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The effect of textural complexity of solid foods on satiation

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Abstract

Previous studies have shown that food texture affects satiation by influencing the eating rate, bite size and oral transit time. However, investigations into the direct effect of texture on satiation are limited. The objective of the current study was to investigate the effect of textural complexity on satiation, independent of oral processing time and energy density. A preload-test meal design was used in this study; model foods with three levels of textural complexity (low, medium and high) were consumed as preload foods followed by a two-course ad libitum meal. This study was a randomised cross-over trial with 38 subjects. The results clearly showed that food with greater textural complexity led to significantly lower food intake overall. The first course of the meal and total food intake was significantly reduced (P <0.05) although food intake at the second course did not differ between groups. Despite the differing total intake, all subjects rated to have the same sense of satiety after three hours post-trial and the time taken to the next eating occasion did not differ between different preload conditions. Increased textural complexity in food enhances satiation and may potentially impact on satiety however this needs to be further confirmed in future studies. The findings suggest that foods with more complex textures can be a helpful tool in reducing the short-term food intake and enhancing the satiation response.

Keywords: textural complexity, satiation, satiety, oral transit time, oral processing
1. Introduction

Food texture has been shown to greatly influence the amount of food consumed; food intake of low viscosity foods (e.g. liquid foods) leads to higher intake compared to that of high viscosity foods (e.g. semi-solid foods)\(^1\)\(^-\)\(^4\), for example. However, the underlying mechanisms in the link of texture to satiation are still not well-understood. One possible explanation based on the study of Zijlstra et al.\(^1\) is that texture affects satiation by influencing eating \textit{rate}. It is hypothesized that higher eating rate leads to higher food intake\(^1\),\(^2\),\(^4\)\(^-\)\(^6\). Therefore, the higher intake of liquid foods may be attributable to the higher eating rate compared to consuming semi-solid foods since the differences between food intake of liquid and semi-solid foods disappeared when the eating rates were standardized\(^1\),\(^4\). The effect of eating rate is proposed to mediate food intake through oral exposure to food texture in the oral cavity (oro-sensory exposure). Bite size and oral processing time which determine the oro-sensory exposure, have also been found to influence satiation\(^7\),\(^8\). Most studies investigating the role of texture in satiation have concentrated on food viscosity, or compared different food forms (e.g. liquids vs. semi-solid), yet it is unclear if this hypothesis also applies to solid foods as the evidence available so far is scarce and equivocal. For solid foods, Bolhuis et al.\(^9\) showed that hard foods consumed slowly with smaller bite size and longer oral residence durations resulted in lower total energy intake when compared to soft foods. Conversely, some studies did not find any evidence of changes to satiation from solid foods with differing bite sizes\(^10\), chewing rates\(^11\)\(^-\)\(^13\), or hardness\(^11\). This reveals that the mechanisms behind the effect of texture on satiation in solid foods may be highly complex due to the complexity of the act of chewing itself.

Oral sensory exposure/stimulation may, in part, be the mechanism for appetite suppression\(^14\). It has been shown that orally consumed foods elicited much stronger satiation response
compared to infusion of foods directly in the stomach\textsuperscript{15-17}. A longer oral exposure to sensory receptors may promote the opportunities for sensing the properties of foods. Sensory signals have an early onset during eating and primarily influence satiation\textsuperscript{18}, and this is a learned behaviour from associations to the post-ingestive consequences for humans from early childhood. Therefore, the learned association about the satiating capacity of foods determines the amount of food to be consumed\textsuperscript{19-24}. Differences between satiation for liquid and semi-solid foods can be partly explained by differences in expectations about the satiating capacity generated from these foods. These cognitive factors in the regulation of food intake occur before and during an eating episode and thus monitor the meal size\textsuperscript{25,26}. The texture is considered to play a mainly sensory or cognitive role to regulate food intake during food consumption.

