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Oral processing, texture and mouthfeel: From rheology to tribology and beyond

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ABSTRACT

Texture and mouthfeel arising from the consumption of food and beverages are critical to consumer choice and acceptability. While the food structure design rules for many existing products have been well established, although not necessarily understood, the current drive to produce healthy consumer acceptable food and beverages is pushing products into a formulation space whereby these design rules no longer apply. Both subtle and large scale alterations to formulations can result in significant changes in texture and mouthfeel, even when measurable texture-related quantities such as rheology are the same. However, we are only able to predict sensations at the initial stages of consumption from knowledge of material properties of intact food.

Research is now on going to develop strategies to capture the dynamic aspects of oral processing, including: from a sensory perspective, the recent development of Temporal Dominance Sensation; from a material science perspective, development of new in vitro techniques in thin film rheology and tribology as well as consideration of the multifaceted effect of saliva. While in vivo, ex vivo, imitative and empirical approaches to studying oral processing are very insightful, they either do not lend themselves to routine use or are too complex to be able to ascertain the mechanism for an observed behaviour or correlation with sensory. For these reasons, we consider that fundamental in vitro techniques are vital for rational design of food, provided they are designed appropriately to capture the important physics taking place during oral processing. We map the oral breakdown trajectory through 6 stages and suggest a dynamic multi-scale approach to capture underlying physics. The ultimate goal is to use fundamental insights and techniques to design new food and beverages that are healthy yet acceptable to consumers.

1. Introduction

Both natural and processed foods contain hierarchical structures and multiples phase, ranging in length scale from the nanoscopic to the macroscopic. These structures are present to provide certain functionality such as nutritional value and texture control or to aid processing and shelf-stability. Rheology is used as an essential design tool in engineering food as it is important to processing, shelf stability and sensory perception, including texture and mouthfeel, and it can probe the overall structure as well as the interplay between individual colloidal components. There is extensive knowledge on the complex relationships between rheology and the dominant underlying structure of foods and beverages, and a good enough understanding exists to re-design different types of foods to have largely the same rheological features [1,2]. Therefore, it is possible to design food rationally to meet rheological criteria and for meeting specific nutritional requirements; for instance, the role of hydrocolloids in nutrition and digestion is covered elsewhere in this issue [3]. However, foods created in this rational way still fail to meet consumer expectations: consumers are let down by the overall sensory experience, which is strongly influenced by the food and beverages' organoleptic properties. We address here consideration of in vitro strategies that provide insights into oral processing and, when coupled to in vivo studies, will better enable rational design of foods and beverages.

Texture and mouthfeel play pivotal roles in product acceptability, and except for the point at which food enters the mouth (e.g., first bite of solids, initial thickness of liquids), we cannot currently predict these percepts using fundamental rheological properties of the food and beverage [4••] or through measurements derived from imitative or empirical techniques such as "texture profile analysis" (TPA) using a texture analyser [5,6•]. Consequently, replicating foods with healthier formulations has proven difficult, and important questions arise as to what role ingredients like fat play that makes it so desired in food and renders the texture of

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products more acceptable [7]. Similarly in beverages, when basic tastants such as bulk sweeteners (e.g., high fructose corn syrup) are substituted with alternative sweeteners (e.g., aspartame), even if apparent sweetness level is the same, the perceived mouthfeel is substantially altered [8,9]. New insights are needed into the physical drivers for texture and mouthfeel if food manufacturers are going to be in a position to rationally design food with an enhanced nutritional profile that is also acceptable to consumers.

Food Oral Processing involves comminuting solid food to small particle sizes, mixing with saliva, and forming a bolus that is then swallowed and transferred to the stomach [4••,10]; the first book on the subject has recently been published [11••]. Regardless of the initial state of food, it undergoes a conversion to a form that is rheologically suitable for swallowing in a highly sophisticated dynamic process [12,13••]. The organoleptic properties of food, including texture perception, should depend on the constantly changing status of the food during oral processing [14] as well as the changing status of the salivary film coating oral surfaces and saliva itself [11••,15•,16•]. Utilising knowledge of oral processing in the rational design of foods is challenging and relevant in vitro measurement techniques are needed that provide mechanistic insights into texture/mouthfeel and can be used in food structure design, but these also require validation using in vivo studies and sensory science.

This review will consider oral processing and texture/mouthfeel with particular emphasis on developing in vitro strategies to capture the dynamic nature of oral processing and the changing status of food during consumption, as well as the underlying physics/mechanics taking place during this process.

2. The multi-dimensional and dynamic nature of texture and mouthfeel

Food texture is regarded as a multidimensional sensory property that is influenced by the food's structure, rheology and surface properties; this has been recently reviewed by Kravchuk et al. [17]. As defined by the International Standards Organisation (ISO, 1994), texture is "*all the mechanical, geometrical and surface attributes of a product perceptible by means of mechanical, tactile, and, where appropriate, visual and auditory receptors*". Mouthfeel is a term often used to refer to the tactile aspects of texture perception during consumption, as defined by Guinard and Mazzucchelli [18•] who state that mouthfeel encompasses all of the "*tactile (feel) properties perceived from the time at which solid, semi-solid or liquid foods or beverages are placed in the mouth until they are swallowed.*" Following consumption, the mouth still senses residue and after effects resulting from the consumed food, such as astringency and mouthcoating; a*fter-feel* is a term commonly used to describe these mechanical sensations that are also inherently part of texture perception. Hence, texture is not just about rheology, but texture also encompasses tactile mechano-sensations associated with the contact between the food, food residue and human oral surfaces [17].

These accepted definitions of texture highlight its truly multidimensional nature and emphasise that it is not a simple food property that can be measured instrumentally [17]. Regardless, a considerable amount of effort has been expended to do just this using imitative mechanical tests and rheology, as covered in the next section. However, these endeavours rarely consider contributions to texture from structural and surface properties, and they are also unable to consider cross-modal influences from the different senses. Tactile mechano-sensation plays a major role in the perception of texture and mouthfeel, yet this is unlikely to be captured through rheology measurements; of closer relevance is measurement techniques in tribology, which considers the forces associated with interacting surfaces in relative motion (covered later in this review). In addition, what is often not considered or quantified in both sensory and mechanical measurements is that food undergoes a major transformation upon entering the mouth, so exactly what structural, mechanical and surface properties of the food and the food bolus are relevant to the perception at any particular time point is open for debate. Fig. 1 depicts the transition in film thickness of fluid-like foods or beverages between oral surface as they are consumed, indicating it goes from a rheology-dominant deformation process to one where tribology (surface properties) dominates.

