Textural complexity model foods assessed with instrumental and sensory measurements

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Abstract

The term textural complexity is associated with a range of different perceivable textures and sensations occurring from first bite through to swallow. The aim of this study was to develop gel-based model foods with “built-in” levels of textural complexity for use in a wider study of the impact of texture on satiation and satiety. The model foods needed to be quantified for textural complexity and that assessment was conducted using instrumental and sensory measurements. Model foods of different structural complexity (based on inclusions and layers with differing mechanical properties) resulted in puncture curves with differing numbers of peaks caused by the sequential puncture of structural features, and in differing lengths; in general higher complexity led to a greater number of peaks and greater length. Consistent with the definition of textural complexity, more texturally complex samples generated a greater number of descriptors during the “chewdown” phase in descriptive sensory analysis. Temporal Dominance of Sensations analysis gave different information on the dynamics of texture perception during chewing sequence compared to descriptive analysis but confirmed the levels of textural complexity of the model foods. In particular TDS indicates the evolution of the number of textures attributes perceived, and the number of times the dominant texture changed.

Key words: texture complexity, heterogeneous model foods, descriptive analysis, Temporal Dominance of Sensations (TDS), gel
**Practical Applications**

These gel-based model foods with different textural complexity, similar nutritional densities and comparable chewing time can be used for investigating the hypothesised relationship between textural complexity and satiation. The instrumental and sensory tests used in this study proved capable of differentiating levels of textural complexity. The findings of QDA and TDS, and using the number of peaks and length of a puncture curve to quantify textural complexity could be expanded upon in the future to create standardised tests.
1. Introduction

Texture is a key determinant of food product identity and it is connected to the sensations experienced when foods are orally processed. During food consumption, chewing behaviour is continually modified when responding to food texture. Many studies have linked chewing behaviour to texture and used a manipulation of texture to influence oral transit time. This is of particular interest due to the correlation between oral transit time and satiation (Zijlstra et al., 2008; Weijzen et al., 2009; Zijlstra et al., 2009; de Graaf and Kok, 2010; Zijlstra et al., 2010). Current satiation studies have been conducted using liquids and semi-solids (Zijlstra et al., 2008; Weijzen et al., 2009; Zijlstra et al., 2009) though little has been done on the effect of solid food texture on satiation also indicates a link (Hogenkamp et al., 2011; Forde et al., 2013). In each case it is clear that the oral transit time plays a crucial role in the impact of texture on satiation. However, the direct link of texture to satiation is still unclear.

The chewing studies to date predominantly used relatively homogeneous foods to simplify the chewing dynamics. However, the mastication of heterogeneous foods with multiple textures, due to complex structures, occurs on a daily basis. To divorce the influence of texture from the influence of oral transit time, the current study has designed texturally complex foods that have the same oral transit time when eaten normally. The “complexity” was created based on a modification of Mosca et al. (2012b) and Hutchings et al. (2011, 2012), by layering the samples and was further enhanced through embedding inclusions into different layers. Hutchings et al. (2011) indicated that a different type of matrix caused different chewing strategies from first bite to formation of a swallowable bolus, but inclusions did not alter the chewing behaviour even though they varied in their physical properties. The samples of Holm et al. (2009) and Mosca et al. (2010) comprised inhomogeneous distribution of sucrose in layered gels, with a related enhancement of perceived sweetness. Nakao et al. (2013) also found a greater degree of inhomogeneous
aroma distribution caused higher perceived intensity and longer oral transit time. Longer mastication duration and higher intensity of sensory signals are also linked to higher satiation(Blundell et al., 2010; Bolhuis et al., 2011). These findings suggest that foods displaying structural and textural heterogeneity may potentially promote satiation through influencing the oral breakdown process and/ or sensory evaluation process, independent of oral transit time.

