Increased textural complexity in food enhances satiation

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Abstract

For the first time this study has shown a direct effect of food textural complexity on satiation. Independent of oral processing time, increasing the textural complexity of a food significantly decreased food intake. Foods with complex textures stimulate many sensory perceptions during oral processing, with a succession of textures perceived between first bite and swallow. Previously the impact of texture on satiation (commonly tested by increasing viscosities of semi-solids) has been explained by texture's influence on oral processing time; a long oral processing time enhances satiation. The results of the current study show that subjects in a randomised cross-over trial who consumed a "starter" (preload) model food with high textural complexity went on to eat significantly less of a two course *ad libitum* meal. Subjects who consumed a "starter" model food with low textural complexity, but with the same flavour, energy density and oral processing time, ate significantly more of the same *ad libitum* meal. The results show that increasing the number of textures perceived during chewing of a solid food triggers the satiation response earlier than when chewing a less texturally complex food. Increasing textural complexity of manufactured foods, to allow for greater sensory stimulation per bite, could potentially be used as a tool to enhance the satiation response and decrease food intake.

Keywords

Food texture; Oral processing; Satiation; Textural complexity; Chewing time; Food oral breakdown; Food structure

Introduction

Food texture is as critical in the perception and enjoyment of food quality as taste, and has a direct impact on the manner in which consumers chew and swallow[1]. Mastication and oral processing parameters such as number of chews, chewing frequency, tongue movement and muscle activity are influenced by, and in turn influence, the perception of food texture[2-6].

There is much evidence to suggest a link between the sensory aspects of food (both flavour and texture) to satiety and satiation effects. Food variability, in terms of flavour, has been related to “sensory specific satiety” by numerous studies[7-9] and there is emerging evidence that the textural attributes of foods also play an essential role[10]. These effects have been most widely studied in liquid and semi-solid foods [11-14] but new possibilities are offered by the exploration of the impact of the texture of solid foods, so far only explored by a small number of research groups[15]. Several studies have investigated the form in which a food is consumed in terms of liquid or solid, finding that the form of a food influences the amount eaten[16-19] Simply increasing the number of chews has been shown to decrease *ad libitum* food intake[20]. This growing body of evidence generally concludes that longer oral processing times promote earlier satiation[21-24].

Textural *complexity* is a relatively new concept in the study of oral processing and can be related to the number and dynamic progression of individual textures perceived from the first bite, through mastication, to the point of swallow[25,26]. Textural complexity has recently been linked to *expected* satiation[27] but to date no-one has shown a link of texture or textural complexity to satiation independent of oral transit time.

The hypothesis of our current investigation was that the additional sensory stimulation during mastication of texturally complex foods makes a significant contribution to the satiation response, *independent* of oral processing time. Isolating every aspect that contributes to satiation would require control for (at least): composition (macro and micro-nutrient), energy density, structure, sensory properties (flavour, aroma, texture, “mouthfeel”)[28], oral transit time, number of chews, and hedonic response[29] . In the current study we controlled for energy density, flavour and, in particular, oral transit time. The number of chews was not significantly different between the model foods either. However, we did not attempt to control for macronutrient composition. Recent progress by other groups on manipulating texture whilst keeping macronutrient content identical has been made and offers an exciting avenue for future work[30].

Methods and Materials

To test the hypothesis, model foods of varying textural complexity (high complexity, HC and low complexity, LC) but equivalent energy, flavour and oral processing time, were developed. These were manufactured as small mouthful size pieces and used as preload foods followed by *ad libitum* meals to test satiation. Questionnaires related to appetite and desire to eat were used at points throughout testing and responses collected on visual analogue scales. This allowed assessment of subjects own perception of hunger and comparison to their behaviour during satiation testing with a two course *ad libitum* meal (pasta and sauce, followed by chocolate cake) where meal termination was quantified with respect to weight of food consumed.