Sensory profiling traditionally involves a descriptive approach and quantification of intensity after eating [19]. Time–intensity (T–I) studies were introduced to account for the dynamics of perception [20], but the main constraint is that evaluation is limited to one or two attributes at a time [21]. Temporal Dominance Sensation (TDS) has been recently introduced as a viable technique to capture the multidimensionality of the perceptual space over time [21–23••]; it involves assessment of the most intense (dominant) percept at any particular time and scoring the intensity (refer to Fig. 3). The challenge with this approach has been in analysing data collectively from different panellists, especially when the attributes are not highly distinguishable or interrelated. In a recent study on brittle cereals, TDS was used to identify the dominant textural attributes with time during mastication [14], which we believe is a promising approach for directly linking the changing status of food and its interaction with saliva during oral processing. Future studies need to focus on mapping the temporal sensory process to relevant physical properties measured in vitro, which will assist in developing suitable in vitro methodologies for rational food design that accounts for texture and mouthfeel.

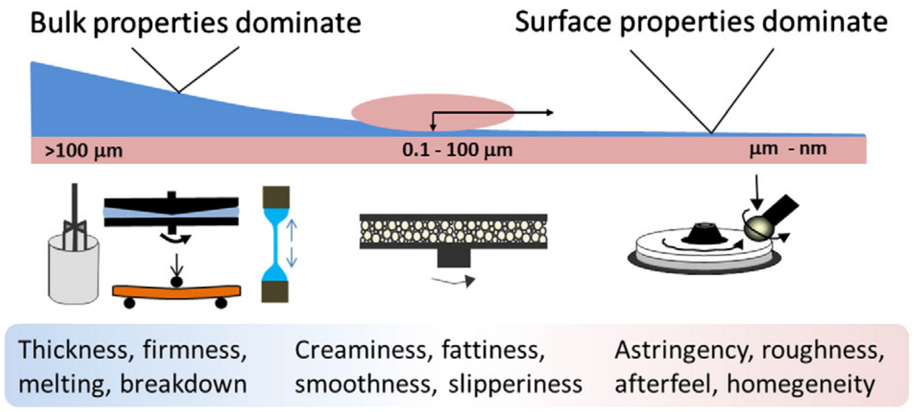

Fig. 1. Depiction of the transition in film thickness of fluid-like (and soft) foods or beverages between oral surfaces as they are consumed, indicating it goes from a rheology-dominant deformation process to where tribology (surface properties) dominates. Also shown is an indicator of the types of techniques that could be used to study the multiscale deformations, and where typical textural mouthfeel attributes may lie.

3. Historic perspective: Can texture be instrumentally measured ?

Food technologists have sought for a long time to instrumentally measure “texture,” despite the caveat that it is a multi-modal sensory percept. There are three key approaches: (i) imitative techniques (e.g., using so-called *texture analysers*), (ii) empirical methods that seek to align any sort of measurement to a sensory perception and (iii) fundamental mechanical properties of the food such as rheology and its underlying structure.

Prior to ca. 1960, there were a range of instruments, claimed to measure food textural properties, that were designed to mimic the deformation (puncture, shear, compression and tension) of specific food types, typically solid-like foods [24–26]. Further developments led to Universal “texture analysers” [5] that are now widely used to characterise the mechanical properties of solid and soft-solid foods [6•,27]. These devices involve application of an axial force or squeeze rate akin to traditional hard material testing devices, and they contain a range of attachments that utilise the principals of fracture mechanics appropriate to the manipulation of food with fingers, lips, tongue, and incisor, cuspid and molar teeth. Universal Texture Analysers can provide true material functions, but they are often used in an empirical or imitative fashion. A particularly popular *imitative* test that purports to provide standardised values of food texture is the so-called “Texture Profile Analysis” [5,6•]. The technique involves measuring the mechanical response during a double compression, which attempts to mimic first and second bite of a food sample and various parts of the measurement are referred to as hardness, elasticity, adhesiveness, cohesiveness, brittleness, chewiness, and gumminess [6•,27,28•]. A major short-coming of the technique is that the correlations on which the sensory tests have been made are not particularly strong or linear [27,29•], and there is substantial potential for abuse as the methods are often used blindly with measurements *incorrectly* reported as definitive measures of “texture” [30]. The range of geometries available for texture analysers has also meant that standard fixtures and procedures are not always used, which makes it difficult to compare between studies. While not always practiced, measurements should always be reported as stress rather than force to allow comparisons to be made between geometries, methodologies and samples [31]. In addition, while the approach may be suitable for comparative purposes, it does not lend itself easily to rational design since there are multiple types of deformations occurring during the test sequence that cannot be easily associated with different structural components or colloidal entities. However, if used correctly and with knowledge of its limitation, TPA can be a valuable tool.

There are numerous detailed papers covering food rheology [4••,32–34••,35••,36,37]. Rheology is used to develop constitutive relationships between stress and strain rate, and foods are generally more complex than most materials because they are also strongly dependent on time scales of the deformation process (thixotropy, elasticity, etc.) as well as shear and thermal history (processing) (see recent review [4••]). While there is much research that seeks to link the triangle of rheology–structure–processing, in the context of texture perception most studies revert to simply measuring the viscosity over a limited set of shear rates as well as the apparent yield stress for soft materials and the storage/loss moduli over a limited set of frequencies as a measure of viscoelasticity. More extensive studies than these are required to fully develop constitutive models for intact food and more still to consider how food behaves under relevant conditions present during oral processing.

Empirical approaches involve discovering correlations between a range of physical measurements (TPA, mechanical properties and rheology) and texture perception with the view to ultimately instrumentally measure “texture.” For solid materials, the modulus and force or stress to fracture are discussed in terms of ‘first bite’ [38–41] and good correlations with sensory at this stage are generally found [40]. For solid foods like cheese and model composite gels, the stress and strain at yield or fracture are found to be related directly to firmness, hardness and springiness [42,43]. Perceived creaminess, crumbliness and graininess do not correlate in a similar fashion, which is because they depend on the response of the food during and following its mastication. For brittle foods, the perception of crispness and brittleness correlates with measures of the maximum force to break [44–46], and similar types of relationships are found for solid food foams (e.g., baked bread, extruded snacks, cooked rice, whipped topping, marshmallow). Another approach to instrumentally measure texture of solid foods has been to measure acoustic signals [47,48] during eating and during mechanical testing (see recent review [49]). Strong correlations are found between ‘crispness’ and acoustic signals for a variety for solid foods [50], and both auditory signals and fracture properties can thus be used to predict crispiness perception [51]. A challenge moving forward is to use such in vivo acoustical approaches to assist in linking mechanical property measurements with particle breakdown mechanics that occur during oral processing.