To quantify the texture of the samples in this study it was necessary to consider the concept of “textural complexity”, currently a poor defined concept we suggest that it might be defined as “a range of different perceivable textures and sensations that occur from first bite through to swallow”(Larsen et al., 2015). Instrumental measurements coupled with descriptive sensory analysis are increasingly used to quantify food texture. There are continual advances in the instruments and measurement techniques for better assessment of texture properties (Oraguzie et al., 2009; Zdunek et al., 2010a; Zdunek et al., 2010b). The evaluation of texture is a complex process that combine food material properties, food structure and the dynamic process of food breakdown in the mouth(Wilkinson et al., 2000). Of these the food oral processing step is a highly dynamic process, Temporal Dominance of Sensation (TDS) is as such being used with increasing frequency since it gives insight into the most dominant texture attribute at any point of chewing sequences, and how the dominance changes during oral breakdown. Compared to classical sensory profiling methods, TDS can assess texture dynamically and evaluate products with complex sensations(Labbe et al., 2009) and foods with subtle sensory differences(Meillon et al., 2010). Currently, nothing has been reported about instrumental assessment of textural complexity as a food property, and TDS has not been used to quantify complexity directly.

The objective of this study was to develop model foods of varied and controlled structural and textural complexity, in order to determine quantitative instrumental measures of
“complexity” related to sensory assessment. Ultimately, these model foods are part of a wider study on the impact of textural complexity on satiation. This paper presents results related to the quantification of complexity in each context, instrumental and sensory.

2. Materials and Methods

This project was reviewed and approved by the University of Auckland Human Ethics Committee (Reference Number: 9887)

2.1 Model foods – ingredients and preparation

Model foods with five levels of textural complexity were tested; development of these foods and confirmation of their textural complexity is published elsewhere (Larsen et al., 2015). The food matrix was a moderately soft gelatine-agar gel containing layers comprising: harder agar gel, edible chewing gum, a hard brittle disc based on gluten flour. The textural complexity was further increased by embedding particulate components including sunflower seeds and poppy seeds in certain layers. Fig.1 illustrates the five levels of complexity (TC1-TC5: from low to high complexity) and their multi-layer structures, while the formulations of each component are shown in Table 1. The nutritional information of the samples is shown in Table 2.

2.1.1 Ingredients

The ingredients used to prepare samples were: gelatine (250 bloom, Gelita NZ Ltd, Christchurch, New Zealand), powdered agar-agar (Seng Huad Ltd, Thailand), white cane sugar (New Zealand Sugar Ltd, New Zealand), glucose syrup (Queen Fine Food Pty, Queensland, Australia), gluten flour ((Healtheries, Vitaco Health NZ Ltd, New Zealand), critic acid (Hansells Food Group Ltd, Auckland, New Zealand), poppy seeds (Cerebos Gregg’s Ltd, Auckland, New Zealand) and sunflower seeds (Freshlife, Scalzo Food
Industries, Melbourne, Australia). All ingredients were purchased from local supermarkets. AVONSET maize starch was sourced from New Zealand Starch Ltd, Auckland, New Zealand.

2.1.2 Sample preparation

The agar gel, edible chewing gum, hard disc and gelatine-agar encasing mixture gel were made following the protocols outline by Larsen et al. (2015). Molds were used to ensure the sample shape was uniform.

Sample assembly – Figure 1

- TC1: the G-A encasing mixture was poured into the mold filling half its volume and left for 2 minutes at room temperature to firm slightly then a 4 mm thick CD (with ground PS) was placed on top. The G-A encasing mixture was then poured over the top, filling the mold completely.

- TC2: the G-A encasing mixture was poured into the mold at ¼ the depth of the mold with six whole sunflower seeds in it and left to firm slightly for 1 minute at room temperature. A 4 mm thick AD was then placed on top and the G-A encasing mixture was then poured over the top, filling the mold completely.

- TC3: the G-A encasing mixture was poured into the mold at ¼ the depth of the mold with three whole sunflower seeds in it and left to firm slightly for 1 minute at room temperature. Two 2 mm thick CD (with whole PS) with a 2mm thick Ad in the middle created a “sandwich” structure. This “sandwich” was placed into the mold on top and the G-A encasing mixture was then poured over the top, filling the mold completely.

- TC4: the G-A encasing mixture was poured into the mold at ¼ the depth of the mold with three whole sunflower seeds in it and left to firm slightly for 1 minute
at room temperature. A 4 mm thick CD (with whole PS) was placed on top and then another three whole sunflower seeds was placed on top of the CD and the G-A encasing mixture was then poured over the top, filling the mold completely.

