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Highlights

- Food design paradigms require solid food oral processing knowledge
- Food structure and oral physiology affect fracture mechanics and particle size
- Saliva and fluid release affect particle interactions, hydration and rheology
- Emerging links between physics and temporal textural percepts
- Mechanistic insight challenged by inter-individual differences in oral physiology

Physics of food structure breakdown and bolus formation during oral processing of hard and soft solids

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Abstract.

Recent studies on the oral processing of hard and soft foods are presented with consideration for the underlying physics involved during the transformation of food to a semifluid bolus for swallowing. Significant insights are being realized about the temporal aspects of the dominant processes of comminution, agglomeration, hydration and dilution, and connections to the dominant textural properties are emerging. The field is still challenged by inter-individual differences in oral physiology, but *in vitro* approaches to characterise the evolution of the food bolus have the potential to provide structure-property-oral processing relationships. Integrated approaches and development of techniques to measure the in-use physics of oral processing are critical for advanced food structure design.

Introduction

The physics associated with the dynamic alteration of food during oral processing is challenging to understand and measure [1]. Fracture mechanics, comminution, particle-particle, particle-saliva and particle-surface interactions, rheology, heat and mass transport mechanisms underlie the transduction of food structure and bolus properties to the temporal sensory perceptions of texture, taste and aroma. These sensory perceptions play a key role in consumer acceptance and liking of food [2], and texture in particular since changes in this attribute for familiar foods are interpreted negatively by consumers [3]. Fracture mechanics and rheology are well used in the rational design of food structure of hard and soft solids foods due to their relevance to product stability and initial texture perception [4**]. This includes measurements on intact foods of viscosity at 50 s^{-1}, hardness, and multiple fracture peaks, which have been related to initial thickness (fluids to soft solids), firmness (soft solids to hard solids) and crispness (brittle solids) perceptions, respectively, via power-law equations [4**-7]. However, it is now realised that texture percepts arising *during* oral processing (i.e. beyond the first-bite) contribute significantly to the consumer experience, including acceptability of healthy food options, yet these percepts are challenging to engineer from a knowledge of intact food structure. This article highlights very recent research concerning oral processing physics of solid (hard and soft) foods and includes commentary on the dynamics of sensory studies, oral physiology, food structure and food-saliva material and interfacial properties. Figure 1 provides a conceptual framework of the dominant physics, sensory and physiological parameters that occur during oral processing of solid food as it is transformed into a swallowable bolus.

Dynamics of Sensory Perception

Quantitative description analysis (QDA) has been used to describe the sensory perception of food and many attempts, of varying success, have been made relating this to food structure [8]. In a recent review, Pascua *et al.* [9**] query whether textural attributes are "evaluated properly with descriptive analysis methods that assign a certain number of chews before scoring the attribute?". The desire to observe changes in sensory perception over time is addressed with techniques such as temporal dominant sensation (TDS) and time intensity (TI) tests, which are recently reviewed [10]. TDS is emerging as a valuable tool to study the dynamics of oral processing and is undergoing constant refinement and enhancement. However, there is a need for adequate numbers of panellists to obtain reliable results from

TDS, and it is noted that TDS increases the oral processing duration and number of chews [11]. In addition, TDS studies that include a dynamic evaluation of consumer liking are found to be more discriminating than classical evaluations of liking [12*].

Attempts are made to mechanistically understand the dynamics of sensory perception during oral processing in relation to the pressures applied on food by the oral physiology using *relatively* non-invasive techniques of electromyography (EMG) and kinematic recordings. These measure jaw muscle activities and jaw displacement during mastication respectively, as recently reviewed by Foegeding *et al.* [13] and Woda *et al.* [14]. These reviews consider the mechanisms for texture perception via oral mechano-receptors, and how mastication is influenced by textural and inter-individual differences in oral physiology.

Of increasing recent interest, and a major challenge in oral processing research, is consideration for saliva's multifaceted dynamic roles [4**,15**]: protecting and lubricating oral surfaces from particle rubbing; promoting aggregation of solid particles via capillary forces (granulation); dispersing particles in a fluid-medium; softening particles via plasticisation, hydration, and solubilisation (including polymers that may be present in the food matrix); and starch digestion. In particular, saliva is stimulated in response to both chemical and mechanical stimuli arising during oral processing, which in itself has been shown to affect sensory properties of beverages [16].