Rheological properties are extensively measured to relate to the texture/mouthfeel of liquid and semi-fluid foods [52–54], despite the early realization that rheology alone is not enough [55]. Initial thickness perception has been found to reasonably correlate to viscosity measurements made at shear rates around $50\ \text{s}^{-1}$ [45,56••,57,58•] (see review of this in [4••]). This shear rate can only be applied to the initial thickness perception and not to any other sensory attribute, and care should be exercised when comparing different types of thickened fluids. For example, using the data of Elejalde and Kokini [59] it was recently shown [4••] that there is seemingly an excellent power law (linear on log-log scale) correlation between the viscosity at $50\ \text{s}^{-1}$ and thickness perception for a large range of different foods over several orders of magnitude; however, when one focuses only on a single decade of viscosity, the correlation is extremely poor. The case is exactly the same for the so-called Kokini shear stress (see [4••]). It should be noted that even when liquid foods are designed using hydrocolloids to have the same viscosity around $50\ \text{s}^{-1}$, they will still vary greatly in their viscosity above and below this shear rate and in their elasticity as measured using normal stress difference or extensional viscosity [60••]. For soft foods, the apparent yield stress and storage modulus have been found to relate strongly to the initial texture perception, such as firmness of yogurts or mayonnaise [54]. However, other rheological parameters may be important but full rheological characterisation of foods, including high shear viscosity, normal stress differences (non-linear viscoelasticity) and extensional viscosity, are rarely determined due to the difficulties in their measurement [4••]. In an extensive collection of research involving a combination of instrumental, sensory and physiological measurements on soft foods including custards by Prinz and co-workers [54,61–63], it is apparent that viscosity at $50\ \text{s}^{-1}$ does not enable prediction of complex sensory sensations of creaminess, fattiness, smoothness, stickiness, etc. These properties are considered to depend on the rheology of the bolus being formed and on “surface-related” properties that may be captured by considering tribology [63].

We conclude that it is possible to *instrumentally predict* key aspects of “texture” perception at the initial stage of oral processing, using a range of imitative, empirical and rheological measurements. However, as food is transformed during the first few seconds of consumption a greater set of complexities arise that cannot be captured by traditional rheological measurement methodologies. Fig. 1 depicts the proposed transition from where “bulk properties dominate” to where “surface properties dominate” in relation to film thickness between shearing surfaces; also shown are potential techniques to characterise the underlying physics and relevant sensory attributes for liquid/soft food.

4. Oral processing and the changing status of food

Eating is a dynamic *process* [13••,64•,65•,66••], and studying the sequence of oral manipulations beyond the first bite has been very challenging. Combinations of in vivo, ex vivo (expectorating chewed food samples) and fully-imitative in vitro (i.e., mechanical chewers [67–69]) measurements have been investigated (see recent reviews

[11••,66••,70,71]). Hutchings and Lillford [13••,72] hypothesized a continuous food breakdown pathway and conceptualized swallowing as occurring when food reaches a certain degree of structure breakdown and degree of lubrication. Structure breakdown relates to the comminution process of reducing the particle size of solid food during mastication while lubrication relates, to some extent, to the rheology and surface properties of the bolus that allow for swallowing. Prinz and Lucas [73] took the ideas forward and proposed general models for mastication and bolus formation: they related the food mechanical properties to a 'breakage function' in order to model, or predict, how a food will break upon eating [74••,75]. They also considered the competing forces of adhesion to oral surfaces and cohesion of food particles via capillary bridging (which is related to the field of granulation) and how those two forces affect the formation of a bolus [76•]. In their recent work on soft foods, clear links are shown between type of sensation and the time point of processing in the mouth [61]: "thickness… (is) relatively immediate and reflect bulk properties of food bolus when the food is relatively intact. Others, such as fattiness and melting, reflect both bulk and surface properties… when food is relatively degraded. … fatty after-feel, are only developed after swallowing is complete".

While significant and valuable knowledge has been gained by studying oral processing using in vivo, ex vivo and *imitative* approaches, their use for rational food design is limited. In our assessment of the field, we conclude that in vitro strategies are required to specifically determine how various food components affect the dynamics of oral processing and ultimately texture perception. We take the approach that there are many deformation and transport processes occurring simultaneously during oral processing [47,77], and to uncover specific roles of ingredients these processes need to be broken down into specific *fundamental* steps. By breaking up oral processing in this manner, we consider it more likely to be able to isolate key in vitro measurements and methodologies that lead to greater insights into food structure design beyond the first bite. For example, as we depict in Fig. 2, Brandt et al. [64•] and others [18•,43] consider the different stages in which texture is *perceived* during oral processing: (i) Initial (first bite); (ii) masticatory (during chewing); and (iii) residual (texture during mastication). However, breaking it up into these three phases inhibits the development of in vitro techniques that seek to capture what the food *experiences* during oral processing. We suggest, for the *purposes of developing* in vitro *approaches* that enable rational design of solid foods, that oral processing is split into the following 6 stages: (i) first bite, (ii) comminution, (iii) granulation, (iv) bolus formation, (v) swallow and (vi) residue. We depict these stages in Fig. 3. The changing status of food should be examined at each stage, and it should be noted that these processes overlap in situ, but studying them separately allows the underlying physics to be decoupled so that insights can be obtained on the specific functionality of food components.