- TC5: the G-A encasing mixture was poured into the mold at ¼ the depth of the mold with six whole sunflower seeds in it and left to firm slightly for 1 minute at room temperature. Two 2 mm thick CD (with whole PS) with a 1.5 mm thick HD in the middle created a “sandwich” structure. This “sandwich” was placed into the mold on top and a 2 mm thick AD was then placed on top of the “sandwich”. The G-A encasing mixture was then poured over the top, filling the mold completely.

The samples were left in the molds to set in a refrigerator for 1 hour at 3 °C. They were then popped out and stored in airtight bags at room temperature until required (no longer than 4 hours). Samples were made fresh for all experiments and were always stored for 1 hour prior to testing in a refrigerator at 3 °C and then equilibrated to room temperature for 20 minutes.

### 2.2 Instrumental assessment

The mechanical properties of the model foods were measured using a CT3 texture analyser (Brookfield Engineering Lab, Inc., Middleboro, MA, USA), equipped with a 10 kg load cell. Puncture tests were conducted with a TA9 probe (1.0 mm diameter needle probe, 43 mm long), setting a target deformation of 90% of the sample original height and a test speed of 0.01 mm/s. The target deformation was selected to ensure the probe punctured each layer while the test speed was selected to maximize the sensitivity of probe to changes in the properties of the layers. All samples were tested at room temperature with 15 replicates for each sample.
2.3 Sensory assessment

2.3.1 Descriptive sensory analysis

Based on the definition of textural complexity (Larsen et al., 2015), a descriptive analysis combining the advantages of Quantitative Descriptive Analysis (QDA) and Flash Profile (FP) was used to quantify the “complexity” (Lawless and Heymann, 2010; Larsen et al., 2015).

A total of 20 un-trained male and female panellists were recruited from food science, School of Chemical Science, the University of Auckland. They all had experience in sensory description tests. Exclusion criteria included smoking, dental surgery within the last 3 months, taking medication that affects sense of taste, low sugar diets and allergies to ingredients.

*Descriptive sensory analysis protocol*

The sensory evaluation was carried out in specialised sensory booths, with an environment controlled for noise and climate. A hatch system was used to pass the samples from the preparation area to the panellists. They were instructed to rinse their mouths with water between samples and expectorate into the spittoon. Panellists were allowed to resample during the trial if required.

*Part 1*

All the samples were served in triplicate, with 3-digit codes, in a randomized order between panellists. Panellists were instructed to place the whole sample in their mouth and chew until the point of swallow. During chewing, panellists were asked to write on their score sheet as many texture descriptors they could detect for each sample. Descriptors were tallied and all non-texture descriptors were discarded, the 12 most frequently mentioned descriptors were
selected to proceed to the next part of sensory analysis.

Part 2

All the samples were served in triplicate, with 3-digit codes, in a randomized order between panellists. They were instructed to place the whole sample in their mouth and chew until the point of swallow. During this process, they evaluated the 12 attributes selected from Part 1 in terms of intensity, using a 100 mm line scale anchored with “Not very” and “Very” at the end points.

2.3.2 Chewing time

The panellists (n = 20) that completed the descriptive analysis study, participated in the chewing time evaluation. Panellists placed the whole samples into their mouth, a stopwatch was started as they signalled the initiation of the chewing process and then they continued to chew normally until they signalled they were ready to swallow. The stopwatch was stopped and the panellists expectorated the sample into a spittoon. All the samples were served in triplicate, with 3-digit codes, in a randomized order between panellists.

2.3.3 Temporal Dominance of Sensations (TDS)

Subject selection

Twenty-one panellists (14 females, 7 males, aged 20-35 years) were recruited on the basis of strict dental criteria (Lenfant et al., 2009) to minimize unexpected influence in mastication ability. Inclusion factors were: healthy and complete dentition (except for the third molars), good oral health, no jaw problems, no dentures, no active tooth decay or gum disease and no
orthodontic before experiment. All panellists were regular users of computers (at least 2 hours a day), and had no experience in a TDS trial.