A recent review of the bolus formation process, involving structural degradation and mixing in saliva, is provided by Bornhorst *et al.* [17]. We emphasise that the analysis of the food structures during oral processing is complicated by the concomitant change in particle size, the multiple actions of saliva, and individual differences in oral physiology including saliva's rheology, flow rate and composition [16], chewing behaviour and oral processing time [11]. Samples obtained via chew-and-spit studies are analysed using a variety of techniques and related directly to sensory properties, oral physiology parameters and/or intact food structure and rheology. The instrumental techniques used include Texture Profile Analysis (TPA) [18], rheology and tribology [4**,19], mechanical testing [20] and microscopy [21**]. The challenge when using empirical and somewhat imitative methods such as TPA is that the mechanics of the double-squeeze process are ill-defined, making it difficult to obtain the fundamental insights required for rational design. Increased mechanistic information on the physics governing food structure during oral processing is required to advance the prospect of designing food structures that will behave predictably.

Comminution and fracture mechanics

Recent studies show how the fracture properties of biscuits [22], fruits and vegetables [23] and model gels [24**] and emulsion-filled gels [25*] are related to sensory hardness/crunchiness during mastication. The fracture stress, observed via a three point bend test, correlates with hardness/crunchiness occurring at first bite and the early stages of mastication, while the critical stress intensity, a measure of crack propagation observed via a single edge notched bend test, correlates well with chew-down. This indicates that sensory texture is dependent on the structure of the food material as well as the presence of any structural defects within it.

The influence of intact food hardness, deformability and stickiness of cheese and caramel [26], and model gels [24**], during masticatory action has been quantitatively assessed using EMG and kinematic recording. Increases in hardness led to the cheese and gels requiring longer chewing times in which a greater total muscle force and force-per-chew are observed. Harder gels (those with a greater stress at fracture) require a greater amount of muscle force to be used over a longer period of time, while increases in the deformability (strain at fracture) of the gels produced a smaller increase in the muscle force and chewing time in comparison to the gels varying in stress at fracture but produced a decrease in the amount of 3-dimensional movement of the jaw during mastication [24**]. The increases in the sensory stickiness of caramel also lead to an increase in the total amount of muscle used, but lead to a slower masticatory process which had larger opening and closing strokes [26].

These studies show that the energy of comminution is dependent on the food's mechanical properties and microstructure. This is broadly in line with studies and modelling on the physics of comminution for hard rock-like materials that are well studied in the engineering literature [27]. Therefore, we suggest this comminution energy requirement is related to the observation that the particle size decreases in following comminution of food in mouth as the hardness or modulus of solid food increases [19,28].

The mechanical properties of emulsion filled gels affect chew down, firmness, creaminess and grittiness [25*]. Creaminess and grittiness dominate the latter stages of mastication of the gels, with creaminess enhanced by low stress and high strain at fracture while graininess is present in low fracture strain samples. An empirical approach found correlations between sensory texture and TPA measurements of boli obtained at different stages of oral processing [29]. Sensory firmness is related to fracture stress, while perceived elasticity and stickiness at the middle stages of oral processing are related to TPA measures of 'resilience' and 'adhesiveness'. At the later stages, gels that generated high numbers of fragments and surfaces area correlated with graininess, while creaminess correlated positively with TPA flowability and negatively with generated fragment area. These correlations are not impacted by the presence or absence of a bound oil phase in the samples. Steiger and van de Velde [30**] provide an overview on the role of microstructure of biopolymer composite gels and emulsion-filled gels on flavour perception.

The textures arising from mastication of peanuts varying in their physical form - whole, peanut meal and peanut paste – has been evaluated using TDS [31]. Six sensations described the peanut samples: hardness, crunchiness, chewiness, tooth packing, softness, and stickiness. All of these sensations are observed in whole peanuts, but not the other two forms. Hardness and crunchiness are no longer observed for peanut meal and paste, while tooth-packing and chewiness is not sensed for the paste. Since each of these forms arise during mastication of whole peanuts, this approach provides greater potential to mechanistically understand the physical basis for the sensations in isolation.