In reference to Fig. 3, *comminution* [78–83] (phase ii) is the crushing and grinding of the solid food into particulates [84]. During comminution, food particles may rub oral surfaces leading to dry sensations, or liquid (aqueous or oil) may be released from the food that along with the saliva secreted from the oral cavity may act as a lubricant against irritation. Hence, there is a tribological interaction between the food particles and the oral surface, which is likely to play a major role in sensations such as grittiness and rough mouthfeel. As solid foods are reduced to particulate form during chewing, they also aggregate via capillary bridging if small amounts of liquid are present [76•]. This is a process commonly referred to as *granulation* in powder processing [85–87] (phase iii). As more saliva is secreted into the oral cavity, the particles become dispersed in saliva, i.e., a bolus forms and may be considered a paste-like suspension (phase iv). At this stage, the particles can be potentially hydrated and subjected to enzymatic breakdown from amylase on the way to the bolus being swallowed, and the bolus rheology will alter with time as more saliva is secreted continually into the oral cavity and from continual shear. The swallowing process (phase v) is thought to be controlled by a combination of particle size, moisture content and bolus rheology, all of which are critical to those with swallowing disorders. Following swallowing, residue from the food can still contribute to mouthfeel/after feel perception along with the subsequent secretion of saliva into the mouth, which is influenced by the food and beverages being consumed (phase vi) [16•,88]. In this way, one can see that there is a transformation from a rheology-dominated process (i.e., first bite) to a tribology-dominated process during oral processing since surface interactions are of paramount importance. This includes both the friction generated between food particles and oral surfaces, friction between tongue and palate and the adherence of food particles and bolus to oral cavity. With this in mind, we highlight in Fig. 3 where mechanics, rheology and tribology are important in the process. In addition, we also show in Fig. 3 how each stage may correspond to points in time during TDS of solid foods. As food forms a bolus, it becomes fluid-like so Fig. 1 is relevant to the latter stages of oral processing.

5. Tribology and multi-scale deformation processes

5.1. Tribology in oral processing

Tribology is the study of friction and lubrication between interacting surfaces in relative motion, and the number of interacting surfaces in the mouth during food consumption is plentiful: teeth–teeth, tongue–palate, tongue–teeth, teeth–food, tongue–food, tongue–bolus, lips, lips–food, bolus–palate, food particles–oral surfaces, etc. Extensive detail on tribology fundamentals and food lubrication can be found in a recent review on 'oral tribology' 89[••] while a recent discussion on the emergence of tribology as a contributing discipline for understanding oral processing, texture and mouthfeel is presented in [35••].

The tongue is rough with papillae being of order 100 μm in height and diameter [90], while its modulus is considered to be of order 1 kPa [91••], and it moves at speeds of up to 200 mm/s [92] and normal loads of up to 90 N [93,94]. Saliva's main function is to lubricate oral surfaces to protect them from damage and to ensure food moves easily around the oral cavity and is swallowed without effort; eating, drinking and talking without saliva is not a pleasant experience, as those who suffer xerostomia (dry mouth) are all too aware [95•]. While tribology is clearly important to oral processing, the challenge is how to interpret

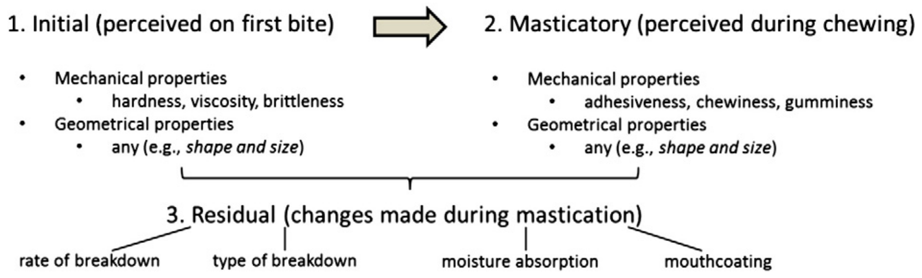

Fig. 2. Procedure for evaluating texture as outlined by Brandt et al. [64•]. This has been adapted from its original source to reflect that the "Residual" phase influences the initial and masticatory phases.

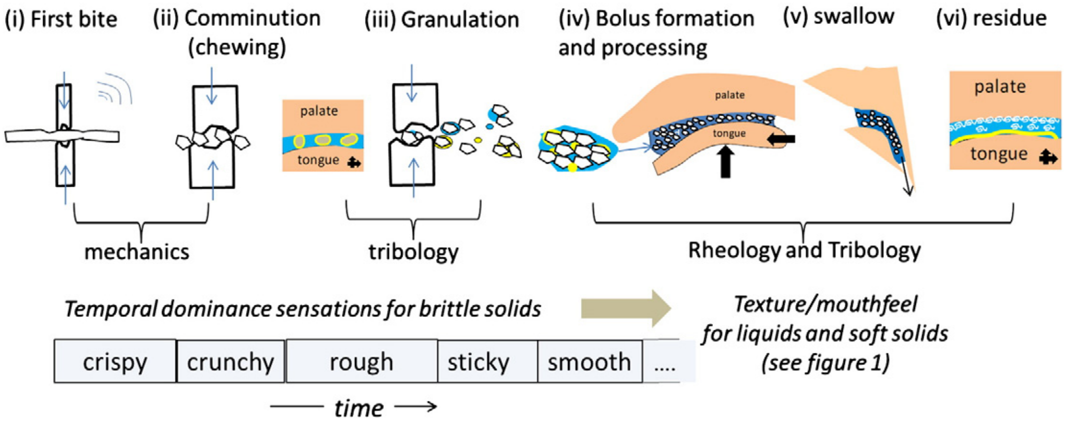

Fig. 3. Depiction of 6 key stages that we propose occur during oral processing of solid food. Also included is indication of where mechanics, rheology and tribology are important. Tribology arises in (iii) because of the interactions that occur between particles as well as at the oral surfaces, while in (iv, v, vi) it arises primarily from interactions occurring between oral surfaces. We also map on this a depiction of TDS curves for solid food that show how the dominant sensations vary over time. For oral processing of the bolus, as well as soft foods/fluids, the scheme presented in Fig. 1 is also relevant.

and utilise tribological measurement techniques to obtain meaningful insights into oral processing, texture and mouthfeel. We should point out that the majority of the discussion below is concerned with the role of food/beverages and its components on the lubrication between tongue and palate.