Oral processing is also an essential phase for cephalic phase responses to sensory signals which regulate whether a meal is continued or terminated\textsuperscript{27,28}. A higher intake of rapidly consumed foods may be attributed to a lack of oral sensory stimulation, meaning signals towards satiation do not have time to occur. Longer oral transit times during chewing mean there is more time for the sensory properties of solid foods to be exposed to sensory receptors, work as satiety-relevant sensory cues. Recent advances in brain imaging studies have shown several neural regions interacting with the satiety signals to decide both the quality and quantity of food consumed\textsuperscript{29}.

Until now, it is unknown if texture has a \textit{direct} effect on satiation. The current study has developed gel-based solid model foods, different in textural complexity but equal in nutritional compositions and eating behavioural parameters: oral transit time and chewing rate. This excludes the effect of different oral transit time on satiation. The idea of textural complexity in food is defined as a wide range of different perceivable textures and sensations
that occur from the first bite through to swallow\textsuperscript{30} and it is expected that high complexity will stimulate the senses and increase satiation and/or satiety. The degree of sensory specific satiety (SSS) is also involved in the termination of eating episode. SSS refers to the decline in the pleasantness of a food compared to a different non-consumed food\textsuperscript{31-33}. Consequently, the preload-test meal design was used in this study, that is, a fixed amount of test products are consumed followed by \textit{ad libitum} meal of other food products. Also, a two-course \textit{ad libitum} test meal with different foods was used to eliminate the effect of sensory-specific satiety in this study.

2. Methods

2.1 Subjects

Thirty-eight healthy subjects (16 females, 22 males) were recruited with normal weight (BMI 18.5-25.0 kg/m\textsuperscript{2}) and were aged between 20 and 32 years (mean ± SD: 25.2 ± 3.4) and also liked pasta with tomato sauce. Exclusion criteria include: smoking, diabetes, intolerance or allergy to any of the ingredients, specific dietary requirements (low calorie/low sugar etc.), gained or lost > 5kg weight during the last 2 months, had undergo dental surgery within the last 2 months, appetite loss, appetite affecting medication, stomach/bowel/kidney disease, thyroid disorder, endocrine disorder, being pregnant or breasting feeding. The testing protocol was approved by the University of Auckland Human Participant Ethics Committee (reference number: 012156). Written informed consent was obtained from all subjects. Subjects received a financial compensation after taking all sessions of testing.
2.2 Preloads and test meals

2.2.1 Preloads

Three different model foods of varying textural complexity were developed for this study, and are referred to in this text as low complexity (LC), medium complexity (MC) and high complexity (HC) samples. The “complexity” was created by using a moderately soft gelatine-agar (G-A) gel containing layers comprising: harder agar disc (AD), edible chewy disc (CD) and a hard, brittle disc (HD) based on gluten flour. The complexity can be further increased by embedding particulate components including poppy seeds (PS) and sunflower seeds (SS) in certain layers. These model foods were developed using the same group of ingredients to ensure similar nutritional densities (Table 1) and the layered arrangements are shown in Figure 1.

![Figure 1. Diagrams of LC, MC and HC samples showing layered arrangements.](image)

Key: LC = low complexity, MC = medium complexity, HC = high complexity, G-A = gelatine-agar, CD = chewy disc, PS = poppy seeds, SS = sunflower seeds, AD = agar disc, HD = hard disc.

Note: The colours here are used to identify different layers, the samples were not coloured for the satiation experiments.

Textural complexity was quantified using instrumental measurement (puncture tests) coupled with sensory evaluations (generic descriptive analysis)\textsuperscript{34}. During the puncture tests, the “structural complexity” in the model foods resulted in puncture curves with a different number of peaks and different lengths, due to the sequential puncture and fracture events.
recorded as a cylindrical probe moves through the sample, contacting differing layers. The number of peaks and the length of the puncture curves were used to represent an instrumental proxy for textural complexity (Table 2). Based on the definition of textural complexity we have suggested\textsuperscript{35}, the number of identified unique texture descriptors in descriptive sensory tests also can be considered as a quantitative feature of textural complexity (Table 2).

Table 1 Nutritional composition of LC, MC and HC samples.