The main procedures used to prepare comminuted food, grinding or shredding using household appliances, are problematic as they do not necessarily replicate the oral-comminution process. To combat this issue, several groups have produced mechanical devices to simulate the oral-comminution process, producing particles with similar size distributions to *in vivo* experiments [32,33]. The development of a standard methodology for food comminution using a lab-scale device is highly desirable for both *in vitro* oral processing and digestion studies. The swallowing process of solid foods has received less attention, but a mechanical mimic of esophogeal swallowing using a peristaltic actuator system has recently been developed [34], which is advancing the ability to design foods for those suffering from dysphagia.

Attempts are underway to model oral processing of foods using smoothed particle hydrodynamics in order to simulate the action of the major oral surfaces upon manipulating fluids, brittle foods, elastoplastic foods and elastobrittle foods [35-37]. The models have so far been able to provide a qualitative fit with the comminution of ideal agar gel samples [37], with the insight that the breakdown path of the food is altered by the starting position of the food, which is indicative of a change in the selection function due to food position [28]. Harrison et al. suggest that extending this work beyond comminution to bolus formation is restricted due to the lack of information on the effect of saliva on the mechanical softening and lubrication of food particles, which is complicated by the continual addition of saliva to the oral process [36].

Towards Bolus Formation

The physics of bolus formation is a dynamic process changing from dry comminuted particles which behave as a flowing powder [38] to agglomeration, driven by particle-particle attraction [39] and facilitated by such processes as capillary bridging and depletion flocculation as fluid is released from food and saliva is continually secreted into the mouth. As increasing amounts of saliva are secreted during mastication, a dispersion is created that produces rheological properties which signify a swallowable bolus [15**]. It has been speculated that extensional viscosity is also important to swallowing function [40]. The bolus formation process is uniquely captured by Rodrigues *et al.* [21**] for the mastication of shortbread biscuits, whereby bolus samples are expectorated at different fractions of total mastication time (TMT) to swallow. Bolus samples are not washed in order to measure the particle size distribution of any agglomerates present in the samples. The measured particle size reduces due to comminution until ~30% TMT, after which time the particle size increases due to agglomeration. This change in mechanism corresponds to a moisture content of ~30%, and the biscuit bolus became paste-like when the moisture increases to ~45%; swallowing occurs at ~55% moisture content. Young *et al.* [41*] link the competing comminution-agglomeration processes for biscuits to dynamic sensory profiles using TDS. Initial texture perception depends on the intact biscuit hardness, but texture then becomes dominated by a dry sensation and subsequently a sticky texture at between 60% TMT and the swallowing point (100% TMT). The dry and sticky textures are likely to be due to the changes in saliva addition/absorption as smaller agglomerated particles form a single whole bolus. The dry texture is expected if the rate of saliva production is less than the rate of adsorption into the food bolus/particles, and a depletion of the lubricating salivary film from oral surfaces occurs, while the sticky texture is likely due to the dissolution of polymers which increase the boluses adhesion to oral surfaces. The biscuit boluses flow more easily (assessed using back extrusion) at the swallowing point than at 60% TMT. While there is no significant difference in flowability between different biscuits at 60% TMT, the biscuit boluses made from softer biscuits are more flowable at the swallow point than for other biscuits.

To examine the influence on mastication from the initial moisture content of dutch cake (22% moisture content) and white bread (44% moisture content), Motoi *et al.*[42]] measured the number of chews to swallow, bolus moisture content and amount of saliva absorbed and adhering to food particles at swallow point. They found that increases in starting moisture content lead to a decrease in the number of chews and the amount of saliva added prior to swallowing, as well as an increase in the final moisture content at the point of swallowing for both foods. However, the absolute value for the final bolus moisture content and number of chews differed between bread and dutch cake, highlighting that the properties of the food particles are still relevant to the final swallowing signal despite similarities in moisture content. In contrast, for relatively dry cereals (3.8 – 8.4%), Loret *et al.* [43] found that the initial moisture content did not influence the amount of moisture in the sample at the swallow point (50%).