Model foods

A low complexity and a high complexity model food of comparable nutritional density were produced following the methodology described in detail in Larsen *et al*[26] and summarised here. The basis of each model food was a gelatine-agar gel mixture enclosing various layered and particulate inclusions, added to create different levels of textural complexity through different sensory attributes . The LC samples comprised homogeneous gelatine and agar with a dispersion of finely ground poppy and sunflower seeds. The HC samples comprised layers of gelatine-agar gel encasing (top to bottom) a disc of firm agar gel, a hard disc of dried gluten dough between two “chewy” discs of an edible chewing gum and a layer of whole sunflower seeds (Figure 1). The model foods were iso-caloric and created as small mouthful size pieces of approximately 8g and 50kJ. Several flavourings were trialled in developing the model foods and it was determined by the researchers that a a faint citrus flavour successfully disguised any flavour differences between the samples. As flavour was not a focus of this study flavour was not explicitly explored with the test subjects.

Textural complexity was quantified using sensory evaluation, a generic Quantitative Descriptive Analysis (QDA), modified Texture Profiling (TP)[25] and Temporal Dominance of Sensations (TDS)[31]. Oral processing parameters, including number of chews, chewing frequency and oral processing time was quantified at 5 points during the chewing cycle (20%, 40%, 60%, 80% and 100% being the point of swallow). Critically, total chewing time to the point of swallow did not differ significantly between the model foods (approximately 17seconds)[25] . This time was measured by direct observation of subjects chewing the model foods, during a separate evaluation (ie not simultaneously with the satiation tests).

Satiation Test - Subjects

The University of Auckland Human Participant Ethics Committee (UAHPEC) granted ethical approval for a period of 3 years to conduct the satiation tests. The test was a randomised cross-over trial with each panellist eating each preload model food in a randomised order. A total of 31 untrained male and female subjects were recruited with the following exclusion criteria; smoking, dental surgery within the last 3 months, taking medication that affects sense of taste, low sugar diets and allergies to ingredients. A further exclusion criterion was BMI, participants calculated their own BMI and indicated the range in which their BMI fell at the first testing session. To avoid the perception of discrimination based on body image or mass all participants were allowed to take part in the trial, but the data from any participant with a BMI falling outside the healthy range was excluded during data analysis. This led to an effective panel of 26 subjects.

The appetite evaluation, and satiation testing, was carried out in isolation in specialised sensory booths. A questionnaire was used with questions and 10cm visual analogue scale (VAS) lines anchored as shown in Table 1. This appetite questionnaire (with the same questions) was repeated five times throughout the satiation testing (referred to as Q1-Q5).

Table 1: Questionnaire questions and VAS anchor points

Question	**Low Anchor**	**High Anchor**
How hungry are you?	Not at all	Extremely hungry/As hungry as I have ever been
How strong is your desire to eat?	Very Weak/Extremely low	Extremely high/Extremely strong
How full are you?	Not at all	Extremely full/As full as I have ever been
How much do you think you could (or want to) eat right now?	Nothing at all	A very large amount

Satiation test - Schedule

The satiation testing progressed by the following schedule:

- Fasted subjects rate appetite on appetite questionnaire (Q1)
- Consume preload (model food).
- Subjects rate appetite (Q2)
- Consume first course *ad libitum* meal
- Subjects rate appetite (Q3)
- Consume second course *ad libitum* meal
- Subjects rate appetite (Q4)
- Subjects leave testing area, complete food diary for 3 hours.
- At end of 3 hours, subjects rate appetite (Q5) and note time of next major meal.

Satiation test - Protocol

Subjects were instructed to eat their normal breakfast to allow 3 hours of fasting before the test meals. Fasting time was selected based on other studies which used fasting times from 0-4 hours[19, 32-34]; 3 hours being a typical, but not excessive, elapsed period between breakfast and lunch. Test meals were administered at the same time of day (either 12pm or 1pm) for each subject, with each subject timing their last major meal (breakfast) accordingly. For each subject a wash-out period of a minimum of 3 days was allowed between testing sessions.