Most engineered mechanical systems are designed to ensure that surfaces are kept apart so that the lubricant can support a load. This is achieved via the hydrodynamic pressure that is created when non-parallel surfaces move at a sufficient velocity relative to each other [96]. In contrast to traditional studies into tribology that use “hard” surfaces, oral tribology involves compliant substrates that can be deformed by contact pressures. Hydrodynamic pressure and thus the film thickness between surfaces in relative motion decreases with decreasing lubricant entrainment speed [97]. Boundary lubrication results at low speeds when the hydrodynamics can no longer support the load. The friction coefficient is dependent on lubricant entrainment speed, which is commonly presented in the form of a Stribeck curve, as shown in Fig. 4. There are three clear regions in a Stribeck lubrication curve: boundary, mixed and elastohydrodynamic (EHD) lubrication [98••]. Both hydrodynamics and boundary film properties are important in the mixed regime. The junction between the regions depends on the substrate roughness and substrate elasticity, as well as on how the lubricant wets a surface; for example, full film lubrication can be extended to lower speeds using a smoother surface. The boundary lubrication regime and the junctions between regimes are strongly influenced by wetting and adsorption of species to the substrate [60••]. A particularly good example of an effective boundary lubricant is saliva; the proteins in saliva absorb to substrates to form a multilayer film that protects oral surfaces from wear and friction, including those interactions arising from food particles (see Section 6) [60••].

In very similar fashion to research on food “texture”/rheology measurements, it is emerging that studies into food oral tribology are also split into three categories: (i) imitative approaches, such as those using pig's tongue, (ii) empirical approaches, which are those merely seeking a relationship between some friction coefficient and texture/mouthfeel perception and (iii) ‘fundamental’ studies into the science/engineering of soft-tribology. All three approaches contribute to our understanding of oral tribology and food lubrication, but care should be exercised when pursuing a purely empirical approach as it does not easily lead to insights into driving mechanisms for any correlation that is found.

Imitative approaches have measured the lubrication properties of primarily emulsion based systems between pigs tongue and oesophagus [91••,99,100] or glass surface [91••,101,102••]. Studies using a novel tribo-optical cell show that papillae on the tongue surface flatten considerably under load so that similar lubrication behaviour is found when emulsions are lubricated between glass-rubber substrates and that mixed-lubrication regime is likely to be dominant during oral processing. Correlations have also been found with fat-related sensory percepts. Using a pig's tongue is challenging due to its variability and inhomogeneity, as well as having unknown surface chemistry. For this reason most studies on food oral lubrication have used a variety of elastomer substrates that are either commercially derived (which usually means unknown surface chemistry) or made in house using polydimethylsiloxane (PDMS) with relatively well-defined surface properties. However, using animal tongues is currently the only way to effectively study how the specific topology of the tongue surface influences lubrication.

Many studies into food oral lubrication have taken an empirical approach of characterising differences between samples and comparing these differences to sensory studies. This approach has shown that correlations can be found between some ‘friction coefficient’ and certain

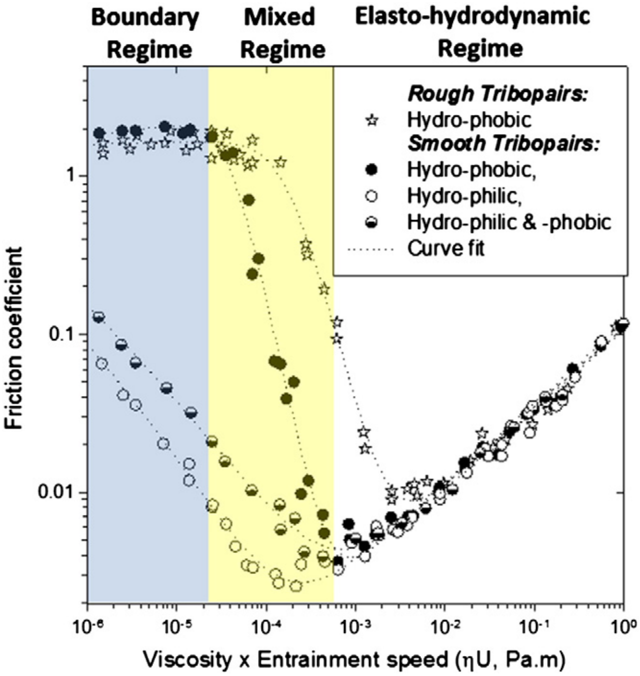

Fig. 4. Collection of Stribeck curves showing the infleunce of surface properties (wetting, roughness) using PDMS ball-disk tribopairs lubricated with a range of aqueous Newtonian fluids varying in viscosity from 1 mPa.s to 2.8 Pa·s. Each shaded region shown is the different lubrication regimes for the hydrophobic smooth tribopairs.
Adapted from [98••,89••].

texture percepts such as smoothness [103•,104•], fattiness [103•,105] and even creaminess [105–109]. Emulsions have been studied extensively with the view to explain fat's influence on texture and mouthfeel and thereby discover suitable replacements. Several studies are indicating that localised coalescence of emulsions in oral tribological contacts may be a driver for fat-related textural attributes such as creaminess. For example, Dresselhuis et al. [109] show that emulsions most sensitive towards in-mouth coalescence give rise to the highest creamy mouth-feel and fatty sensations as well as oily taste sensation. Recent explorations on the lubrication of dairy products with varying fat content have also found some correlation between friction and sensory perception [108,110]. The friction coefficient at low entrainment speeds decreases with increasing fat levels above a certain threshold [108], which is a very promising result for product differentiation and design. We express one note of caution when considering instrumental measures of 'creaminess': while many argue that creamy perception is associated with the friction coefficient, the multimodal nature of this percept is often ignored. Creaminess perception arises from an integration of several percepts including flavour as well as texture, and the correlation may arise due to intensity of the flavour altering with fat rather than from 'friction' [111].

While great strides are being made in relating tribology to sensory, we are not at the stage where a simple friction coefficient can predict a texture or mouthfeel attribute or where it can be used for rational design by product developers. The difficulty arises that there are a large range of different configurations being used, including surfaces and geometries that are not particularly well-defined, which makes it difficult to determine underlying mechanisms for observed tribological responses. For example, tribological techniques have included the design of special tribo-fixtures to stress-controlled rheometers [112,113], but these are proving difficult to use which may be due to a current lack of foundational knowledge and peer-reviewed publications, although the potential to capture mouthfeel is emphasised in a patent [114•]. It is very much reminiscent of the development of texturometers in the 1960/70s before a universal texture analyser was created.