A significant complication to the study of bolus formation *in vivo/ex vivo* relates to significant inter-individual variability. This is highlighted particularly strongly by Tournier *et al.* [44], who found significant inter-individual differences in the amount of saliva taken up by the bolus following mastication of bread. Mastication (number of chews) and salivation may adapt to the differences in composition and structure of the bread, although in this study it is difficult to distinguish the contributions from bread hardness, moisture content, taste and other parameters. The saliva content and structural homogeneity vary greatly in the swallowable bolus between individuals; the saliva content ranges from 10 to 70%. This is in stark contrast to the relatively similar particle size distributions found in the swallowable bolus from comminution of hard and brittle natural foods such as carrots and nuts [45]. Similarly, large inter-individual differences are found in the rheological properties of cereal boluses, although interestingly these contained similar levels of moisture (~50%) which is speculated to be a marker for swallowing [43]. Inter-individual differences in bolus rheology formed from breads varying in hardness could not be explained by inter-individual differences in the physiological parameters of the panellists, including masticatory efficiency, oral cavity volume, salivary sodium content and salivary α-amylase activity [46**]. Regardless of the individual variability, Panouille *et al* [46**] found that more dense breads were perceived as soft and dense while the high and low fat breads were sensed as hard and chewy at early stages of mastication. Additionally, Pentakäinen et al. [47] found that the total work and work-per-bite required to chew denser rye bread was higher than for wheat bread. At the point of swallow all breads were perceived as hydrated or crumbly and sticky, with the dense bread producing a sticky sensation significantly earlier. Both the storage (G') and loss (G") modulus of all boluses decrease with time as the moisture content increases in all the bread samples. Despite this, the dense bread displayed a lower tanδ (G"/G'), indicating these boluses are more solid-like than the other breads. Panouille *et al.* [46**] speculate this difference in bolus structure is due to the dense bread having approximately twice the density and young's modulus, and we suggest this leads to a higher concentration of total solids per volume of saliva. In addition, differences in bolus rheology may arise from differences in the mechanical properties of the food particles and their ability to absorb saliva and potentially undergo hydration, swelling and/or dissolution. The point in mastication at which both Tournier et al. [44] and Panouille et al. [46**] observe a loss of dominance for hardness-based perception is approximately when agglomeration and pasting is observed to occur by Rodrigues et al., indicating the importance of this rheological transition to temporal aspects of perception.

Physiological differences in chewing, mastication strength, age and salivary flow rate are factors affecting bolus properties, oral processing time and sensory percepts including texture [48-50]. Differences in oral processing behaviour have been used to explain variations in dynamic texture perception between individuals who differ in their 'natural' eating time. Brown et al [51] highlight four different groupings in chewing behaviour, and differences in such aspects as oral processing time are being shown to affect texture perception [52,53]. Jeltema *et al.* [54] suggest the preferred way individuals manipulate food in their mouths is a major driver of texture preference; the individual groupings are categorised as Crunchers, Chewers, Suckers, and Smooshers. One approach to clarify these differences is to segregate individuals on the basis of physiological groups (e.g. salivary flow rate, taster status, chewer-type) and examine how foods are perceived within and between groups. Physical measurements of food structures produced with these physiological differences in mind may enhance the development of causal relationships between an individual's perception and the collective food-material properties.

To avoid inter- and intra-individual differences in chewing behaviour and saliva-secretion, Boehm et al. [55*,56*] form simulated boluses from potato chips (i.e. crisps) using an *in vitro* process of comminution and addition of a physiological buffer (The advantages of an in vitro approach to studying oral processing is reviewed in Stokes *et al.* [15**]). This enabled a quantitative study on the influence of oil/fat of potato chips on bolus rheology. Decreasing oil content has a negligible effect on the fracture properties of potato chips (via a three point bend test) but it increases G' and yield stress of the simulated bolus [55*]. This increase arises from higher solids content per mass of sample, as also shown by Panouille *et al.* [46**], as the fat is lowered since the oil acts as a dispersed filler in the bolus. Rheology is also used to study how the development of the bolus depends on kinetics of hydration and α-amylase digestion by measuring G' with time immediately after mixing the comminuted solids with a buffer and amylase solution respectively. G' of the suspensions increases by orders of magnitude with time due to hydration and swelling of the solids, and this is only partially affected by amylase digestion of starch. The effect of the amylase is well described by the diffusion of water into the dry potato chips allowing the enzymes access [56*]; this approach offers the possibility of modelling water, and eventually saliva, movement within and between particles in the bolus and exemplifies the importance of substrate solubility for α-amylase activity [57]. Hydration is a key rate-determining-step during oral processing of hydratable semi-dry foods, which is also supported by Panouille *et al.* [46**] study on the oral processing of bread.