Texture attributes

To ensure good quality TDS data, it is recommended that the attribute list contains a maximum of 8-10 attributes (Pineau et al., 2012). Ten texture attributes were selected in the current study based on the descriptive analysis tests and previous sensory evaluations of the gel-based model foods, using two different techniques – QDA and modified TP(Larsen et al., 2015). Texture definitions were provided to panellists in a table format (Table 3) and reference foods were also available for each attribute used during the training session.

Training session

To ensure full understanding of texture definitions and operation of TDS software, a one-on-one training session was conducted with each panellist. The TDS method was explained, emphasizing two important concepts: dominance and sequence. The most intense attribute at a given point of time was defined as the dominant sensation. The dominant sensation changes naturally over time generating a sequence of sensations. The definition of texture attributes was explained alongside photos of reference foods. Before starting the TDS test, panellists were asked to practise until they were confident in using the computerized system. During the training session panellists were able to ask questions at any time to ensure there was no confusion over the attributes and the operation of the TDS program.

TDS session
Panellists fasted for at least 2 hours prior to the TDS session and it took approximately 20-30 minutes to complete each session. Three replicates of each sample were served in a random order to ensure no prior expectation that would affect the perception of texture (15 samples in total for each panellist).

TDS software (Morgenstern©, The New Zealand Institute for Plant & Food Research Limited) was used to collect data for each sample following the procedure described by Pineau et al. (2009). Panellists clicked the start button when they placed the whole sample in their mouth and then selected the first dominant attribute when it appeared. As soon as the dominant texture changed, they chose a new dominant attribute. This process continued until the main swallow occurred, at which point the panellists clicked the stop button. Between each sample, a 1 minute break was given to take a sip of water. Panellists were advised that they did not have to use all attributes in the list and they could choose the same attribute more than once, and also there was no right and wrong selection.

2.4 Data analysis

2.4.1 Instrumental data analysis

The data recorded by the texture analyzer was distance (mm) and load (g). The percentage distance moved by the probe was calculated using sample height. Puncture curves were generated by plotting deformation (%) against load (g) (Origin 9.1 software, OriginLab Corporation, Northampton, USA). The second derivative puncture curves were created by Origin 9.1 software and the peaks were found automatically by setting a value of threshold height to exclude noise. Image-J software (National Institutes of Health, Bethesda, Maryland, USA) was used to calculate the length of the curves. One-way analysis of variance (ANOVA) with a Tukey post hoc test was conducted using SPSS® version 21.0, (IBM Corporation, USA) at a level of significance of p< 0.05.
2.4.2 Descriptive tests data analysis

All the marks on the line scales were converted into distance (mm) from the left end point of the scale. The distances were used as a measure of intensity. One-way analysis of variance (ANOVA) with a Tukey post hoc test was used to compare differences of the intensity between the attributes at a level of significance of \( p < 0.05 \) (SPSS® version 21.0, IBM Corporation, USA).

2.4.3 Chewing time

The differences of chewing time between the samples were compared by one-way analysis of variance (ANOVA) with a Tukey post hoc test at a level of significance of \( p < 0.05 \) (SPSS® version 21.0, IBM Corporation, USA).

2.4.4 TDS measurement

The TDS software automatically calculated the dominance rates against standardized time following the methods presented by Pineau et al.(2009) and Lenfant et al.(2009). The percentage dominance was calculated from the total number of times an attribute was selected (across all panellists and repetitions) divided by the panel level (panellist × replications). During the TDS test, panellists can only select one attribute from the attribute list at a certain time, hence the dominance rate represents the percentage of population of panellists (across all replicates) selecting a particular attribute. The total duration time was converted to percentage of time from ‘start’ to ‘stop’ for each sequence to generate a standardized time axis.

TDS curves also include a ‘chance line’ and ‘significant line’. The chance line represents the possibility an attribute can be selected by chance. The value, \( P_0 \), is equal to \( 1/P \), \( P \) being the
number of attributes. While the significant line represents the possibility that an attribute is selected is significant higher than chance (P > 0.05) (Meillon et al., 2009).

