The dynamics of texture perception of hard solid food: a review of the contribution of the Temporal Dominance of Sensations technique

Susana Fiszman* and Amparo Tarrega

*Corresponding author: Susana Fiszman

Email address: sfiszman@iata.csic.es

Running title: TDS and texture

Abstract

The present paper reviews the use of TDS sensory methodology in relation to texture evaluation. From more than 100 papers initially screened, 28 dealing with the texture of hard solid foods that require mastication were selected. The attributes evaluated by TDS were comprehensively analysed and the phases of the mastication period in which they occurred were studied. The relation between these attributes and the initial mechanical food properties, the particle size, shape, and aggregation of the increasingly destroyed food structure, and the evolving properties of the bolus through to swallowing were also examined. Results from complementary techniques used alongside TDS, both sensory and non-sensory, were also analysed. The contribution of TDS methodology to understanding the texture construct is shown to be reliable and suggestions are made for future lines of research.

Keywords: TDS; Dynamics; Texture perception; Oral processing; Masticatory phases

Practical Applications: The literature on the TDS method is constantly increasing. The present review examines the application of this method to the dynamics of texture perception of hard solid foods. The key texture attributes perceived in each phase of mastication, together with their relation to the initial food structure, gradual comminution, and bolus formation, will shed light on the usefulness of this methodology for food texture appraisal.

28 INTRODUCTION

29 Fifteen years ago Alina wrote (Szczesniak, 2002): “the recognition that texture is a multiparameter
30 attribute is reflected in the development of the profiling methodology for both its sensory and
31 instrumental assessment. The dynamic aspects of texture evaluation in the mouth, however, are
32 presently considered seriously only in sensory profiling [...] Without doubt the dynamic aspects of
33 texture assessment should be studied in depth.”

34 These dynamic aspects are related to the transformation that any piece of food undergoes in the
35 mouth, from its initial, solid state (first bite) to a swallowable mass (bolus). Although this process
36 takes only a few seconds, the mouthful of food goes through a series of changes, not only in
37 structure but also in its physicochemical properties.

38 At each instant, throughout an (unconscious) chewing sequence, subjects adapt their oral
39 processing to the properties of the bolus they are forming (Foegeding, Vinyard, Essick, Guest, &
40 Campbell, 2015), which depend on the degree of comminution of the food and their own in-mouth
41 performance (need for insalivation, particle shape and size, etc.). This “breakdown path” in the
42 mouth is characteristic of each food and comprises three dimensions: structure, degree of
43 lubrication, and time (Hutchings & Lillford, 1988). A logical inference from this model is that to
44 appraise the changes taking place on this breakdown path, methods involving time as a variable
45 could make a very useful contribution to building up the texture construct.

46 The “Temporal Dominance of Sensations” (TDS) method is still young, as it was presented for the
47 first time at the 5th Pangborn Sensory Science Symposium (Pineau, Cordelle, & Schlich, 2003).

48 Basically, this method consists in the panellists putting the food sample into their mouths and
49 simultaneously starting the software by clicking on the Start button to start the chronometer, then
50 selecting from a given list the sensation they perceive as dominant at each instant while consuming
51 the sample. The evaluation ends when the panellists click the Stop button, stopping the
52 chronometer. The panellists are free to choose the same attribute for the same sample as often as
53 they think necessary or never to select any particular attribute as dominant.

54 Although TDS was conceived to record the sequential appearance (and intensity) of any sensation
55 that is dominant at any moment of food consumption, including taste, aroma, etc., its value for
56 following the evolution of food texture during mastication became evident. To the best of the
57 present authors’ knowledge, Lenfant, Loret, Pineau, Hartmann and Martin (2009) were the first to
58 apply the method to a hard solid food (breakfast cereals) and record the occurrence of texture

59 attributes over time, making it possible to describe the succession of perceptual events that take
60 place in the mouth during the mastication period.