The test protocol coupled a preload with a two course *ad libitum* meal to combat sensory specific satiety. Rarely is a second course offered in *ad libitum* meal testing but this worked well in the current study to ensure participants had not simply stopped eating due to feeling bored with the first course.

Preload

Subjects were randomly assigned 4 pieces of either the LC or the HC model food at random and they consumed all the pieces within 10 minutes, 250 mL of tap water was provided if required. Subjects indicated when they had finished, waited 10 minutes and then filled out an appetite questionnaire (Q2).

Ad libitum meal, course 1

The first *ad libitum* course consisted of pre-weighed (250 g) servings of pasta in tomato sauce (2406kJ/serve). Subjects were given 20 minutes in which to finish this course, they were allowed as many refills as they liked until they were completely and comfortably full. They could stop eating, or decline the further servings if they could not eat any more. Approximately half of participants requested a second serving. Tap water (250 mL) was provided. After indicating they were finished, the subjects waited 10 minutes before filling out the next appetite questionnaire (Q3). The amount of food leftover (if any) was weighed to calculate the total amount consumed. After the 5 minutes of allotted time to fill out Q3, the subjects were given the next course.

Ad libitum meal, course 2

The second *ad libitum* course consisted of pre-weighed (100 g) servings of chocolate cake with chocolate icing (1182 KJ/serve). Subjects could ask for further servings and only stopped eating when they were completely full. Tap water was provided (250 mL) and this course had to be consumed within 20 minutes. After finishing, subjects waited 10 minutes and filled out the next appetite questionnaire (Q4). The amount of food leftover (if any) was weighed to calculate the total amount consumed.

Post-test

Subjects were given a take-home food diary in which they noted the time, amount and type of all food or drink consumed for 3 hours after the test. After this time, the subjects filled out the last appetite questionnaire (Q5). They also sent a text message to the researchers indicating when they had their next major meal (e.g. dinner).

The whole satiation test was repeated on a different day with subjects receiving the alternate preload to that they had consumed previously.

NB. A small pilot test was conducted on 6 subjects prior to the main satiation testing. These subjects undertook the full satiation test having the HC preload in triplicate and the LC preload in triplicate. There were no significant differences between the amounts of *ad libitum* meal(s) consumed within data of the same preload group ($p > 0.05$) (data not shown).

Statistical analysis

All data were checked for normality using the Shapiro-Wilk test with a level of significance of $p < 0.05$. A repeated measures ANOVA was conducted for the meal consumption data. The level of significance was set at $p < 0.05$. All statistical analysis was performed in R (R Development Core Team. 2011) using the aov function for ANOVA analysis and the Shapiro Wilk function. Analysis on appetite ratings conducted using 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.

Results and Discussion

The results show that the HC preload group consumed a significantly lower amount of food ($p < 0.01$) for the first course of the *ad libitum* meal (pasta and sauce) than the LC preload group (Figure 3). The difference in consumed weight equated to 156.6 g or approximately 1507 kJ. This coincides with the prediction of the preceding appetite questionnaire (Q2) and reinforces the suggestion that the satiation process (to some extent) was progressing. However, the next appetite questionnaire (Q3) did not reflect any difference between the LC and HC groups (Figure 2), indicating that both groups felt equally sated.

There was no significant difference between the LC and HC groups ($p = 0.08$) in the total weight of food consumed during the second course of the *ad libitum* meal (chocolate cake). This was corroborated by Q4 (Figure 2), which again showed no significant differences in appetite ratings ($p > 0.05$).

Prior to the satiation test, fasted subjects showed no significant differences in their responses to the questions from the first appetite questionnaire (Q1) "how hungry are you?", "how full are you?" and "how much do you think you could (or want to) eat right now?" (Figure 2). However, the group who were to go on to consume the low complexity (LC) preload gave a significantly higher rating to the question "how strong is your desire to eat?", than the high complexity (HC) preload group ($p < 0.05$). It is unclear why this occurred, as all subjects had fasted for the same length of time prior to filling out Q1.