In vitro processing and measurements that capture the biophysical stages occurring during oral processing avoids the full-complexity of the mouth, and provides a basis for the development of predictable theoretical models. We suggest that an integrated multi-physics computational approach is required to capture the complex processes occuring during food oral processing, but that a universal model is well-beyond current know-how. Coarse grained approaches are usually used to model the mechanical properties of intact foods to their underlying microstructure, and developments in multi-scale modelling [58] and soft matter physics enable their continual improvement. The use of multiscale modelling requires the capability to predict the transformation of food microstructures (see figure 1) through the oral process; this requires a thorough understanding of structural change during comminution, particle agglomeration and hydration on the incorporation of saliva and finally the dilution of a soft-particle suspension. There are relevant models and theories available that use soft matter physics, thermodynamics and mass transport theories to predict hydration processes and swelling/deswelling of porous-particles and microstructures in water for a broad range of food material systems [59-62], and these could be utilised when considering the evolution of food particles in the bolus. The bolus is structurally changing during oral processing which leads to thixotropic rheological properties. There is thus a complex structure-property-processing relationship for boli, and the challenge is exemplified by noting that there are limited models available that can dynamically capture this even for well-designed model (non-food) thixotropic suspensions sheared in a rheometer [63]. Despite this complexity, multi-physics models that incorporate the relevant physics and transport processes for particular food systems are tangible if performed alongside systematic experiments. We suggest that the field needs such approaches in order to rationally design food and engineer particular food textures, and thus go beyond the empiricism common in many food oral processing experiments.

Concluding remarks

In recent years, great strides are being made in developing mechanistic insights into the mastication process. We provide a schematic in Figure 1 of the dominant mechanical, structural, physics, textural and physiological properties of solid foods during mastication. It includes a depiction of the structural changes in the food in terms of particle size and increase in bolus size as food is chewed and saliva secreted into the oral cavity to agglomerate, hydrate and disperse the food particles. These indicate how the solid food-saliva system undergoes a transition from a granular system to a paste-like soft glassy material of food particles in a saliva matrix for swallowing.

Many challenges exist in studying the physics of oral processing. A key observation from the recent literature is that the middle stages of oral processing is still not well understood beyond observations of agglomeration, moisture increases and a sensation of dryness/hydration [41*,44,46]. In the later periods of oral processing, bolus rheology is considered important, but inter-individual differences make it challenging to quantify how it influences sensory perception. There is thus limited mechanistic explanation for attributes such as dryness in the middle stages and stickiness in the latter stages of mastication for both biscuit and breads that form the basis of many recent studies. These attributes play a major role in consumer acceptance of food, and there is aspiration from food manufacturers to rationally design food structure beyond the early stages of oral processing.

Advances in TDS and its utilisation provides the potential to link the dynamic textural changes occurring during oral processing to structural and physical properties of the food and food-bolus. In vitro studies using simulated boluses provide a systematic methodology to connect the physics to food structure, which is essential for rational design, but often lacks validation with findings from *in vivo* chew-and-spit or sensory studies. Greater knowledge on inter-individual differences in oral physiology and how this affects oral processing and sensory perception is still required, as this provides key inputs to a mechanistic understanding of *in vivo / ex vivo* findings and to the development of suitable *in vitro* approaches. In addition, there have so far been limited studies on the physics of oral processing in the context of temporal aroma and taste perceptions, which may also strongly influence physiological responses such as salivary flow rate and rheology. We suggest that further research be performed on developing multi-physics computational models to capture the physics occurring at various stages of oral processing, and preferably in the *first instance* to perform these in combination with well-defined *in vitro* experiments prior to considering predicting outcomes from *in vivo* studies. An integrated approach to studying the physics of oral processing is essential to next generation food structure design.