<table>
<thead>
<tr>
<th>Nutrition information – gel based model food</th>
<th>Average Quantity per Serving</th>
<th>Average Quantity per gram</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Weight (g)</td>
<td>LC 9.11±0.18, MC 9.39±0.15, HC 9.27±0.12</td>
<td>LC 6.3, MC 6.3, HC 6.5</td>
</tr>
<tr>
<td>Serving Size (piece)</td>
<td>1</td>
<td>0.13, 0.12, 0.13</td>
</tr>
<tr>
<td>Energy (kJ)</td>
<td>57(13.6kcal), 59(14.1kcal), 60(14.3kcal)</td>
<td>0.03, 0.02, 0.01</td>
</tr>
<tr>
<td>Protein (g)</td>
<td>1.2, 1.1, 1.2</td>
<td>0.003, 0.002, 0.002</td>
</tr>
<tr>
<td>Fat, total (g)</td>
<td>0.3, 0.2, 0.1</td>
<td>0.2, 0.2, 0.2</td>
</tr>
<tr>
<td>-saturated (g)</td>
<td>0.0, 0.0, 0.0</td>
<td>0.2, 0.2, 0.2</td>
</tr>
<tr>
<td>Carbohydrate (g)</td>
<td>1.6, 2.0, 2.1</td>
<td>0.2, 0.2, 0.2</td>
</tr>
<tr>
<td>-sugars (g)</td>
<td>1.4, 1.6, 1.6</td>
<td>0.2, 0.2, 0.2</td>
</tr>
<tr>
<td>Sodium (mg)</td>
<td>5, 6, 6</td>
<td>0.6, 0.2, 0.6</td>
</tr>
</tbody>
</table>

Oral processing parameters, including the oral processing time, the total number of chews and chewing frequency were quantified during the chewing cycle. A panel of 20 subjects placed one piece ~10g of the model food into their mouths and oral processing time was measured from the first chew to the point of swallow. The number of chews was counted by the researcher watching for upward vertical lower jaw movement. Samples were served in triplicate, with 3-digit codes, in a randomised order; the detailed methodology of
measurement followed our previous study. The oral processing time, starting from the first chew to the point of swallow, did not differ significantly between the model foods (Table 3).

The preparation of model foods followed the protocols outlined in our previous study. Whilst the foods were isocaloric no particular effort was made to keep the macronutrient composition the same as the concentration of this study was on oral processing time. However, given the acknowledged importance of fibre in satiation the foods were kept as uniform as possible for fibre. The dietary fibre in the model foods is predominantly sourced from the sunflower seeds. All three levels of textural complexity contained the same amount of sunflower seeds but in different forms: LC: ground sunflower seeds; MC: ground sunflower seeds and whole sunflower seeds; HC: whole sunflower seeds. The samples were set in a refrigerator at 3 °C for 1 hour and then stored in airtight bags at room temperature until required (no longer than 4 hours). All samples were made fresh on testing days and were always stored in a refrigerator at 3 °C for 1 hour before testing and then equilibrated to room temperature for at least 20 minutes.

Table 2 Quantifiable differences in textural complexity between LC, MC and HC samples.

<table>
<thead>
<tr>
<th></th>
<th>LC</th>
<th>MC</th>
<th>HC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Puncture tests</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of peaks</td>
<td>$1 \pm 1.3^a$</td>
<td>$5 \pm 3.6^b$</td>
<td>$12 \pm 4.2^c$</td>
</tr>
<tr>
<td>Length of puncture curve (mm)</td>
<td>$425.7 \pm 4.9^a$</td>
<td>$435.1 \pm 3.9^b$</td>
<td>$492.7 \pm 35.9^c$</td>
</tr>
<tr>
<td>QDA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Texture Descriptors</td>
<td>41</td>
<td>55</td>
<td>67</td>
</tr>
<tr>
<td>(Total Unique Descriptors)</td>
<td>18</td>
<td>22</td>
<td>27</td>
</tr>
</tbody>
</table>

Different superscript letters indicate that products are significantly different at $p < 0.05$. 
2.2.2 Test foods

The *ad libitum* test meal was a two-course lunch consisting of penne pasta (Diamond, Wilson food Ltd, Auckland, New Zealand) served in tomato sauce with garlic (Wattie’s, Heinz Wattie’s Ltd, Hastings, New Zealand) and followed by chocolate cake (Countdown, Progressive Enterprises Ltd, Manukau, New Zealand). Pasta was freshly prepared on each testing day by boiling for 11 minutes in salted water (salt: water = 5g/L) and the heated tomato sauce was evenly mixed together with pasta before serving (pasta: sauce = 2.5: 1). The combined pasta and sauce was served at a temperature of 60-65 °C.