61 Very recently, Jourden, Saint-Eve, Panouillé, Lejeune, Délérís and Souchon (2016) used several
62 instrumental and sensory techniques, including TDS, to study breads made from the same dough
63 but baked with different processes to obtain crumbs and crusts with different structures. According
64 to these authors, the variations in bolus properties (due to modifications of the bolus structure) had
65 a greater impact than the initial characteristics of the breads on the kinetics of sensory attribute
66 variation during food consumption. This study thus highlighted oral processing as a key process for
67 a better understanding of texture perceptions. However, in the opinion of the present authors, the
68 very first food texture impact in the mouth should also be of major importance, even if it changes
69 one second later, as the first sensory sensations could determine the oral processing strategy to be
70 followed and could constitute an important facet of the complete perception of texture. Following
71 the same reasoning, the texture of the bolus just before swallowing should also have a role,
72 although in this case it would not depend exclusively on the food itself but also on the efficiency of
73 the insalivation and comminution processes.

74 Since the first paper dealing with TDS (Le Révérend, Hidrio, Fernandes & Aubry, 2008), nearly 110
75 more have applied and discussed this temporal method. One group of papers has discussed purely
76 methodological issues, while others have focused exclusively on taste perception.

77 The present work aims to review the contribution of TDS to a deeper understanding of the
78 temporal aspects of food texture as a dynamic sensory attribute. Consequently, only papers dealing
79 with solid food that requires mastication were studied.

80

81 **GENERATION OF TDS ATTRIBUTES**

82 Definition of the attribute list is a key element in TDS performance since it determines the
83 responses of the panellists (Pineau, de Bouillé, Lepage, Lenfant, Schlich, Martin & Rytz, 2012), who
84 continuously have to make a choice among the listed attributes, throughout the evaluation, to
85 determine the sequence of dominant sensations. The authors cited recommend using 8-10
86 attributes to reduce the impact of differences in the panellists' behaviour with regard to the list.

87 Albert, Salvador, Schlich, & Fiszman (2012) commented that it is important for the panel to
88 introduce a sense of temporality into the selection of attributes for use in the TDS sessions). In the
89 opinion of Pineau et al (2012) the training must be oriented towards identifying the different
90 sensory qualities (i.e. the sensory attributes), to improve dominant attribute selection.

91 The samples used in the attribute generation sessions are usually part of the set of samples to be
92 evaluated by TDS. This normally creates a context of unconscious comparison between samples.
93 For example, if one tastes a biscuit with an “extremely” hard first bite there is a logical tendency for
94 “soft” to be elicited by another biscuit that has “normal” hardness but is softer than the first one.
95 This situation habitually favours the elicitation of bipolar sensations (hard/soft, moist/dry, etc.) to
96 include in the list, leading to a blurring effect that the researcher should take into consideration
97 when deciding whether to include one or both poles in the attribute list for evaluation of the
98 complete set of samples.

99 According to Pineau et al. (2012), in a TDS task the assessors are able to assess several modalities
100 (e.g. flavour and texture) simultaneously. Depending on their aim, some studies have evaluated
101 only one modality (for example only taste attributes) and others have evaluated two (for example
102 taste and texture attributes). In the case of two modalities, two separate TDS runs can be made or
103 they can be evaluated simultaneously in the same TDS run. Since 8-10 is normally considered a
104 comfortable number of attributes, separate runs for different modalities could be a good option
105 when the aim is to characterize the sequence of all the sensations elicited by a food product. In the
106 case of more specific aims such as evaluating the appearance of a specific taste sensation (for
107 example salty) in the context of oral destruction of the food, the mixed model would be more
108 appropriate.

109

110 **TDS PROTOCOL: TIME AND PARTICIPANTS**

111 TDS provides information on qualitative changes perceived over time during the eating process
112 (Labbe, Schlich, Pineau, Gilbert, & Martin, 2009). To register the time of consumption, in a number
113 of studies the participants were instructed to click on the “stop” button at the time of principal
114 swallow, but in others they were instructed to click it at the time when no more sensations were
115 perceived. In the latter way, residual sensations after swallowing can also be recorded (mouth
116 coating, perception of residues, etc.) if they are of interest.

117 Taking into account that the duration of mastication differs from one subject to another, Lenfant et
118 al. (2009) proposed standardizing the TDS time when computing the TDS curves, in which case the
119 data from each subject are standardized according to individual mastication durations. Since then,
120 many researchers have adopted this form of time computation. As the real time each participant
121 takes to perform the TDS task is registered, the data can also be used to compare the consumption
122 time of several samples by the same participant, or the consumption time of each sample across

123 the panel (Marcano, Varela, Cunha & Fiszman, 2015), regardless of how time is computed to
124 construct the TDS curves.