A Principal Component Analysis was performed on the standardized data (Unscrambler® X software V10.2, CAMO software, Norway) to evaluate the sequential perceptions throughout the entire chewing sequence and to obtain the sensory trajectories of all samples (Lenfant et al., 2009). The loading of the PCA plot were the sensory attributes. Textural complexity samples were plotted over their dominance rates at twenty equally spaced time points, representing 5%, 10%, ..., 100% of the chewing sequence. Sensory trajectories are represented by the lines linking from the first score (t₀) to the last score (t₁₀₀).

3. Results and Discussion

3.1 Textural complexity quantification

Since textural complexity is ill-defined it does not have a standard instrumental measurement method; the puncture test was used in this study to simulate a simplified chewing process between the molars. Samples of differing structural complexity resulted in puncture curves with different number of peaks and different lengths. This was due to sequential puncture and fracture events recorded as the probe contacted differing layers. These sequential events produced curves with numerous peaks and troughs (Fig. 2). The greater the textural complexity, the more peaks and troughs and longer lengths were observed.

As shown in Fig. 2, the appearance of the puncture curves generated from the samples were highly correlated to their structures (Fig. 2 top). The spatial distribution of each inclusion was apparent and the second derivative curves (Fig. 2 bottom) reflect the differing mechanical properties between different components in samples. For example, when the probe punctured
through one component (e.g. soft G-A gel), contacted and started to puncture another different component (e.g. hard sunflower seeds), fluctuations were observed in the second derivative curves (Fig.2B, 2C, 2D, 2E. bottom).

Sample TC1, with a low level of “complexity”, produced a smooth curve without perceptible fracture events (Fig. 2A top), giving a simple horizontal line in the second derivative curve (Fig. 2A bottom). This indicates that mechanical differences between the G-A gel and the CD were not detectable with the puncture tests. The puncture curves of TC2-TC5 have more complex perimeters with a very “jagged” shape with many distinct peaks and overall greater amplitude due to stronger components (Fig.2B, 2C, 2D, 2E). This behaviour commonly occurs in structurally heterogeneous foods with components of differing mechanical properties (Dan et al., 2003; Kohyama et al., 2005).

Due to the similar properties of G-A gel, CD and AD, the puncture curve of TC3 followed a similar pattern to TC2 even though there were two chewy discs on both sides of the AD in TC3 compared to TC2 (Fig.1, Fig.2B, 2C). Unlike TC2 and TC3, TC4 generated a puncture curve with an upward trend after 50% deformation followed by a reduction in load at ~80% deformation, caused by the fracture of sunflower seeds (Fig2D). Similarly, the sunflower seeds, embedded in the first layer of TC2-TC5 samples, fractured at the first 10% deformation during puncture testing (Fig.2B, 2C, 2D, 2E). TC5, the highest level of complexity, produced the most complex puncture curve. The greatest reduction in load was caused by the fracture of the hard disc (at ~58% deformation). The maximum load was reached at ~53% deformation which was where the probe contacted the hard disc and started applying downward force. Cracks appeared on the surface of the hard disc, however, due to its strength and the springy layers of gelatine-agar encasing mixture underneath it, more force had to be applied until the fracture point (~58% deformation) was reached (Fig.2E top). Further fractures were caused by the continuous fracture of the hard disc (Fig2E top). The
small reduction in load at ~25% and ~67% deformation was most likely caused by the chewy
disc (containing whole poppy seeds). As expected, there was no visible fracture point of the
agar disc due to its weak nature.

Since the “structural complexity” is highly correlated with the appearance of puncture curves,
the number of peaks and the length of the puncture curves represent a suitable, if limited,
instrumental proxy for textural complexity. The layering technique and embedded inclusions
varying in their mechanical properties created the diverse range of perceived textures, thus
the greater textural complexity, the greater number of peaks and the longer length of puncture
curve. As shown in Table 4, the number of peaks and the lengths of puncture curves
increased from TC1 to TC5, sample TC5 particularly has significantly greater number of
peaks and longer (p < 0.05) puncture curve compared to the others. Sample TC4 also had a
significant difference (p < 0.05) in the amount of peaks and length of puncture curve
compared to TC1 and TC5. However, puncture curves did not show any significant
differences in number of peaks and length, for samples TC2 and TC3 even though there were
detectable, if subtle differences in sensory assessment of texture. As such the puncture test is
adequate but not quite as discriminating as sensory tests for the quantification of textural
complexity.