*Table 3 Oral parameters (mean ± SD) of LC, MC and HC samples during the chewing cycle (All p-value > 0.05).*

<table>
<thead>
<tr>
<th>Oral parameters of model food</th>
<th>LC</th>
<th>MC</th>
<th>HC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total oral processing time (s)</td>
<td>20.4 ± 5.9</td>
<td>21.4 ± 8.1</td>
<td>22.0 ± 5.8</td>
</tr>
<tr>
<td>Chewing rate (chews/s)</td>
<td>1.7 ± 0.2</td>
<td>1.7 ± 0.2</td>
<td>1.7 ± 0.3</td>
</tr>
<tr>
<td>Chewing rate (chews/gram)</td>
<td>3.8 ± 0.9</td>
<td>3.8 ± 1.0</td>
<td>3.8 ± 0.5</td>
</tr>
<tr>
<td>Total number of chews</td>
<td>34.2 ± 8.4</td>
<td>35.5 ± 9.8</td>
<td>36.0 ± 4.5</td>
</tr>
</tbody>
</table>

2.3 Experiment design

This study was a single-blind, randomized, crossover design consisting of three sessions. The subjects were unaware of their randomized preload sequences, and they participated in three sessions at the same time on the same day of the week for three consecutive weeks, which generated a one-week wash out period between each of the testing sessions.
A preload-test meal design was used to assess the effect of textural complexity on satiation. This is a frequently used experimental design for satiation studies, where subjects consume a fixed amount of the product under study followed by an *ad libitum* meal of another food product after a pre-determined time interval. The effects on subsequent food intake are then observed, which are regarded as the effect of the test food on short-term regulation of food intake (satiation). The model foods of differing textural complexity were consumed as preload foods followed by a two-course *ad libitum* lunch. The amount of *ad libitum* food intake was compared between different preload conditions. Two-course test meals were used to combat sensory specific satiety (SSS). Subjects recorded their subsequent food intake three hours post testing sessions and their dinner time on the testing day. The time interval between the point of lunch termination and dinner is considered as the potential effect of textural complexity on satiety.

**2.4 Testing procedure**

Prior to each testing session, subjects were instructed to fast at least 3 hours (only drinking water). Subjects chose their usual breakfast but were required to consume this exact breakfast at the same time, prior to 9 am, on each testing day to ensure similar initial satiety state.

![Figure 2. Schematic of the experimental procedure.](image-url)
The procedure of each testing session is shown in Figure 2. Subjects arrived at the sensory evaluation laboratory at 12 pm on each testing day. At the start of each testing session, subjects were asked to report the time at which breakfast was consumed, write down the type and amount of foods consumed at breakfast, and also complete the VAS questionnaire for baseline appetite ratings. Then a small portion of model foods (three pieces = ~30g) was served on a small white plate with a fork. Subjects were asked to chew the model foods in their normal way and swallow them when ready. Once they had eaten all model foods, a 10 minutes interval was given before another set of VAS appetite ratings. 125ml water was provided during this period.

After rating appetite, a 500g portion of pasta with tomato sauce was served, and also 125ml water was provided. This amount of pasta had previously been determined to be appropriate. In a smaller study, with an entirely separate panel (n= 26) and only two levels of complexity (LC and HC) pasta was provided in 250 g/ serving and most of the subjects asked for re-fills, but no one consumed in excess 500 g of pasta\textsuperscript{38}. Subjects were instructed to eat as much as they wanted until they felt comfortably full, after which subjects repeated the appetite ratings. A 100g portion of chocolate cake was then served in order to catch anyone who was still hungry and used to combat sensory specific satiety (SSS). At the end of the second meal, subjects were asked to rate their appetite again. Refills were allowed during the meal session, and each course of the meal had to be consumed within 20 minutes. Any leftovers were weighed so that the amount of foods consumed could be calculated.