Figure 2 shows that after the preload (model food consumption), the appetite ratings (Q2) showed no significant differences between the LC and HC preload groups for "hunger" or "how much subjects wanted to eat" but there was a significant ($p < 0.05$) decrease in the "desire to eat" and increase in "fullness" for the HC group. This suggests that the higher textural complexity in the HC samples may already have been influencing the satiation process, starting to give subjects the notion that they didn't want to eat as much in the following meals, despite having consumed an isocaloric preload to the LC samples.

The results show a slowing down in eating amount during the second course, as the average weight consumed was only 105g and 132.3g for the HC and LC groups respectively. This observation might draw into question the effectiveness of a one course *ad libitum* test, as sensory fatigue, rather than complete satiation, could be playing a greater role than initially thought in meal termination. In the current study the second course was designed to have completely different sensory properties to the first to combat any sensory fatigue or sensory specific satiety (SSS). In some cases SSS has been noticed as early as 2 minutes after an *ad libitum* intake and prior to food entering the intestinal tract and absorption[35-37].

However, the Q4 ratings all approached the extreme end of the VAS line suggesting that participants had previously (Q3) listened to the instruction to stop eating when "comfortably full" and the second course had, potentially, led to being *more* than comfortably full. Anecdotally it might be noted that this is frequently the case with chocolate cake.

When combining the weight of food consumed during both courses of the meal that was consumed by subjects in the HC group, this was significantly lower than that consumed by the LC group ($p < 0.01$) (Figure 3). On average the subjects consumed 183.9 g less food when they had consumed the HC preload. The *ad libitum* meal results were corroborated with the appetite questionnaire results at each step, even three hours post-eating where there were significant decreases in ratings of "hunger" "desire to eat", "how much subjects wanted to eat" and a significant increase in "fullness" in subjects from the HC preload group (Figure 2).

Interestingly an impact of the HC pre-load starter food on satiety, as well as satiation, is suggested by these subjects with this reporting of lower hunger ratings three hours following the meal (Q5). This was recorded from subjects' food diaries and was not a particular focus of the satiation trial, and many other factors could have influenced these ratings.

Mechanism

The direct contribution of texture to satiation is still a nascent area of study since divorcing texture from oral transit time whilst keeping all other parameters equal is challenging. In the current study the model foods used as preload in the satiation trials, whilst iso-caloric, were not controlled for macronutrient similarity.

The aspects of the cephalic response that contribute to satiation have been studied elsewhere, and recent advances in functional magnetic resonance imaging (fMRI) have indicated the neural regions of brain that interact with both short- and long-term satiety signals[38-40]. These signals influence both quality and quantity of food consumed[41]. There have been fewer studies of the areas of the brain related to perception of food texture directly[42]. Using the model foods developed in this current programme the authors are now embarking on a neuroimaging study to identify cortex activation that scales with food complexity in areas of the brain that process sensory information and areas associated with food reward.

The subjects in this study ate significantly less when preloaded with a high textural complexity food, although they rated their hunger/fullness the same at the conclusion of the meal. This indicates that the impact of the textural complexity effectively went "unnoticed" which is a promising result for managing food intake.

Conclusions

Textural complexity can be built into model foods resulting in similar oral processing times, though probably only if the foods are small, allowing control of the oral transit for testing the impact of texture on satiation.

The significance of the results of the current study is that, for the first time, an impact of food texture on satiation has been shown independent of oral processing time. We propose that the increased sensory stimulation from more complex textures can contribute to and accelerate the satiation response.