The fundamental approach to study the oral tribology of foods is to use well-defined substrates and configurations, as well as well-defined model fluids that provide insights into full food formulations [115]. The ball-on-disk in a mixed rolling and sliding contact using at least one (preferably two) PDMS substrate is the most widely set up for such studies, mainly using the mini-traction machine from PCS Instruments. PDMS is used because it has a low modulus, can be easily modified to be hydrophobic, hydrophilic, rough, smooth, etc. [98••]; it can be micro-engineered to have specific topology [90,116] to emulate the tongue surface; it is relatively easy to functionalise and it readily adsorbs macromolecules such as salivary proteins including mucin and saliva itself, etc.[15•,117,118]. It is also relatively easy to create films of PDMS that can be used in complimentary techniques to study adsorption and interactions with food components [119,120•]. Film thickness measurements are also now possible in soft-ball-and-disk configuration [121,122], as well as Raman spectroscopy [123], and the film thickness can be predicted numerically for Newtonian fluids in the hydrodynamic regime [124•]. There is a rich set of literature on which to develop insights on the driving mechanisms on the lubrication properties of food and beverage formulations and in particular identify the role of various food ingredients [60••,115,119,125–129].

Fundamental studies on soft-tribology demonstrate that a key variable defining tribological response is simply viscosity; a friction coefficient in the mixed and hydrodynamic regimes is usually directly related to the viscosity of the fluid in the contact zone, although this may not necessarily be same as the bulk product. The shear rate in tribological contact is predicted to exceed 1000 s^{-1} in most situations, far beyond that normally measured in rheology studies. By measuring the viscosity at shear rates of order 10^4–10^5 s^{-1} (see [130•,131] on how to do this on a standard rheometer), the observed friction coefficients for polymer solutions can be mostly accounted for by this high-shear viscosity, although adsorption of the polymer to tribo-surfaces also defines the friction coefficient and the limits between the regimes [60••,115,126,128]. Meso-stable emulsion systems are well documented in the tribology literature, where low surfactant concentrations are known to ensure preferential surfactant adsorption to hydrophilic steel surfaces, resulting in the emulsion break-up and releasing oil to enter the tribological contact [132–134,135•]; this explains many of the measurements reviewed above on food emulsions. Fundamental studies show that oil droplet size is of critical importance; for example, droplets that are smaller than the surface roughness do not contribute significantly to the lubrication properties of the emulsion [129,136]. It was also discovered that provided drop sizes are similar or larger than the width of the gap, the more viscous phase is typically entrained into the contact, provided they can both wet at least one surface [89••].

In soft-tribological contacts, the hydrodynamic lubrication properties of oil are the same as that of an aqueous fluid of the same viscosity [135•]. This highlights that oil does not necessarily have unique lubricating properties in a soft-tribological context except that it is Newtonian whereas many aqueous polymers that are used for thickening are highly shear thinning so their viscosity at high shear rates is not necessarily much more than water. This low-viscosity at high shear may explain why they are not that effective as replacers for fat-related texture/mouthfeel properties since friction is dominated by the high-shear viscosity of whatever is in the contact zone. Fig. 5 shows how the rheology (viscosity and elasticity) of polysaccharide solutions that were matched in viscosity at 100 s^{-1} differ widely above and below this region. Their lubrication properties also differ markedly (Fig. 5b), which is partly explained by their high-shear viscosity as well as their ability to form a hydrated film on tribo-surfaces [60••].

Through fundamental approaches in soft tribology, rational guidelines can be easily formulated with respect to tribological contacts in the mouth. Key considerations for rational design include the following: high-shear viscosity will mostly define the lubrication properties of homogenous fluids; small droplets or particles (perhaps less than a micron) are likely to 'pass through' a soft tribological contact, with only their phase volume affecting viscosity; large droplets may locally coalesce in the contact and coat oral surfaces; and surface properties (including polymer adsorption) affect the limits of hydrodynamic lubrication as well as the friction coefficient in the boundary regime.

Fundamental approaches have the benefit that they can pull apart the potential behaviour of food in soft-tribological contacts, which allows empirical correlations to be more fully explained and thus provide a greater potential for the use of tribology in ration design. However, there is still much that is fundamentally unknown, which makes it a rich area for future research.

5.2. Gap dependent and thin film rheology

The key difference between rheology and tribology is that rheological measurements require the fluid to be a continuum, but tribological measurements involve application of load that shears the sample at the length scales of its constituents. This is precisely why tribology provides different information to rheological measurements, although the friction coefficient is dependent on the viscosity (rheology) of the lubricant in the contact and the fluid between the surfaces is still treated as a continuum; the lubricant in the contact, however, may be completely different to the bulk fluid. Hence, the flow behaviour of the material is dependent on gap.

To bridge the gap between rheology and tribology, several researchers have begun to explore how gap affects the rheological properties of fluids and soft solids, although there are no published literature to date that attempts to relate these to sensory properties. Rheological measurements at narrow gaps (100 nm to 100 μm) reveal two key system attributes: the gap-dependent rheology is strongly dependent on the local mechanics of the dispersed phase (e.g. particle modulus, interfacial tension of droplets) and the interaction between the dispersed phase and the surface