125

126 **DYNAMICS OF TEXTURE PERCEPTION ASSESSED BY TDS**

127 Table 1 shows all the TDS-based papers dealing with texture assessment of hard solid food that
128 were analysed in the present review, classified by food category. The categories with the highest
129 numbers of papers were dairy and cereal-based products. Fewer papers dealt with meat products,
130 gels, or other food categories.

131 In the above-mentioned paper by Lenfant et al. (2009), which deals with a hard solid food
132 (breakfast cereals), the TDS results were reported and analysed as comprising three different
133 stages: the “beginning”, “middle”, and “end” of the mastication period. Most subsequent TDS
134 studies have followed the same pattern of analysis. This way of presenting the results was not new.
135 More than 50 years ago, Texture Profile Analysis (Brandt, Skinner & Coleman, 1963) was proposed
136 due to “the necessity to design a sensory procedure whereby the entire texture of a food product
137 could be assessed from first bite through complete mastication”. The same paper stated that
138 because texture follows a definite pattern regarding the order in which texture characteristics are
139 perceived, it should be divided into the *Initial* (first bite), *Masticatory*, and *Residual* phases. This
140 philosophy is not far from current analyses of TDS results, which mostly follow the same phases,
141 studying the 1st, 2nd, and 3rd thirds of the TDS curves, which comprise a complete masticatory
142 cycle.

143 Table 2 shows all the texture attributes recorded in the selected papers, classified by food category
144 and product and by consumption phase.

145

146 *Early stage of mastication*

147 During the first masticatory phase, the terms *Hard*, *Soft*, and *Firm* were found to be dominant in all
148 the hard solid food products analysed except for Emmental cheese, two kinds of biscuits, two kinds
149 of gels, polenta sticks, fish sticks, and one kind of chocolate (Table 2). These attributes correspond
150 to the reaction of the food piece to stress and are normally sensed and measured by the tongue,
151 teeth and palate at the instant of initiating the first bite. After this first sensory impact, the food can
152 undergo high or low breakage (Chen, 2015). The former normally entails a smaller number of
153 chewing cycles to complete an eating process (no matter how hard a food is), as in biscuits, nuts,
154 and certain firm cheeses, while low breakage function is usually associated with fibrous wet solids

155 such as fruits or vegetables, for which no TDS-based papers were found in the texture modality. The
156 breakage function is related to fracture and consequently to the degree of food size reduction
157 (destructive process) (Lucas, Prinz, Agrawal, & Bruce, 2002).

158 *Crispy/ crunchy* were other terms typically found in the first third of the mastication process. For
159 most hard solid products, stiffness and fracture behaviour in relation to water content are essential.
160 Indeed, these attributes were perceived as dominant in the early stage of mastication of some of
161 the foods cited as exceptions to hard/soft/firm dominance: polenta sticks and fish sticks (breaded
162 food), potato crisps, and one kind of dark chocolate (Table 2). For dry cellular solid products
163 (containing only air within their cells) the main factors determining crispness are water content and
164 distribution, and the architecture of the product (van Vliet, van Aken, de Jongh, & Hamer, 2009),
165 while for wet solids (those that contain fluids within their cells) the main factors are the strength,
166 stiffness, size and shape of the cell walls, middle lamellae and fibrous tissues and the turgor
167 pressure of the living cells, which contributes greatly to firmness or rigidity (Varela, Salvador, &
168 Fizman, 2007). Crispy/crunchy food has a characteristic breakage behaviour that is essential for the
169 corresponding sensory sensation. As a result of the resistance and breakage of the food particles,
170 the jaw decelerates and accelerates. These sensations can be prolonged into the second
171 masticatory phase, as occurred in several biscuits, potato crisps, and dark chocolate (Table 2), since
172 these texture attributes depend on new fractures occurring during the more advanced chewing
173 period. It is worth noting that sound (noise) emission was not found as a dominant attribute in any
174 of the papers examined, even though it is a well-recognized texture attribute for crispy/crunchy
175 food. These parameters have been widely studied, probably because although they are easily
176 recognized by consumers (or panel members), their assessment and quantification are very
177 complex.