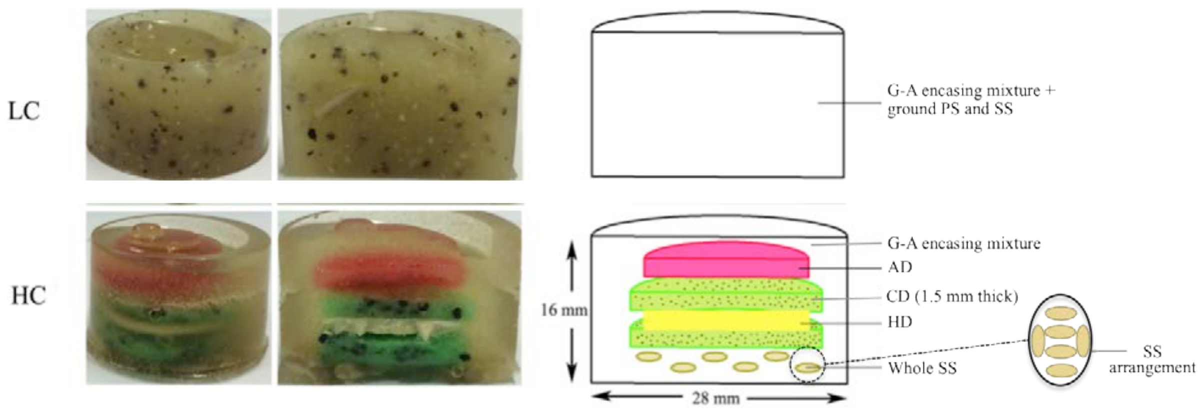

Figure 1: Model foods.

LC: Low complexity. HC: High complexity. G-A: Gelatin-Agar gel. AD: Agar disc. CD: Chewy disc. HD: Hard disc. PS: Poppy seeds. SS: Sunflower seeds.

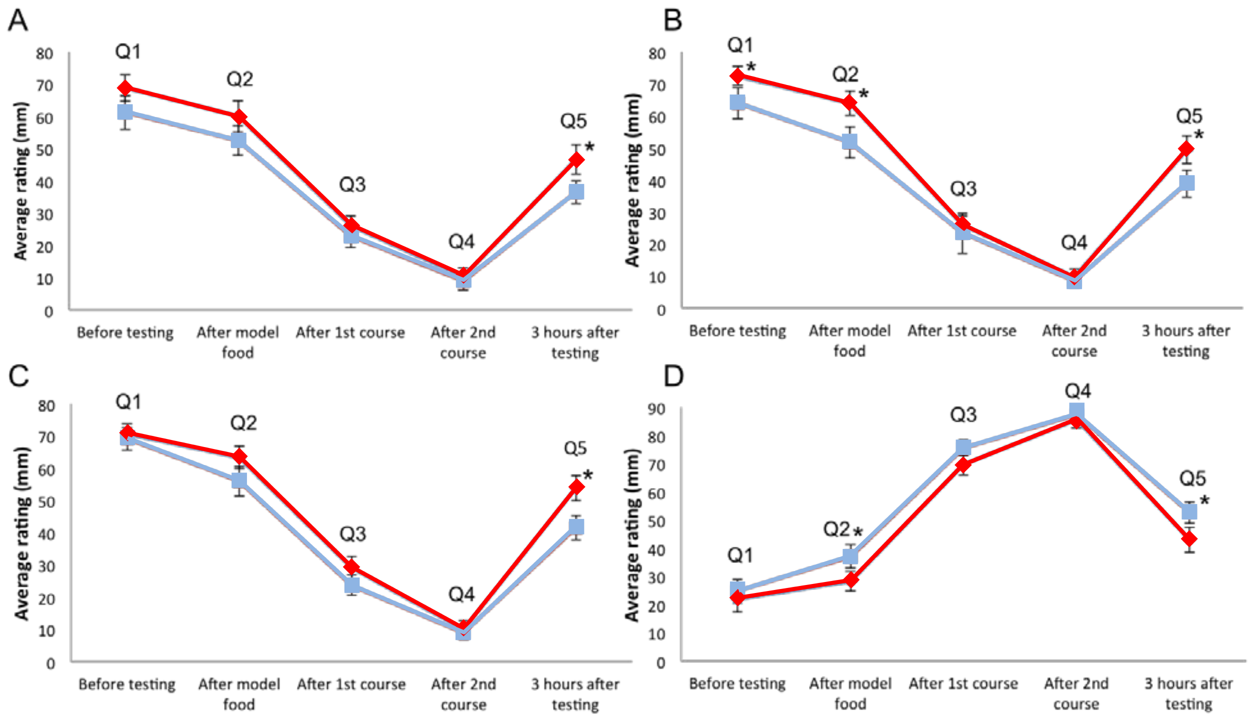

Figure 2 Graphs showing the average ratings from the appetite questionnaires during satiation testing (Q1 – Q5).