Finally, subjects left the sensory evaluation laboratory with a post-meal questionnaire, which was a basic food diary in which they recorded the type and amount of foods and/or beverages in the following 3 hours, and a VAS appetite questionnaire completed after 3 hours post-meal. Additionally, subjects were asked to record the time of the next eating occasion (i.e. dinner)
in the food diary. The VAS appetite questionnaire and food diary were returned when the subjects attended their next testing session, and the ratings and diary in final session were scanned and sent by email.

2.5 Data analysis

Statistical analysis was performed using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). Data are presented as mean ± SE, p-values < 0.05 were considered significant.

Effect of textural complexity, testing sessions, the order of preload sequences and their interaction on ad libitum food intakes (pasta intake, cake intake and total intake) were assessed with a mixed linear model that include the random effect of the subject. Least squares means were used for post hoc comparisons for significant effect(s).

Analysis on appetite ratings and durations between lunch and dinner were conducted by one-way ANOVA with a Tukey post hoc test (preload conditions as the independent variable). The differences of appetite ratings between pre- and post-preloads were compared by a paired t-test on each preload condition.

3. Results

3.1 Ad libitum intake

Ad libitum intake of pasta varied significantly depending on the preload conditions ($F_{2.72} = 4.02, p = 0.024$). Post hoc analysis revealed that HC preload condition led to 41.8g ($p < 0.01$) and 29.4g ($p < 0.05$) less pasta intake compared to LC and MC preload conditions respectively (Figure 3). However, the consumption of cake was comparable regardless of
preload conditions (LC: 83.3 ± 4.2g, MC: 82.7 ± 6.7g and HC: 87.4 ± 5.2g, \( p = 0.839 \)). In total, subjects treated by HC preload consumed 37.6g (\( p < 0.05 \)) and 24.6g (\( p = 0.099 \)) less food compared to LC and MC preload conditions (Figure 3). There are no effects of testing period (\( F_{2,72} = 1.835, p = 0.167 \)) and sequence of preloads (\( F_{5,32} = 0.829, p = 0.539 \)) on pasta intake. Similarly, testing period and sequence of preloads did not affect the cake intake (\( F_{2,72} = 0.977, p = 0.381 \); \( F_{5,32} = 0.886, p = 0.502 \)) and total intake (\( F_{2,72} = 1.426, p = 0.247 \); \( F_{5,32} = 0.384, p = 0.856 \)).

![Figure 3. First course meal (pasta) intake (g) and second course meal (cake) intake (g) during lunch time following different textural complexity preload conditions (LC, MC or HC), \( n =38 \) (means ± SE).](image)

### 3.2 Changes in appetite ratings before and after food intake

The appetite ratings (i.e., hunger, fullness, desire to eat and prospective consumption) over the testing period have been shown in Table 4. There were no significant differences observed at all time points (all \( p \)-values > 0.05). The identical initial appetite ratings (\( p > 0.05 \)) indicated
that all subjects were in the same state of satiety before receiving the preloads (Table 4) while the subjects reached the same state of satiety again after ad libitum consumption (Table 4).