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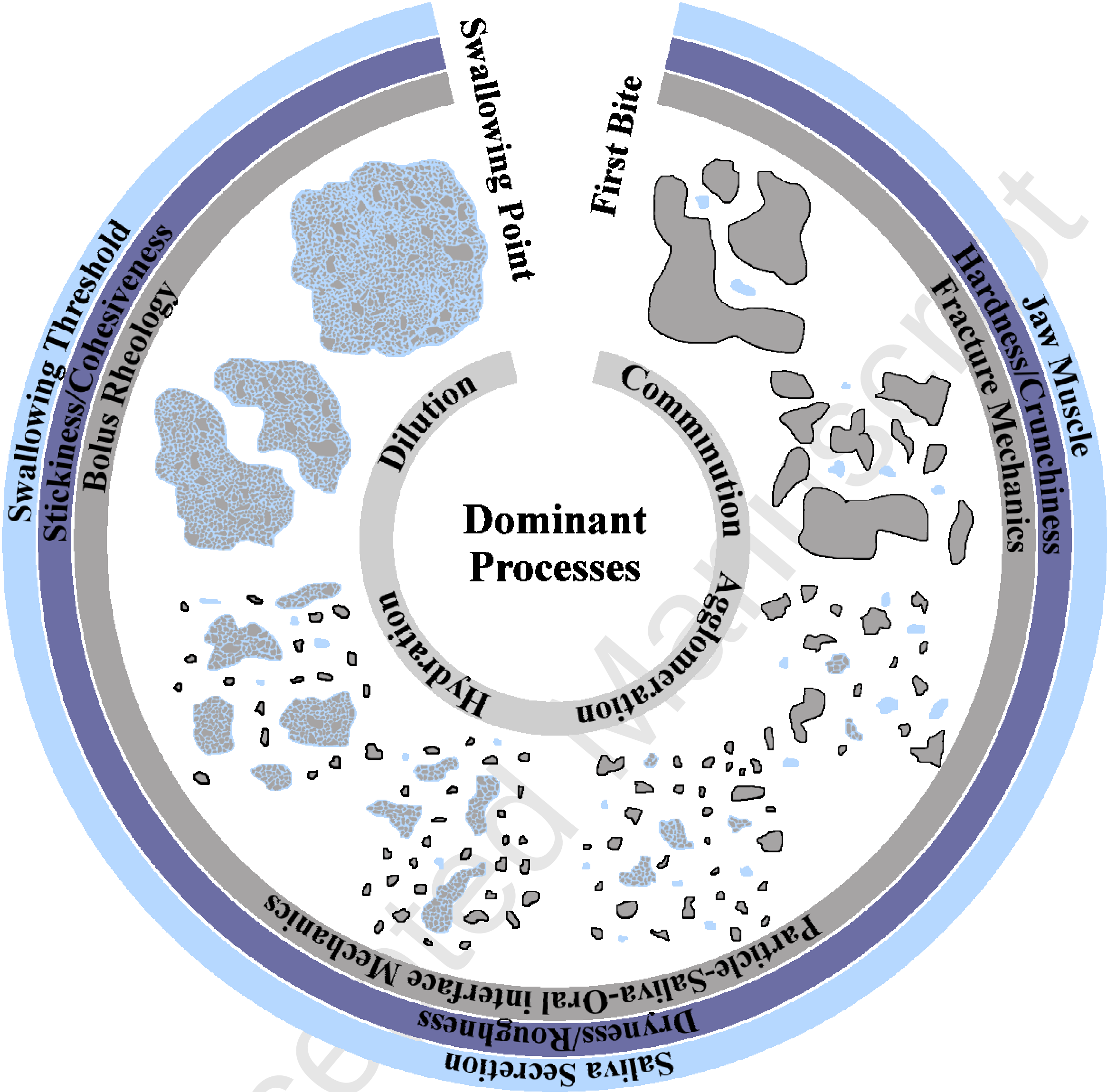

Figure 1: A schematic of the oral processing of a solid food piece from first bite to swallowing point (clockwise direction). The dominant processes are described centrally with hypothetical food-saliva systems, which describe the two concomitant processes of decreasing food particle size from comminution and increasing salivary content. The particle size decreases with time until a 'minimum' size is reached. The addition of saliva is constant with it absorbing/adsorbing to the particles, leading them to swell, soften and agglomerate before becoming a paste (soft glassy material) that dilutes with further ingress of saliva until the 'swallowing threshold'. The oral process can be described temporally by the changes to the: (inner-ring) food physics; (middle-ring) sensorial; and (outer-ring) oral physiological