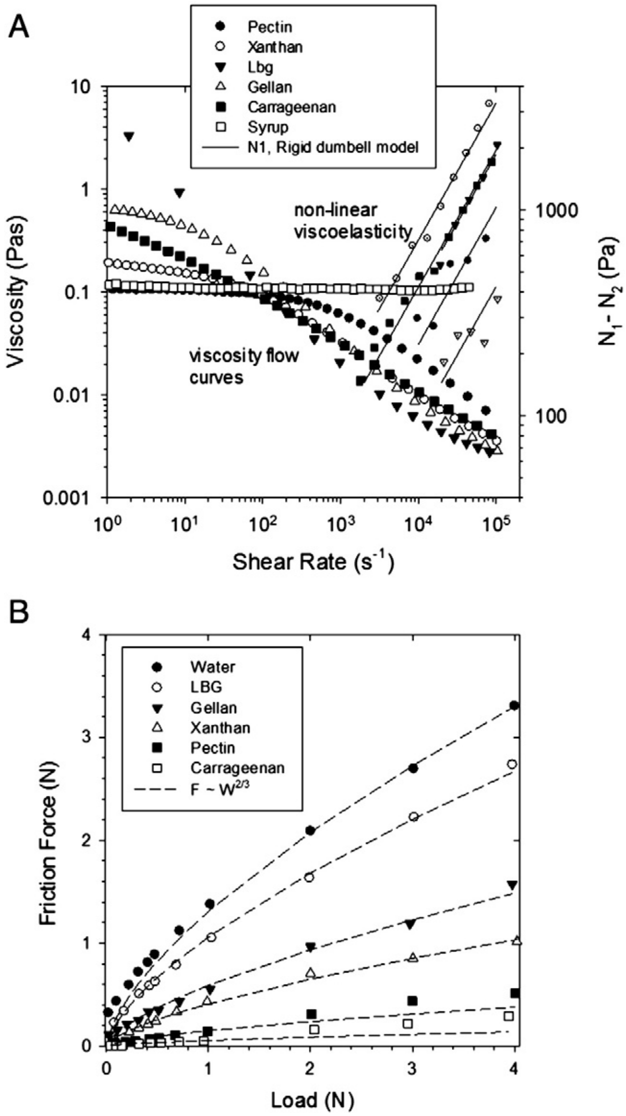

Fig. 5. Rheology and Lubrication properties of aqueous polysaccharide solutions that are viscosity matched at ~100 s^{-1}. There are clear differences in their (a) viscosity above and below 100 s^{-1} and in viscoelasticity as measured via the normal stress differences (smaller dotted-symbols; lines are fits to the rigid dumbbell model); and (b) measured force–load relationship in the boundary regime at an entrainment speed of 5 mm/s using a PDMS ball and rough PDMS disk (lines correspond to fits for the friction force to $W^{2/3}$).
Adapted and reprinted with permission from [60••] Copyright (2011) American Chemical Society.

[130•,131,137,138]. This is potentially important for certain sensory attributes like grittiness and creaminess. Grittiness is a common mouthfeel perception when hard particulates are present in a food (particularly corresponding to (ii)–(iii) in Fig. 3), while soft particles may not be noticeable. From a rheological point of view, the rheology of hard and soft particles is the same for low phase volumes (<40%), so the perception of grittiness implies that particles are confined to a narrow length scale where particle hardness is detectable by human senses. Burbidge et al. [139] discuss the perception of smoothness and grittiness in the human mouth from the perspective of continuum mechanics and drew some conclusions about the likely interactions between hydrodynamically arising stress fluctuations and stimulation of biological mechanoreceptor structures, based on the fact that two classes of mechanoreceptors respond to either static or dynamic stresses. It was shown that static stresses arising from inclusions are very small relative to the background stresses generated by squeeze flow unless the inclusion is very close to the palate, tongue or free surface.

Measurements of rheology under microscale confinement on food-related dispersions (e.g., mayonnaise [138,140], soft and hard particle suspensions [130•,136,141]) show that the measured rheology alters dramatically with gap. Dynamic measurements reveal that a fluid-like suspension jams once the gap is lowered to about 5 particle diameters, which leads to an apparent increase in yield stress. Under shear, complex microstructural fluids may exhibit several apparent yielding transitions, arising from partial structural breakdown processes during flow at different stress levels. Studies using smooth surfaces reveal complex slip behaviour, part of which can be explained by depletion of particulates from the vicinity of the surface via hydrodynamic and elastohydrodynamic lubrication. This also depends on particle and suspension modulus [142,143] as well as on how the dispersed phase or any liquid in the sample adheres and wets the surface [144]. It should be noted that one of saliva's many functions is to lubricate oral surfaces, including slip inducement between the food material and the oral surface; swallowing is very painful without such a property.

Gap-dependent rheology is thus a potential in vitro route for studying the tribological interactions between food bolus and the shearing surfaces themselves. Therefore much more research is required to better understand the relevance of gap-dependant rheology and slip of multi-phased soft materials and how it influences both the sensory perception and more critically aids the transport of the bolus through the oral cavity and the swallowing function [4••].

6. Saliva and oral interfaces

Saliva is a critical component in the consumption of food and beverage, and its properties are important to texture, mouthfeel and taste perception. It contains hundreds of proteins, with mucin being of paramount importance and is present in the mouth as a highly viscoelastic low-viscosity fluid and as a multilayer adsorbed film on oral surfaces, as depicted in Fig. 6. The secretion of saliva into the oral cavity occurs during the consumption of foods and beverages due to stimulation from taste, aroma and mechanical action. The stimulated saliva binds food material together to form a bolus (capillary bridging, flocculation), it assists in the digestion of starch and lipids and it dilutes and clears the mouth of food and bacteria. Saliva is essential for transporting taste molecules to taste receptors, which is evident in patients with xerostomia (dry mouth syndrome) who have been found to have a diminished sense of taste [145,146]. Saliva plays a vital role in the breakdown and perceived texture of food [145–147]. For example, the digestion of starch by enzymes in saliva such as amylase can decrease thickness perception of foods as it is consumed [100,148] while the diluting behaviour of saliva on thickeners has been speculated to affect taste and texture perception [149,150]. On this note, a recent study highlighted that in vivo flavour delivery measurements can only be theoretically explained by incorporating dilution of saliva into a mass transport model [151••,152]. The interaction of saliva with particular food components has been related to the food's textural and mouthfeel attributes [109,153–155•,156]. For example, flocculation of protein-stabilised oil-in-water emulsion droplets in the presence of saliva has been found to influence fat-related sensory attributes such as creaminess and thickness [154,155•,157••]. It has also been found that whole mouth saliva rheology alters substantially in response to different tastes and mechanical action, and for beverages and flavourless chewing gum a sensory study has indicated that this is influencing mouthfeel and after-feel perception during and following consumption, respectively [16•,88].

The proteins in saliva adhere to oral surfaces to provide a multicomponent protein-rich film (≈25 μm [95•]) that is highly lubricating and necessary for the efficient transport of food through the oral cavity and for protecting the oral surfaces from irritation and damage. Its essential lubrication function is exemplified by sufferers of dry mouth (xerostomia) having problems with mastication, swallowing and speech as well as rapid wear of their teeth. During consumption