**Table 4** Mean appetite ratings (mm) over testing period for subjects eating LC, MC or HC preloads, n = 38 (means ± SE, all p-values > 0.05)

<table>
<thead>
<tr>
<th></th>
<th>N = 38</th>
<th>LC</th>
<th>MC</th>
<th>HC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hunger</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>64.9 ± 3.2</td>
<td>64.4 ± 3.3</td>
<td>65.3 ± 3.4</td>
<td></td>
</tr>
<tr>
<td>Post-preload</td>
<td>61.2 ± 3.2</td>
<td>60.4 ± 3.2</td>
<td>59.8 ± 3.5</td>
<td></td>
</tr>
<tr>
<td>Post-pasta</td>
<td>16.6 ± 2.1</td>
<td>16.3 ± 2.6</td>
<td>15.5 ± 1.7</td>
<td></td>
</tr>
<tr>
<td>Post-cake</td>
<td>5.3 ± 1.1</td>
<td>4.3 ± 1.1</td>
<td>5.0 ± 1.1</td>
<td></td>
</tr>
<tr>
<td><strong>Fullness</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>21.7 ± 2.0</td>
<td>23.8 ± 2.9</td>
<td>22.7 ± 2.9</td>
<td></td>
</tr>
<tr>
<td>Post-preload</td>
<td>24.6 ± 2.1</td>
<td>28.5 ± 2.9</td>
<td>29.2 ± 3.1</td>
<td></td>
</tr>
<tr>
<td>Post-pasta</td>
<td>77.0 ± 2.1</td>
<td>77.8 ± 2.0</td>
<td>78.3 ± 2.0</td>
<td></td>
</tr>
<tr>
<td>Post-cake</td>
<td>86.1 ± 2.2</td>
<td>84.5 ± 2.7</td>
<td>86.9 ± 1.6</td>
<td></td>
</tr>
<tr>
<td><strong>Desire to eat</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>68.3 ± 3.3</td>
<td>65.4 ± 3.3</td>
<td>69.0 ± 3.5</td>
<td></td>
</tr>
<tr>
<td>Post-preload</td>
<td>62.9 ± 3.2</td>
<td>60.0 ± 3.6</td>
<td>62.0 ± 3.8</td>
<td></td>
</tr>
<tr>
<td>Post-pasta</td>
<td>20.2 ± 2.8</td>
<td>21.0 ± 3.5</td>
<td>17.8 ± 1.7</td>
<td></td>
</tr>
<tr>
<td>Post-cake</td>
<td>6.0 ± 1.2</td>
<td>8.4 ± 2.7</td>
<td>6.7 ± 1.3</td>
<td></td>
</tr>
<tr>
<td><strong>Prospective consumption</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>66.7 ± 2.6</td>
<td>63.9 ± 3.1</td>
<td>66.2 ± 3.2</td>
<td></td>
</tr>
<tr>
<td>Post-preload</td>
<td>63.9 ± 2.2</td>
<td>61.4 ± 3.2</td>
<td>63.7 ± 3.5</td>
<td></td>
</tr>
<tr>
<td>Post-pasta</td>
<td>21.7 ± 1.9</td>
<td>18.6 ± 2.5</td>
<td>19.7 ± 1.7</td>
<td></td>
</tr>
<tr>
<td>Post-cake</td>
<td>7.2 ± 1.2</td>
<td>5.9 ± 1.1</td>
<td>7.9 ± 1.4</td>
<td></td>
</tr>
</tbody>
</table>

*Figure 4* shows the changes in appetite ratings before and after intake of preloads, pasta and cake, respectively. Similarly, there were no significant differences observed between three preload conditions (all p-values > 0.05). However, the appetite ratings significantly changed from pre- to post-ad libitum intake (all p-values < 0.05), regardless of the preload conditions. After intake of preloads, the HC preload led to greater decrease in ratings of hunger (p < 0.05).
and desire to eat \((p < 0.001)\), and also correspondingly resulted in greater increase in fullness \((p < 0.01)\) than LC and MC preloads (Figure 4A, 4B and 4C). Similarly, MC preload led to significant increase in fullness \((p < 0.05)\) and decrease in desire to eat \((p < 0.05)\), but the changes were greater than that of LC preload but smaller than that of HC preload (Figure B, 4C). These changes were in line with the amount of *ad libitum* food intake. Interestingly, the changes of prospective consumption were comparable between three preloads \((p > 0.05)\) (Figure 4D). That is, subjects estimating their potential intakes were similar after eating different preloads though less food intake was observed in higher complexity preload conditions.