178 *Brittle* and *Crumbly* were also normally perceived in this early phase of mastication and are strongly
179 related to the way the food is processed in the mouth. With these two attributes, all the food
180 products that were mentioned as exceptions to the hard/soft/firm group have been accounted for
181 (Emmental cheese and the two kinds of biscuits). Both attributes are related to the ease (difficulty)
182 of food fracturing under pressure, the formation of free running cracks during eating, and the
183 number and size of the particles produced. According to Van Vliet et al. (2009), crumbly is among
184 the texture attributes that cannot be related directly to the physical properties of foods. For
185 products showing this attribute, their initial physical and colloid-chemical properties and oral

186 processing must be well understood. This understanding is essential for grasping the interplay
187 between perception, oral physiology and food properties.

188 *Aerated* was also selected in the first step of mastication, but only for bread (Table 2). In this case
189 the product felt full of air, corresponding to an open crumb structure (Jourdain, et al., 2016).

190 Finally, *Elastic/ Springy* were selected for Emmental cheese and various types of gels (Table 2).
191 These attributes referred to the capacity of the piece of food to recover its shape after
192 compression. It is worth noting that they were selected during the early and middle phases of
193 mastication, denoting the persistence of these sensations until the structure of these samples was
194 disrupted.

195

196 Generally speaking, this phase of the mastication process seemed to be governed by the
197 mechanical properties, which in turn depend on the structural architecture of the food. This was
198 true for all the food products studied in the 28 papers analysed, despite their very different nature.

199

200 *Middle stage of mastication*

201 Considering the whole set of papers analysed, the second phase of mastication is the period when
202 more varied attributes were mentioned (Table 2). During this period, particle size reduction and an
203 increased food-saliva contact area predominated.

204 *Moist/ Watery/ Hydrated/* were terms perceived in this middle stage for cheese pie, gels, and
205 bread, whereas *Oily/ Fatty/ Greasy* were selected as dominant for Emmental cheese, sausages,
206 polenta sticks, fish sticks, potato crisps, nuts, and chocolate (Table 2), which are all foods with high
207 oil or fat contents. Not surprisingly, *Juicy* was selected for ham and sausages (Table 2), probably
208 because this term is much used in the meat products field. All the terms mentioned are attributes
209 that are related not only to the total amount of water and fat contained in the food piece but also
210 to the rate and ease with which this liquid phase is released from the food matrix during
211 compression. When detected in the mouth, the liquid gives rise to these sensory sensations.
212 Returning to a previously-mentioned article, Szczesniak (1963) considered water and fat contents,
213 jointly with mechanical and geometrical properties, to be important food characteristics for food
214 texture appraisal.

215 *Dry* was also consistently elicited in this phase of the consumption period. It was selected for all the
216 biscuit samples and for one bread sample (Table 2). Dry products require the addition of enough
217 saliva to form a cohesive bolus suitable for swallowing, and this saliva-requiring sensation is

probably identified as a *Dry* texture perception. Van der Bilt, Engelen, Pereira, van der Glas & Abbink (2006) showed that adding water to a solid dry food like melba toast or cake clearly facilitated chewing but observed no significant influences on perception of the additional water for carrots (90% water) or cheese (35% water and 31% fat). *Dry* was also selected as dominant in the middle stage for gels, nuts, and dark chocolate. Dark chocolate (high cocoa content) is normally perceived as astringent and this sensation can be defined as a “drying sensation in the mouth after tasting, such as after drinking red wine or having chewed grape seeds” (Visalli, Lange, Mallet, Cordelle, & Schlich, 2016), so in this case the dryness could be attributed in part to astringency and the lack of a melting sensation in some samples.

Apart from *Brittle* and *Crumbly*, which in many studies were present in both the early and middle masticatory phases, *Smooth/ Grainy/ Gritty/ Sharp/ Rough/ Coarse/ Homogeneous/ Heterogeneous* is other group of attributes that was present in the second masticatory phase (Table 2). It is related to the perception of the shape and size of the food particles in the mouth and how they are left (loose or clustered). Oral selection is a critically important operation in the processing of solid foods. It ensures that large particles are chosen for further size reduction while small-enough particles are moved to the back of oral cavity for bolus formation. This oral selection is part of the size reduction operation (Chen, 2009).