3.2 Sensory evaluation

3.2.1 Descriptive sensory analysis: A measure of textural complexity

As defined (Larsen et al., 2015) the “textural complexity” is “a range of different perceivable
textures and sensations during the whole chewing cycle”, the total number of descriptors
gathered from the descriptive analysis showed a clear upward trend from TC1 to TC5
samples (Table 5). The same trend was also observed in the total number of unique
Prior to Part 2 of the descriptive analysis, the 12 most frequently observed texture descriptors were selected to be analysed based on their intensities in the five samples. The mean descriptive analysis intensity scores with standard deviations and results from the post-hoc test of all products and attributes are summarised in Table 6. Across all the samples, there were no significant difference in 5 descriptors – “Floury”, “Springy”, “Gummy”, “Sticky” and “Crumbly”. This can be partly attributed to the gelatine-agar mixture gel which was present in all samples; Studies have shown that most of those attributes can be perceived from gelatine/ mixed gelatine gels (DeMars and Ziegler, 2001; Mosca et al., 2012a; Hutchings et al., 2014). The descriptive analysis results (Table 6) show that sample TC5 was rated to have a significantly greater intensity (p<0.05) than the other samples for 4 out of 12 descriptors – “Hard/firm”, “Crunchy” “Crispy” and “Rough”. In agreement with mechanical tests, the greater firmness/hardness of the TC5 sample can be attributed to the embedded inclusions, especially the hardest component – the hard disc. The difference in the descriptors “Crunchy” and “Crispy” can be attributed to the whole poppy seeds, whole sunflower seeds and the hard disc, which were not present in TC1 samples and thus “Crunchy” and “Crispy” had significantly less (P < 0.05) intensity ratings for TC1 samples (Table 6). The only descriptor for which the TC1 sample was found to have greater intensity than other samples was “Meltability” due to the melting nature of G-A gel (Mosca et al., 2012a). “Chewy” was rated as less intense for the TC2 samples, which comprised only the brittle components (gelatine-agar gel and agar disc) compared to the other samples all of which containing the chewy disc. Unlike TC5 samples, no specific textural descriptors were observed as significantly different in TC2, TC3 and TC4 samples, though significant differences (p <
(0.05) can be identified through pairwise comparisons (Table 6). This is because the formulation of components for the intermediate complexity samples is similar, and they only differ in thickness. However, this subtle difference successfully influenced the intensity of the different textures perceived (and thus the unique distinguishable sensations perceived).

Overall, descriptive analysis tests provided a general understanding for the textural complexity of model foods. The number of unique descriptors for each sample suggests the samples could be distinguished and that differing and distinguishable textures were perceived during consumption, which is consistent with the definition of “textural complexity”. Also, the increasing number of unique descriptors from TC1 to TC5 correlated with the mechanical results indicating that structural and textural complexity increased. However, the information obtained from descriptive analysis was still limited since oral processing is dynamic, hence the need for characterising the samples using a dynamic technique such as Temporal Dominance of Sensations (TDS).

### 3.2.2 TDS: dynamics of texture attribute changes during chewing sequence

The TDS dominance curves show the changes and dominance rate of each attribute during the chewing sequence for each sample type (Fig. 3). Only attributes with dominance rates above the significance line are considered as dominant. A general overview of the TDS curves shows a similar succession of dominant sensations for TC1 and TC2 samples, namely soft at beginning, dry/floury in the middle stage of mastication and melting at the end. The only difference in TC2 samples was that “brittle/crumbly” was also experienced as dominant in the middle stage of mastication, which can be attributed to the brittle component – the agar disc. Sticky, dry/floury and soft were also perceived as dominant sensations close to the end of chewing sequence in TC2 samples. Although TC3 and TC4 followed similar pattern with
hard/firm at the beginning, grainy/rough at various stages (the middle and the end) and melting at the end of mastication, the differences between them were still distinguishable. Specifically, it should be noted that the dominant sensations change frequently during ~20%~50% of the chewing sequence for TC3 and TC4 samples, which was not found in other samples (Fig.3). For TC5 samples, hard/firm was the first selected dominant sensation. Subsequently, crunchy/crispy was selected, followed by brittle/crumbly and then melting was selected with a minimal dominance rate (Fig.3). Melting was the only attribute perceived at the end of mastication for all the samples attributable to the melting nature of gelatine gel.