*Figure 4. Changes in appetite ratings (means ± SE) after intake of preload, pasta and cake \((n=38)\). *, **, ***Significant changes from pre- to post- intake \((*P < 0.05, **P < 0.01, ***P < 0.001)\)*
3.3 Durations between the test meals to the next eating occasion

Most subjects did not consume any foods (except water) during the following three hours post-trial apart from six subjects consumed < 100 kcal foods (i.e. fruit or coffee without milk), therefore their data was kept for analysis (n = 38). The average appetite ratings did not differ (p > 0.05) at the point of three hours post meal regardless of preload conditions. Interestingly, subjects rated their appetite at around 40-50mm of the VAS line scale (total length = 100mm) (Figure 5A), which indicates subjects’ “state of satiety” halved compared to the ratings at the point of satiation. The time intervals observed between the point of satiation and next eating occasion for different preload conditions was around six hours (LC: 5.5 hours, MC: 5.8 hours and HC: 5.7 hours, p > 0.05) (Figure 5B).

![Figure 5](image_url)

*Figure 5. A) Mean appetite ratings three hours testing session and B) Time interval (hours) from the point of satiation to the next eating occasion (i.e. dinner, > 100 kcal), n = 38 (means ± SE)*

4. Discussion

4.1 The role of textural complexity of food in satiation

Results from our present study are the first to show a direct effect of textural complexity on ad libitum food intake/satiation without the potential confounders of chewing rate and oral
transit time. Since previous studies\textsuperscript{4,7,8,39} found a correlation between increased oral transit time and increased satiation, it was crucial to ensure that oral transit time did not vary between the samples used in this current study. Even with equivalent oral transit time, foods with increased textural complexity resulted in a faster satiation response indicated by decreased \textit{ad libitum} food intake.

Oro-sensory stimulation is a necessary step for food intake regulation, as has been shown, feeding with normal oral stimulation compared to feeding the same food without this stimulation (e.g. infusion of food directly in stomach)\textsuperscript{15-17}. Higher intensity of oro-sensory stimulation has been linked to earlier meal termination\textsuperscript{7,40}. The act of chewing (e.g. tongue movement, compressions between molars and food particle size reduction) facilitates sensing of textural properties of foods in contact with the sensory receptors in the oral cavity. In this study, the time taken to breakdown the samples from the first bite to the point of swallow was long enough (with all samples taking \textasciitilde 20s/ piece) to ensure the many different textures could be sensed by subjects\textsuperscript{34,36}. As described in our previous descriptive analysis tests\textsuperscript{34}, more texturally complex model foods were perceived with a greater number of distinguishable textures and rated to have a significantly higher intensity for some of these descriptors during the chewing sequence. The increased number of sensory stimulations, other than texture, have already been linked to a greater satiation response\textsuperscript{41}.

Additionally, higher intensity of oro-sensory stimulation has been studied for salt and sweet foods\textsuperscript{7,40}. Although taste intensity is considered as a predictor of nutrient content, researchers have suggested that increased taste intensity may increase the intensity of stimulation of the oral taste receptors per bite, and ultimately, weaken the response of the taste receptors after continuous exposure, and then caused oral sensory satisfaction\textsuperscript{40,42}. Therefore, it can be proposed that multiple textures, with high perceived intensity, may initially enhance the
stimulation of sensory receptors but ultimately lead to sensory fatigue that accelerates satiation.

Furthermore, a high intensity of oro-sensory stimulation may facilitate the cognitive association between sensory signals and metabolic consequences. Textural complexity has recently linked to expected satiation; higher textural complexity in food generated greater expectation about its satiating capacity. Visual cues coupled with the diverse range of distinguishable textures perceived from the high complexity preload food in this study may enhance the expectations of its satiating capacity. As explained in Blundell’s description of the “satiety cascade”, these learned associations have an early onset during an eating episode and primarily influence satiation.