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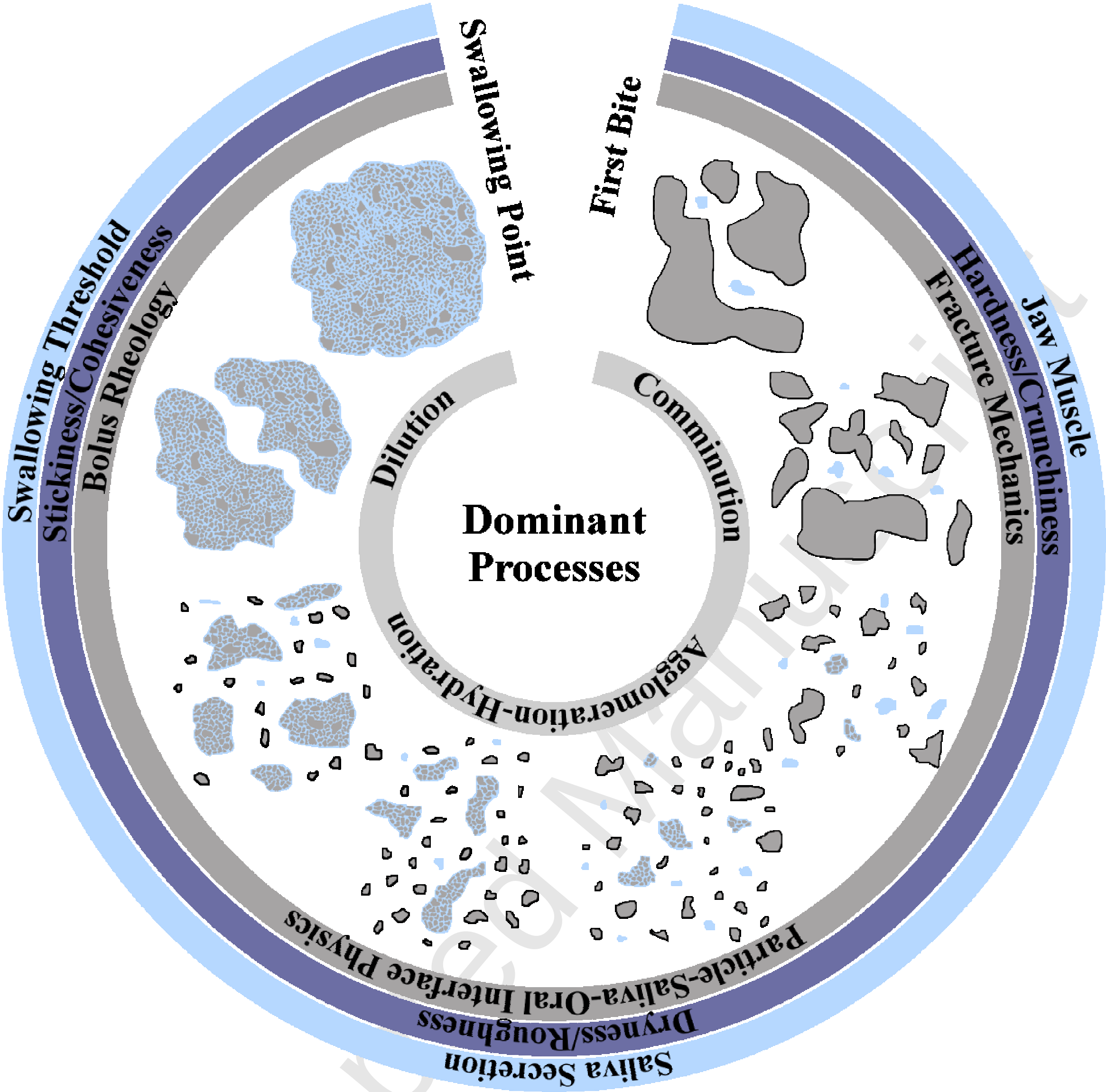

Graphical Abstract