Dense/ Compact/ Chewy were selected for agar gels, nuts, cured ham, and sausage. This group of attributes is related to the cohesive forces that keep the particles together during the mastication process. Food that elicits these attributes normally requires more laborious and time-consuming chewing (number and force of chews). *Light* was also perceived as dominant in this middle stage of the masticatory cycle, for wafer bars and breakfast cereals (in this case also in the first stage), denoting a perception of (low) density in the mouth (Lenfant et al., 2009).

241

242 *Last stage of mastication*

243 A dominance of *Sticky/ Sticks-to-palate/ Pasty/ Doughy/ Cohesive bolus* as texture perceptions in
244 TDS evaluation was found in all the cereal category products and in Edam cheese, sausages, gel,
245 nuts and chocolate (Table 2). The different nature of these food products shows that during this last
246 phase of the masticatory process, the texture requirements for the bolus to be swallowed are
247 similar. At this stage all kinds of food, whatever their initial structure or composition, should have
248 been transformed into a swallowable bolus. In very few seconds, the hardness of the bolus should
249 decrease rapidly and its adhesiveness and cohesiveness should increase until swallowing takes

place. Bolus properties have been widely investigated in relation to their potential involvement in swallowing initiation (Peyron, Gierczynski, Hartmann, Loret, Dardevet, Martin, & Woda, 2011), among other features. For safe and comfortable swallowing, a certain degree of stickiness and cohesiveness are necessary – besides appropriate rheological properties.

In this last masticatory phase, *Melting/ Fondant/ Easy-to-swallow* perceptions were also found in cheese pie, gels, and chocolate. These attributes accounted for the sensation of the bolus dissolving or disappearing rapidly in the mouth. Indeed, chocolate is taken as reference food to define a *Melty* sensation (“degree to which the sample melts during mastication”) (Tang, Larsen, Ferguson, & James, 2016).

Finally, other textural properties selected in this final phase of mastication were *Mouth coating/ Oily/ Fatty/ Fat mouthcoating/ Covering*. These were selected as dominant in cheese, cheese pie, a kind of biscuit, sausage, nuts, and chocolate, which all contain fat. The sensation that the mouth is covered with an oily or fatty layer depends on how easily the tongue and saliva effect cleansing actions and the degree to which this layer remains in the mouth after-the bolus is swallowed. As mentioned above, the participants can be instructed to click the Stop button when no more sensations are perceived (rather than when swallowing occurs), allowing them to select post-swallowing attribute perceptions.

In short, through real-time monitoring of the texture attributes that panellists or consumers consider relevant during food consumption, the TDS technique confirms and validates Brandt’s 1963 proposal (mentioned above) that all the characteristics of the “entire texture” of a food product from first bite through complete mastication (divided in three phases) should be recorded systematically, using the texture characteristics classification of Szczesniak (1963) and Szczesniak, Brandt, and Friedman (1963).

SCOPE AND SIGNIFICANCE OF TDS IN TEXTURE PERCEPTION

From a physical point of view, a piece of food placed in the mouth follows a logical course from intact to destroyed (bolus). The sequence of texture attributes that appear during this process is thus foreseeable. Certainly the nature of the attributes will change according to the initial food structure and composition, but it can be broadly said that initially the mechanical properties of the food dominate the first phase of mastication, geometry and cohesion between particles (greatly influenced by moisture and fat content and distribution) dominate the central phase of the mastication and, finally, the stickiness of the completely formed bolus is the principal texture

feature of the last phase. At this point it could be claimed that this knowledge is not new. What is new, however, is that TDS shows which attributes are the most salient and predominate over the rest at each moment of food consumption. This does not mean that an attribute with a high dominance rate is necessarily the most intense at that instant but that it is the one that most captures the participants' attention and, in consequence, their perception. This is the principal conceptual idea of the TDS method.

288

RELATION OF TDS WITH OTHER SENSORY TECHNIQUES

Only seven years have passed since the first paper on TDS was published. Considering only papers dealing with texture perception in hard solid foods, many have combined TDS with other sensory techniques (Table 3).