The sensory signals generated from the texturally complex foods would also have been involved in the cephalic phase response. These sensory signals convert into reward signals in the brain during consumption, which control food intake, and will finally be overruled to bring a meal to an end. Recent advances in functional magnetic resonance imaging (fMRI) have shown that several neural regions of the brain interact with both short- and long-term satiety signals to influence both quality and quantity of food consumed. These studies have shown it takes time for neuro-feedback to register during eating, hence the 10 minutes provided between preloads and test meal in the current study.

An encouraging finding of this current study, in the wider context of obesity control, is that subjects estimated they would consume a similar amount of food regardless of preload conditions, before ad libitum food intake, implying that they did not consciously sense a greater or lesser hunger. However, those treated with the higher level of textural complexity preloads consumed less ad libitum food before finally reaching the same state of satiety.
compared to those treated with other preload conditions. This indicates a sub-conscious impact of the textural complexity on satiation.

4.2 Potential effect of textural complexity on satiety

In this study, textural complexity may potentially have been shown to have an effect on satiety, though this was not the main focus of the study. As suggested by the “satiety cascade” textural complexity, might be expected to mainly play a role associated only with satiation, whilst satiety is mainly driven by post-ingestion processes. The subjects in this study who consumed less ad libitum (following the higher textural complexity preloads) might be predicted to experience lower levels of satiety. However, all subjects had the same sense of satiety after three hours post-trial and the time taken to the next eating occasion did not differ between different preload conditions. This suggests higher levels of textural complexity may have impacts on post-ingestion or post-absorption processes – indicated in this instance as slowing the feeling of hunger. However, this study focused on effects of textural complexity on the short-term food regulation, and satiety was not measured directly.

4.3 Sensory-specific satiation (SSS)

Another crucial factor when measuring satiation is the effect of sensory-specific satiation (SSS), which is a mechanism of satiation that associates with declining pleasantness of a consumed food compared to a different, non-consumed, food. Studies of SSS have shown that the pleasantness of a food starts to decline immediately after the first intake and decreases continuously over the eating episode, finally bringing the meal to an end. As a result, due to the boredom of consuming the same food, subjects may terminate their eating earlier than when they were really full.
To combat SSS, the testing protocol in this study was based on the preload-test meal design. More importantly, the test protocol used a two-course *ad libitum* meal. The idea of a second course, with different sensory properties to the first, was designed to observe if there were any subjects that were still hungry after first meal but stopped their eating because they felt bored eating the same food. Previous studies using two-course test meals found a tendency for subjects to terminate the first course earlier in order to switch to dessert\textsuperscript{48,49}, which was not observed in the current study. When offering the second course, all subjects, regardless of preload conditions, continued eating although they had indicated they were full before the second course was served. It has been well reported that meal variety increases food intake\textsuperscript{50-52}. However, the results did show a “slowing down” in eating amount as nobody consumed a large amount of the second meal (no more than 100g). Additionally, all subjects consumed a similar amount regardless of preload conditions. This partly supported that all subjects reached the same state of satiation after the first course, which is in line with the appetite rating. Subjects continued eating probably due to “hedonic hunger” rather than homeostatic hunger\textsuperscript{53} as a different non-consumed food was more attractive. Additionally, after the second course, subjects rated their appetite very close to the end point of the VAS line, regarded as the extreme answer to the questions (i.e. extremely full, not hungry at all, etc.), which suggested subjects were “comfortably full” after the first course.

5. Conclusions

Varying textural complexity in solid foods led to significant differences in the satiation response as measured by food intake and appetite questionnaires. The impact appears to scale with the level of textural complexity; the more highly complex textured preload foods in this study led to faster satiation than the medium complexity and those to faster satiation than the low complexity preloads. This impact is a direct effect of texture independent of oral transit
time and energy density. It can be proposed that the higher level of textural complexity may facilitate the “sensory-learning-neural” response towards satiation through enhancing the oro-sensory stimulation.
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References


Highlights

- Increased textural complexity in solid food directly enhances satiation, independent of oral transit time and energy density
- More texturally complex preload results in significant reduction in the first course of an ad libitum meal, and total food intake
- Satiety is potentially impacted by the textural complexity in food
- A two course ad libitum meal was designed and shown useful in combatting sensory specific satiety (SSS) in test meals.