, FOP has emerged as a rapidly expanding research subject in the food science discipline. For food scientists, FOP provides very different thinking and approaches to understanding the fundamental principles of food sensory and eating experiences. For the food industry, new findings from FOP research provide strong theoretical and technological backup for the designing and manufacturing of quality tasty food. For governments and regulatory bodies, supports become available for policy making on food provision, in particular special food for consumers in particular need.

A unique feature of FOP research is its multidisciplinary nature, as it involves food physics, oral physiology, sensory psychology, material science, dentistry, neurology, and brain science, etc. The interplay between food physics and oral physiology provides a strong anchor for sensory psychology research. The FOP wheel shown in **Figure 6** attempts to provide an overall profile of FOP research from which one can see multilayer sciences and highly complicated interplays between different disciplines and subject areas at three different levels. Even though the five main areas—food material, oral physiology, food sensory, eating behavior, and brain responses (as well as their subareas)—are highlighted individually, one must recognize that interplays and/or interfaces between different subject areas are most likely. We tend to believe that the interplays could be exciting areas of possible new breakthroughs in FOP research, and new FOP frontiers are fully open to food scientists, in particular to those early in their careers.

Figure 6

A food oral processing (FOP) wheel showing research areas and subareas as well as research disciplines/approaches of FOP research. From the inside out: inner circle is major research areas, middle circle is the main concern, and outer circle is the specific researched subjects.

SUMMARY POINTS

1. As an emerging cross-disciplinary research area in the food science discipline, FOP offers new opportunities to reveal scientific insights into eating and sensory perception.
2. Food physics, material science, oral physiology, sensory psychology, and neurology are the main disciplines contributing to FOP research.
3. Eating and sensory perception have strong dynamic features, and food material seldom reaches its equilibrium status during oral processing.
4. Sensory perception does not come from the stimuli of the food but the stimuli of the mixture of food and saliva.

5. Saliva is an indispensable ingredient for eating and sensory perception and actively interacts with food (and food components).
6. Good control of bolus flow and swallowing is essential for eating safety. Appropriate cohesiveness of food bolus appears to be critical.
7. OSE could be an important factor in influencing satiation and satiety.

FUTURE ISSUES

1. The role of saliva has long been neglected by food scientists, in both sensory and nutrition studies. The physics and physiology of saliva remain to be explored. In particular, the control and manipulation of food–saliva interactions could provide new ways to optimize the eating experience. Moreover, the individuality (as well as ethnic variation) of saliva secretion and composition may provide useful clues about sensory variation among populations.
2. The oral thin film should be seen as another phase inside the oral cavity. The thin film provides not only the coverage of oral surfaces but also functional roles of separating and/or interconnecting food and oral surfaces, providing lubrication mechanisms, serving as a media for aroma and taste compounds, etc. How the functional properties of this thin film are affected by its composition, fluid dynamics, mechanical strength, colloidal behavior, permeability, etc. could be hugely important to sensory perception. A good understanding of these aspects will likely lead to new breakthroughs in FOP research.
3. Oral physiology could be a bit difficult to comprehend by food scientists but, with the availability of new experimental techniques, this should no longer be a barrier. Revealing the functions of the tongue, saliva, oral/orofacial muscles, and sensory receptors requires a great understanding of their physiology and operational principles as well as influencing factors.
4. Oral physics has been applied and dealt with in many aspects of FOP research over the past decades. In particular, food rheology and oral tribology have been the most extensively studied, which has led to significant progress. However, there is still much confusion and many unknowns about the underpinning physical principles of eating and sensory perception. Questions include, e.g., how structural changes at multiple length scales influence mouthfeel; what happens at the food–saliva interface; and how the mass transfer at particle and molecule levels is regulated inside the oral and nasal cavities.
5. Two main technical barriers remain for FOP research. One is the ethical restrictions on in vivo studies. The other is the limitation of feasible research techniques for oral access, either noninvasive or invasive. It is predictable that in vitro studies will remain the main approach in the future for FOP research. New in vitro experimental setups that can mimic oral conditions will be welcome, in particular for industrial research. Nevertheless, the development of new technologies or equipment for noninvasive oral access will be definitely needed for in situ FOP research.

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