The other sensory methods employed in TDS-based papers comprised: Temporal Check All That Apply (TCATA), Progressive profiling (PP), Time Intensity (TI), Dynamic liking, Consumer acceptance assessment, Quantitative Descriptive Analysis (QDA), Key-attribute sensory profiling (KASP), and Visual aspect of food and bolus characteristics. The first four, like TDS, are temporal methods, so their performance was compared with that of TDS. For example Ares et al. (2015) compared the performance of TDS and TCATA for dynamic sensory characterization of food products. Liking and dynamic liking were not very often measured in the papers analysed, but the appearance and dominance of certain texture features could have a role in liking or rejecting a food product. In Laguna, Varela, Salvador, and Fiszman (2013), a penalty analysis conducted for some biscuit attributes evaluated by just-about-right scales found that "too much" hardness and "too much" dry mouthfeel were the most penalizing attributes, so it could be deduced that an early appearance or a high dominance of these attributes could affect liking. Combining TDS and consumer liking data, Bemfeito, Rodrigues, Silva, and Abreu (2016) inferred that creamy, soft, hard, and firm are positive texture attributes for Minas cheese. However, perhaps due to the different nature of the TDS and liking assessment data, the relation between the two is difficult to study. Finally, some other sensory characterization methods, such as descriptive analysis, have been used to complement TDS. Tang, et al. (2016) used both techniques to distinguish levels of complexity in model foods. Jourden et al. (2016) correlated the sensory PP scores of a trained panel with instrumental mechanical determinations in the intact food products and stated that the TDS and PP results were coherent and complementary. In other papers, TDS and the other sensory techniques were applied to food products with different mechanical properties checked with instrumental measurements of

the samples (Devezeaux de Lavergne, Van Delft, Van de Velde, Van Boekel & Stieger, 2015b). Finally, visual inspection has been used to identify paste-like clumps or large intact biscuit particles in boli at different times of mastication (Young, Cheong, Hedderley, Morgenstern & James, 2013), showing the difficulty of analysing such a highly heterogeneous material.

318

RELATION OF TDS WITH TECHNIQUES FOR PRODUCT, BOLUS, AND SUBJECT CHARACTERIZATION

A larger space than other sensory techniques is occupied by instrumental and other complementary methods applied alongside TDS, undoubtedly linked to the aims of the different studies. A broad classification encompasses initial physical and chemical properties of the food, bolus characteristics, and also some of the physical and physiological characteristics of the participants (Table 3).

325

Food product characterization

Physical properties of the food

The initial and evolving food characteristics measured by the different instrumental techniques can be classified as: a) initial mechanical properties of the food (breakdown test, instrumental Texture Profile Analysis (TPA), penetration test, bending test, fracture test, dynamic oscillatory rheology), b) food composition (fat, salt, moisture and protein content, pH), c) food microstructure, and d) other characteristics such as density, water absorbing capacity, salt release under compression, etc. (Table 3).

The application of all these techniques aims to relate objectively-measured food characteristics to texture attributes. Selecting one or more of these techniques largely depends on the food item and on the aim of each particular study. However, depending on what point of mastication is being considered, the three-step format analysis applies here too.

Results from instrumental texture measurements of the intact food piece will be relevant for the first stage of the masticatory cycle. Penetration, bending, or fracture test values are normally related to the initial food breakdown behaviour and, consequently, to the appearance and dominance of attributes in the 1st third of TDS curves. Cheong, Foster, Morgenstern, Grigor, Bronlund, Hutchings & Hedderley (2014) used a single-edge notched bend test to measure the hardness of biscuits with different fat/sugar ratios subjected to TDS. Equally, TPA measurements of cohesiveness (related to how well the product withstands a second deformation relative to its resistance under the first deformation) could be related to difficulty/ease of chewing and

crumbliness, although no examples analysing this parameter have been found. Finally a dynamic oscillatory parameter ($\tan \delta$) of the food product (soft cheese) has been found to be highly correlated with the rheological parameters of the bolus, but no relation to TDS attributes was established (Saint-Eve, Panouille, Capitaine, Deleris, & Souchon 2015).