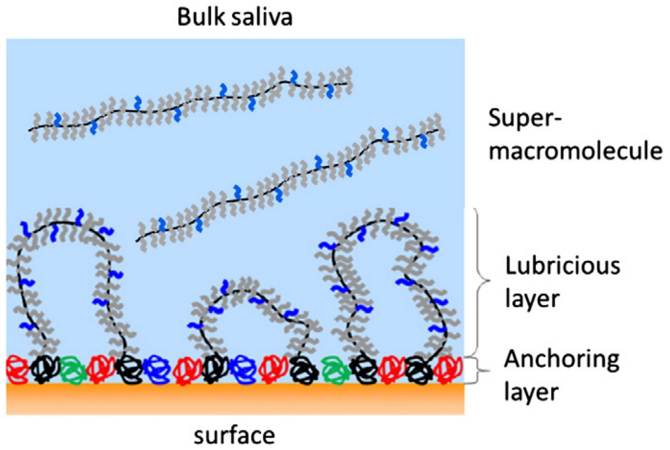

Fig. 6. Sketch (adapted from [120•]) of the salivary proteins (e.g., high-molecular weight mucin) in an extended conformation adsorbed to surfaces (for boundary lubrication) and in bulk solution (origin for saliva's viscoelasticity). Food and beverages can interact with the salivary proteins on the surface and in bulk solution due to physico-chemical interactions or altering salivary protein conformations, as well as affect the composition and rheology of the saliva subsequently secreted into the oral cavity during and after consumption.

of food and beverages, the rough and dry mouthfeel that can result is likely to be linked to the disruption of the salivary film coating; even subtle changes in salt and pH affects its hydration and lubricating properties (e.g., see [119,120•]). Astringency mouthfeel perception, which is a dry puckering sensation, has been linked to a loss of lubrication from the interaction of salivary proteins with astringent molecules such polyphenols in wine and tea [15•], as well as β-lactoglobulin [158] and acid. However, lubrication studies performed by adsorbing saliva to PDMS substrates and following the response upon contact with astringent molecules has highlighted that while strongly astringent molecules lead to a loss of salivary-lubrication, weakly astringent molecules did not affect the film; hence, it is concluded that a loss of lubrication is not essential for astringency to be perceived [15•]. Mucin's amphiphilic nature with both hydrophobic and hydrophilic regions, that have ability to from H-bonds and electrostatic interactions with these types of interactions, are likely to govern the material properties and barrier properties of the salivary films. Therefore, saliva films are essentially dynamic semipermeable barrier systems that, like mucus, enables the exchange of nutrients [159].

One of the major challenges when considering oral processing research is how to evaluate the influence of saliva on sensory perception and in-mouth behaviour of food; there is no fluid that mimics all or even several of the unique physico-chemical properties of saliva [4••]. For this reason many studies rely on the use of whole mouth saliva, but this can be highly variable in terms of composition, abundance and rheology, which makes it difficult to study and incorporate into standard testing procedures and hence care is needed during saliva collection and handling. Stimulated saliva is often used to generate sufficient amounts of saliva for study, but it should be emphasised that there are major rheological and compositional differences between acid and mechanically stimulated saliva [88]. Ex vivo, saliva's physical properties undergo rapid deterioration and so it is essential to use containers that resist protein adsorption and preferably kept on ice for a minimal period of time (minutes) before being used. Freezing and centrifuging cause a severe loss of saliva's viscoelastic properties [117], although its lubrication properties are not significantly affected. Due to these issues, to understand food–saliva interactions it is also necessary to study independently specific properties of saliva: buffering, salt content, amylase solutions and interactions with purified salivary proteins such as mucin (note, the rheology and interfacial properties of mucin solutions do not replicate those of saliva). Such an approach was taken when studying the interaction of saliva with oil-in-water emulsions [155•,157••]. While such studies are time consuming, it is a way to isolate the different factors that may play a role in the changing properties of food during oral processing, but it is also essential to compare model experiments to real saliva.

7. Concluding remarks and outlook

Food oral processing is a highly dynamic process encompassing a collection of sensory features perceived during eating and handling of a food. During eating, an individual sensory feature changes its intensity and accordingly there will be a changing profile of the dominating sensory feature, which reflects the continuous evolution of the food material properties as it undergoes the different unit operations present in oral processing. This dynamic process is directly linked to, or caused by, the changing length-scale of food particles and the length-scale involved in the deformation process that controls a material's mechanical response. Therefore, the textural features sensed at early stages of oral processing are those mostly dominated by bulk phase properties (i.e., *rheology*), whereas those sensed at a later stage of oral processing are related to thin film properties of a product and/or product–saliva combination (i.e., *oral tribology*). Oral processing goes *beyond* when food is swallowed as the sensations experienced affect the flow rate and rheology of saliva, which continues to interact with any residue.

A number of useful techniques and methodologies are being used to tackle how to 'measure' and capture the influence of oral processing of food, including empirical, in vivo and imitative approaches. Since food is structurally and compositionally complex, we favor fundamental in vitro approaches, including consideration of saliva, to capture the underlying physics and determine the physical basis of textural and mouthfeel attributes. However, the insights and hypotheses gained from in vitro studies may be tested using sensory science and/or validation with in-vivo measurements [160•]. For example, Adams et al. [161] demonstrate in-mouth imaging using endoscopic fluorescence to visualize emulsions and residue in situ. In addition, in silica modeling approaches are yet to be developed to any significant extent, which may not be surprising given the complexity of food and oral processing. However, as recently shown [151••,152], relatively simple mass transport models are capable of predicting flavour delivery when saliva dilution is incorporated. Hence we feel that more activity in this area could be pursued.

In recent times, tribology has been seen as a potential tool to uncover and instrumentally measure properties of foods that relate to mouthfeel during oral processing. Significant developments have been made in this field, and thus tribology is providing valuable insights into oral processing and texture/mouthfeel, as we have highlighted here and elsewhere [35••,89••]. However, we caution those seeking to obtain simple correlations between friction coefficient and textural attributes. While simple correlations may exist, the following should be noted: (i) many sensory mouthfeel/textural attributes are multi-modal (e.g., creaminess); (ii) the surfaces used in tribology do not have the same surface chemistry or topology as real oral surfaces; (iii) differences in hydrodynamic conditions exist during tribological measurements and those occurring in mouth; and (iv) different mechanisms affect the friction in the boundary, mixed and hydrodynamic lubrication regimes, thus it is difficult to isolate causality at a single speed; for example, increasing lubricant viscosity decreases friction in the mixed regime and increases it in the hydrodynamic regime. To move towards tribology as a *truly* predictive tool, significant developments are required in each of these areas so that a universal approach is obtained.

In conclusion, we consider that the oral breakdown trajectory can be mapped through 6 stages, which can be captured through a multi-scale approach encompassing rheology and tribology as well as consideration of saliva. The types of insights gained will then provide the rationalisation in terms of product design and functionality, and ultimately lead to new products that are healthy, yet possessing the eating characteristics of current food.

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