Throughout the evolution in dominant attributes for all the samples, this TDS assessment is well correlated with the initial structure and the physical breakdown properties of samples. The G-A mixture played a role in timing the release of inclusions and thus specific attributes appearing at certain stage of the chewing sequence. The chewing dynamics (oral breakdown pathway) of heterogeneous model foods has previously been studied (Hutchings et al., 2011, 2012), where researchers hypothesised that the food matrix influenced the selection function. A similar finding arises from the current samples; as the properties of gelatine-agar mixture gel control the release of inclusions during the chewing sequence, larger particles were more easily size selected during chewing, so “Chewy” which can be attributed to the chewy disc and “Brittle” which can be attributed to the agar disc were perceived at the early stage of mastication of TC2, TC3 and TC4 samples. “Grainy/rough” was selected as dominant in the middle and late stage of mastication for TC3, TC4 and TC5 samples which can be attributed to the whole poppy seeds which were not present in TC1 and TC2 samples.

Considering the definition of “textural complexity” (Larsen et al., 2015), the number of perceived textures from first bite to swallow is critical. Descriptive analysis and instrumental measures agreed with the apparent structural complexity of the samples with complexity increasing from TC1 to TC5. TDS also indicated the same trend of “textural complexity” but
only from TC1 to TC4. As shown in Fig.3, the texture attributes changed more frequently and more unique texture attributes were selected as dominant from TC1 to TC4 samples, suggesting more sensory stimulations were perceived and thus greater textural complexity. However, TC5 samples, the higher level of textural complexity, were evaluated with fewer dominant sensations throughout the whole chewing cycle. This can be clarified by combining and comparing the results of descriptive analysis and TDS.

3.2.3 Comparison of descriptive analysis and TDS

Both descriptive analysis and TDS methods could identify the “complexity” of the samples but gave different types of information in terms of the dynamics of texture perception during oral processing. Descriptive analysis encompassed the whole sensory process, from first bite to the point of swallow, freely assessing all the texture attributes and gave insight into many attributes that TDS could not measure. TDS indicated the dominance of attributes appearing dynamically at different stage of mastication. However, TDS only focuses on dominant sensations, thus an attribute with high intensity is more likely perceived by panellists and a higher dominance rate is observed (Meillon et al., 2009).

TC5 samples have significantly greater (p<0.05) intensity in “Hard/firm”, “Crunchy” “Crispy” and “Rough” (Table 6), this increased the likelihood of these four attributes being selected as dominant. The s average intensity (Table 6), coupled with the high number of peaks in the instrumental puncture test, clearly indicate that the components of TC5 impart a high number of intense sensations. Since TDS is a plot of panel consensus intense sensations are more likely to be perceived by a greater number of panellists (Meillon et al., 2009). The dominant attributes changed frequently for TC3 and TC4 samples because the intensity of all 12 attributes was very similar (Table 6). The result was that TC5 had fewer dominant sensations identified throughout TDS but a high number of identified sensations sitting below
the significance line “jockeying for position”. This is an interesting finding for researchers aiming to quantify textural complexity, since strategies have to be developed to account for varying intensity as well as changes in perceived texture.