Chemical properties of the food product

As stated above, moisture and fat contents and release are directly related to the moist/ hydrated and oily/ fatty/ greasy texture sensations normally perceived in the middle stage of the mastication process. Fat content could also be related to mouth-coating and creamy sensations at the end of the masticatory process and even after swallowing. In addition, the moisture and fat contents can also influence the perceptions of other texture attributes greatly, and their values are normally discussed jointly with other results, not only from TDS but also from other sensory techniques. Deegan et al (2013) associated the high moisture content of Emmental cheese samples to reduced elasticity and increased crumbliness, which, in certain samples, dominated throughout mastication; this is characteristic of longer-ripened cheeses. Along the same lines, the dominance of juiciness in dry-cured ham has been related to fat content by Lorigo Hort, Estévez, & Ventanas (2016), and fat content to lasting perception of oiliness in sausages (Braghieri, Piazzolla, Galgano, Condelli, De Rosa, & Napolitano, 2016). De Loubens, Panouillé, Saint-Eve, Délérís, Tréléa, & Souchon (2011) monitored the kinetics of salt release in the areas of contact during food breakdown and related them to perceptions of saltiness and texture in gels. Structure and geometrical properties studied by microscopy techniques were barely found in papers dealing with TDS in hard solid food. Although it would seem logical to relate some structural features to texture perception, no papers were found that related microstructure to the dominance or appearance of TDS attributes. Some authors did use microstructure results to relate them, for example, to bolus properties, as Saint-Eve et al (2015) did with fat globule size and distribution in soft cheese. Other specific physical and chemical determinations have been made to relate compositional features to the in-mouth food trajectory. Jourden et al (2016) stated that for a soft solid food like bread, the capacity to absorb saliva (measured instrumentally as water-absorbing capacity) modified texture perceptions much more than breakdown of the structure into small particles.

Bolus characterization

377 The characteristics of the boli (Table 3) expectorated at different times and measured by different
378 instrumental techniques help in the interpretation of what is happening in the mouth over the
379 masticatory period. In-mouth food particle reduction, besides its obvious relation to food texture
380 perception, has long been recognised as critical in producing the stimulus marking both the
381 endpoint of mastication and the starting-point of swallowing. Bolus particle characterization
382 (number, size, area, roundness, and distribution) is normally performed to find out how the
383 comminution process evolves over the mastication period and is obviously linked to perceptions of
384 brittleness, crumbliness, grittiness, mealiness, etc. which in turn are dependent on the structure
385 and geometry of the bolus particles. Devezeaux de Lavergne, Derks, Ketel, de Wijk & Stieger
386 (2015a) observed that fewer and larger fragmentations of sausage boli resulted in different TDS
387 texture perceptions during the masticatory phases. Several methods have been used to determine
388 the number of expectorated boli and when to collect them, for instance: fixed times of mastication
389 measured in seconds (Devezeaux et al., 2015b), a percentage of the individual “natural” eating time
390 (Devezeaux et al., 2015a), and visual inspection (Young, Cheong, Foster, Hedderley, Morgenstern, &
391 James, 2016).

392 Compositional factors such as moisture, saliva and fat content, and physical characteristics such as
393 hydration rate, density, mass and volume, also provide information about bolus evolution during
394 oral processing of the food. The role of lubrication due to both saliva and fluids from foods is
395 considered essential and is a further source of sensory information (Hutchings & Lillford, 1988).
396 Saliva (water) incorporation softens the bolus, making in-mouth food handling easier and more
397 comfortable, while insufficient particle hydration gives rise to perceptions of dryness and difficulty
398 in chewing. Alpha-amylase activity has been determined in some cases of studies dealing with
399 starchy food (Jourdren et al., 2016; Panouillé, Saint-Eve, Délérís, Le Bleis, & Souchon, 2014),
400 although no important conclusions were drawn.

401 A number of rheological techniques have been applied to determine how the bolus behaves under
402 physical forces (deformation, shear, etc.); they include penetration behaviour, two-cycle
403 compression behaviour, dynamic oscillatory rheological properties, spreading characteristics, and
404 back-extrusion behaviour. At this point, it should be borne in mind that this sensory information on
405 the state of the bolus at any time in the chewing sequence is not only a matter of “pleasantness”
406 but is also relevant to the decision to either continue mastication for further food transformation,
407 or to stop chewing (Steele & Miller, 2010). Finally, as in the case of the mechanical properties of the
408 intact food, but at later stages of oral processing, food bolus rheology has also been used to

understand the behaviour of the food piece during oral transit. The physical and chemical characteristics of the boli have aided interpretation of the TDS results, principally in relation to the middle and last phases of the masticatory period.