A= average ratings for ‘subjects’ hunger’, B= average ratings for ‘subjects’ desire to eat’, C= average ratings for ‘how much subjects want to eat’, D= average ratings for ‘subjects’ fullness’. The red line with diamond symbols denotes the LC group (subjects that consumed the LC model food) and the blue line with square symbols denotes the HC group Error bars indicate standard error and * designates a significant difference between the LC and HC group ($p < 0.05$).

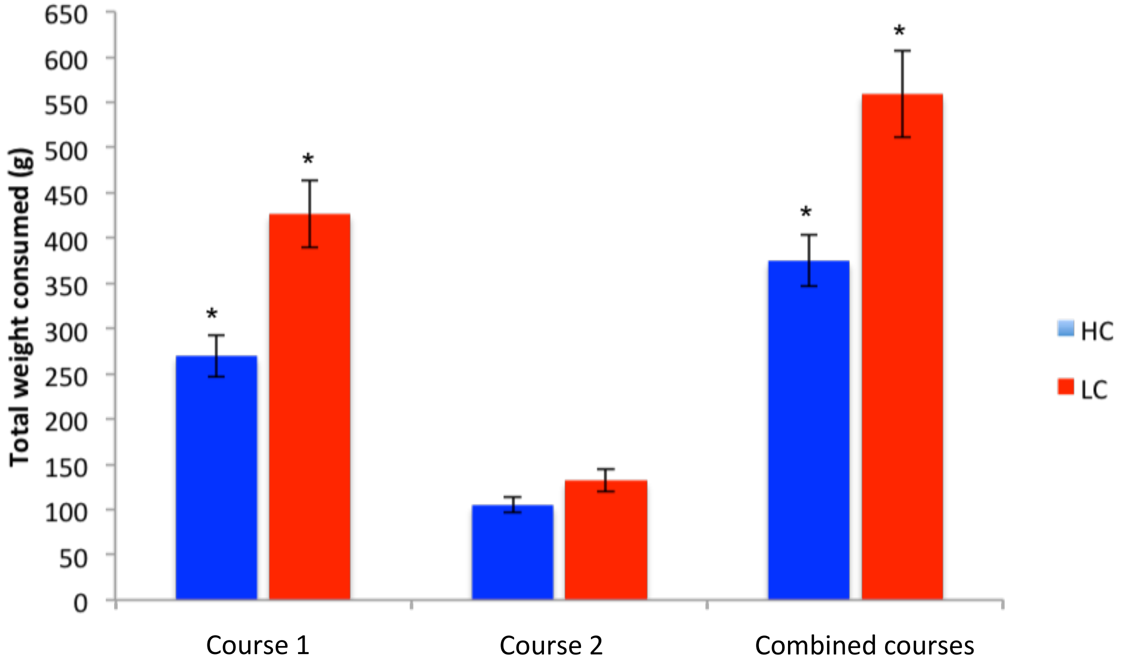

Figure 3. Average weight consumed during each *ad libitum* course and the total combined weight consumed (course 1 + course 2). Error bars indicate standard error and * indicates a significant difference between LC and HC ($p < 0.05$).

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Author contribution statement

Larsen designed the experiments, conducted the satiation trials and conducted the statistical analysis of the data. Larsen and Tang designed and made the model foods. Tang assisted in conducting the satiation trials. Ferguson provided nutrition expertise and guidance. James conceived and designed the programme. Larsen and James wrote the paper.

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