### 3.2.4 Sensory trajectories

The sensory trajectories, which describes the dynamics of succession of textures experienced in the mouth when the food structure breaks down during chewing process, were calculated following the procedure described by Lenfant et al. (2009), are shown in (Fig.4). The first two PCA components account for 63% of the total variance among the model foods. It can be seen that dominance rates are a dynamic process for all model foods during the chewing sequence. Sensory trajectories of TC1 and TC2 start close to the attributes “springy/gummy” and “chewy/cohesive”, move to “Dry/floury” and “Brittle/crumble” attributes in the middle of chewing, and finish towards “Melting”. The trajectories of TC3 and TC4 follow a different path to TC1 and TC2 but are similar to each other with their succession of dominant sensations: “Chewing/cohesive” and “Crunchy/crispy” at the beginning, and “Melting” in the end. Almost all the attributes in the lower ellipse on the PCA plot (Fig.4) are close to the middle of the trajectories of TC3 and TC4. This indicates texture attributes changed more frequently, and more unique texture attributes were selected as dominant for TC3 and TC4, agreeing with the assessment that more textures were perceived and thus the samples had greater textural complexity (Fig.4, Table 5). TC5 generate a unique trajectory with its starting point close to “Crunchy/crispy” and “Hard/firm”, moving through “Grainy/rough” in the middle and ending towards “Melting”. The oral breakdown pathway of each component in each sample resulted in different sensory trajectories. The most frequently selected attributes are highly correlated to the mechanical properties of the components. As has been shown in previous studies it can be assumed that the food matrix influences the sensory perceptions of the inclusions by controlling their release into the occlusion.
zones (Hutchings et al., 2012); as the texture sensations related to the inclusions were mainly selected in the middle and later stage of chewing sequence.

3.3 Chewing time

A critical aspect of the current study is that chewing time and nutritional density are comparable across all samples when they are later used for satiation tests. Figure 5 shows chewing time when the panellists chewed normally and they were simultaneously completing TDS assessment for all samples. As can be seen in the figure, all samples except TC2 have comparable chewing time to each other when consumers were not conducting TDS. This is somewhat counterintuitive and suggests that chewing time is independent of textural complexity; however, in this instance it is because of the nature of the structural components used to make the model foods. Each model food sample was designed as a single mouthful. The chewing time is strongly influenced by the presence of the chewy disc and the G-A gel. The harder, and more easily fractured components, contribute less to the overall oral breakdown time, whilst their small hard particle size contributes strongly to the number of perceived textures. This is confirmed by the chewing time of sample TC2, the only sample with no chewy disc, which has a significantly shorter chewing time. TC2 will be excluded for later satiation tests; as this model food also had a significantly lower calorie count (Table 5) there are additional reasons to exclude it from any subsequent satiation trials.

The chewing time is strongly influenced when a consumer simultaneously conducts TDS, the unnatural chewing situation, with the consumer concentrating on conducting the TDS at the same time, leads to longer total chewing times. Previous studies (Devezeaux de Lavergne et al., 2015) have also indicated that TDS testing prolonged chewing time as panellists concentrate on the analytical task of sensory evaluation. Not only was this increase observed in the current study, in addition chewing time was longest for TC3 and TC4 samples. Whilst
not specifically the focus of this study it is proposed that this is due to the nature of TDS which requires the subject to make a decision about the dominant attribute and select it on the computer screen, multiple times throughout the test. As explained previously TC3 and TC4 had similar intensity for all textural attributes and the TDS results had numerous shifts of dominance. As such TDS testing of these sample in particular required the consumers to concentrate closely on chewing and selecting attributes.

4. Conclusions

In this study, instrumental and sensory tests were used to assess the textural complexity properties of model foods and it is clear that both have advantages and disadvantages. They give different types of information on the textural complexity properties of samples. Mechanical measurement, descriptive analysis and TDS were all capable of distinguishing between levels of textural complexity that were built-in via structural complexity. The model foods themselves are good samples for controlled textural complexity, the dynamics of the texture attribute changes indicates the gelatine-agar mixture gel is controlling the release of the inclusions and increasing the possibility of perceiving different textures during oral processing. The TDS testing indicated that the intensity of texture attributes can swamp complexity by offering a small number of dominant textures.

Since many studies have identified that oral transit time is an important factor in satiation studies (De Wijk et al., 2008; Mars et al., 2009; Bolhuis et al., 2011; Hogenkamp et al., 2011), it is important that any model foods developed for satiation or satiety studies control for this. The model foods developed in this study have equivalent chewing time to the point of swallow (excluding TC2) and are thus suitable for satiation and satiety trials. As other
researchers have found TDS testing itself prolonged the eating behaviour of some samples and it appears that the increase scales with textural complexity.
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