Physical and physiological characteristics of the subjects

Some of the physiological characteristics of the participants that have been considered of interest in the various studies (Table 3) are: masticatory performance (time, number of chews, chewing frequency and efficiency), duration of the masticatory period, stimulated salivary flow, salivary alpha-amylase activity, saliva composition, and oral and pharyngeal volume. All these characteristics have evident relationships to bolus formation and complement the information given by the properties of the bolus itself by accounting for the importance of individual differences when working with human beings. Saint-Eve, et al. (2015) highlighted inter-individual variability by measuring stimulated salivary flow values, masticatory efficiency and oral pharyngeal volume; these authors related bolus properties to some of the physiological characteristics of the participants and found this information to be both complementary and pertinent to describing the dynamics of sensory perception.

Apart from the features just mentioned, other physical measurements have been performed in TDS-based papers, although to a lesser extent. One interesting determination made by Joudren et al. (2016) is in-mouth residue, related to the food mass not recovered from the bolus; although no further conclusion were drawn from these values, it could be of interest to relate them to a secondary swallow need or to texture perceptions generated by food adhesion to teeth, lack of cohesiveness, and difficult handling. Another feature that has been studied is the age of the participants, considered in a number of studies dealing with an age-related dominance of some texture attributes such as stickiness or brittleness (Hutchings, Foster, Grigor, Bronlund, & Morgenstern, 2014b). Masseter muscle activity values (assessed by electromyography) were applied by Devezeaux de Lavergne, et al. (2015a) to measuring the “natural eating time” of the participants in order to personalize the boli collection times.

Finally, states of hunger and thirst have been determined to study the effect of modifying the aftertaste of potato crisps on temporal sensory perception and appetite (Hutchings, Horner, Dible, & Grigor, 2017).

Looking at the complete set of studies, the variety and, in some cases, the specificity of the methods that have been combined with TDS to study the characteristics of both the initial food and the forming bolus show that the dynamics of oral perception have aroused strong interest in recent years. A deeper understanding of texture perception and its relationship with oral processing is one of the factors that have led to TDS application. It has been said a million times that texture is a complex sensory property. Why? Because its perception depends on an organized and efficient ballet (Fizman, 2016) in which almost all the organs of the mouth move in a coordinated fashion in a process involving continuous feedback and the characteristics of the food mouthful and the forming bolus influence their processing (and vice versa) in a dynamic, evolving way. TDS contributes to understanding how the most dominant sensation at each moment influences the entirety of this perception. As stated by Le Révérend, Saucy, Moser & Loret (2016), since eating behaviour is significantly modified during consumption it is of interest to describe how adaptive mastication is to a narrow range of textures. Different foods follow different breakdown pathways during oral processing, depending on their initial structural properties, as dictated by their formulation and manufacturing process. A heterogeneous complex texture such as peanuts (with low and high moisture contents) embedded within two types of food matrices was studied by Hutchings, Foster, Bronlund, Lentle, Jones, & Morgenstern (2011), highlighting the mutual influence of both components on mastication efficiency and bolus properties and the consequent effect on texture perception. The whole picture indicates that it could be possible to design foods for specific populations that cannot accomplish specific oral processing tasks.

CONCLUDING REMARKS AND FUTURE RESEARCH

According to this overview of the texture attributes evaluated in a number of studies covering a series of food categories, TDS effectively collects information on natural dynamic perceptual changes during mastication, giving a more natural representation of sensory perception.

The results confirm that food texture perception is both complex and highly dependent on oral processing. TDS was pertinent, in part, to describe the dynamic perception of texture. A number of complementary properties and characteristics of the food mouthful itself, the forming bolus, and individual physiological human characteristics will contribute to understanding texture perception.

As this perception has a role in human eating behaviour, with obvious physiological and psychological consequences, understanding it paves the way for a number of related issues such as better nutrition for populations with special needs (children, elderly people, people with

472 masticatory deficiencies and other physiological disorders), fat-, sugar-, and salt-reduction in food,
473 fibre-enriched food, functional foods, satiety/ satiation and overweight management, food design,
474 food changes during storage and shelf life, food liking and choice, etc.

475

476 ETHICAL STATEMENTS

477 Conflict of Interest: The authors declare that they do not have any conflict of interest.

478 Ethical Review: This study does not involve any human or animal testing; in consequence no
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480

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