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The effect of textural complexity of solid foods on satiation

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HIGHLIGHTS

- Increased textural complexity in solid food directly enhances satiation.
- More texturally complex preload results in significant reduction in food intake.
- Satiety is potentially impacted by the textural complexity in food.
- Two-course test meal design was useful in combatting SSS.

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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 randomized 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.

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 *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 [15–17]. A longer oral exposure to

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sensory receptors may promote the opportunities for sensing the properties of foods. Sensory signals have an early onset during eating and primarily influence satiation [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 [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 [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 [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 [29].

Until now, it is unknown if texture has a *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 [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 [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 *ad libitum* meal of other food products. Also, a two-course *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^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 >5 kg 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 Fig. 1.

Textural complexity was quantified using instrumental measurement (puncture tests) coupled with sensory evaluations (generic descriptive analysis) [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 [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).

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 ~10 g 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 randomized order; the detailed methodology of measurement followed our previous study [36]. 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 [30]. 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 h and then stored in airtight bags at room temperature until required (no longer than 4 h). All samples were made fresh on testing days and were always stored in a refrigerator at 3 °C for 1 h before testing and then equilibrated to room temperature for at least 20 min.

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

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

Nutrition information – gel based model food						
	Average quantity per serving			Average quantity per gram		
	LC	MC	HC	LC	MC	HC
Sample weight (g)	9.11 ± 0.18	9.39 ± 0.15	9.27 ± 0.12			
Serving size (piece)	1	1	1			
Energy (kJ)	57 (13.6 kcal)	59 (14.1 kcal)	60 (14.3 kcal)	6.3	6.3	6.5
Protein (g)	1.2	1.1	1.2	0.13	0.12	0.13
Fat, total (g)	0.3	0.2	0.1	0.03	0.02	0.01
Saturated (g)	0.0	0.0	0.0	0.003	0.002	0.002
Carbohydrate (g)	1.6	2.0	2.1	0.2	0.2	0.2
Sugars (g)	1.4	1.6	1.6	0.2	0.2	0.2
Sodium (mg)	5	6	6	0.6	0.2	0.6