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Haptic signals of texture while eating a food.

Multisensory cognition as interacting discriminations from norm

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Abstract

This study started to characterise the cognitive processes by which physical effects on the senses are transformed into quantitative judgments about conceptualised aspects of a food. Using words provided by assessors, discriminations of a shortbread biscuit's fracturing patterns during eating from each assessor's internal norm were measured for the initial steps of denting, biting and crushing the material. The haptic concept of dentability (lack of crispness) often discriminated cracks in the biscuit that were the lowest in force, but was also sensitive to high-force cracks and frequency of cracks. How hard it was to bite through the sample was most often sensitive to the force of snapping the biscuit and to high-force cracks. Frequency of cracks usually dominated how "crunchy" the biscuits were rated to be. Interactions among the normed discrimination functions accounted for judgments of overall distance from the personal norm for the complex overall texture of the biscuit and revealed each assessor's cognitive strategies in reaching those integrative judgments. Use of the haptic concepts tended to shift mentation from control of the integrative texture ratings directly by sensory stimulation to the relating of those concepts to the sensed patterns, i.e. to describing texture.

Keywords. Normed multiple discrimination. Personal cognition. Auditory texture. Tactile texture. Biscuit fracture perception.

Introduction

Enjoying a cookie is a challenging mental task. Even just the sensory appreciation involves not only sweetness but also subliminal saltiness, the aroma from the many volatile compounds produced during baking, visual appearance and, physically and mentally the most complex of all, the textures created in the mouth by 'grasping' the biscuit between the teeth (haptic perception).

Therefore the task of reading the mind of each eater of a biscuit has to be even more challenging. In fact, no such work has been published until this paper. We report here the first implementation for food texture of the cognitive technology of Freeman *et al*. (1993; Booth & Freeman, 1993), explained below.

An immediate worry had to be, as with any non-trivial task, that the procedures needed to characterise cognition altered the cognitive processes being diagnosed. That issue was faced earlier with the simplest form of this approach, varying just one sensed ingedient of the food (Conner *et al*., 1988a). Cognitive adaptation to the task is well known in the assessment of complex stimuli (e.g., Abercrombie, 1960; Ballester *et al*., 2008). This paper returns to that problem as an aspect of starting to apply individualised cognitive analysis to multiple sensed aspects of a foodstuff.

Discrimination of the sample from the norm

Rated similarity of a sample to the standard version of a category of object, such as shortbread biscuits, plotted against levels of a feature of the object (such as how sweet it is) logically should peak at that feature's level in the standard (the sweetness of the usually eaten biscuit, for example). Shepard (1957) pointed out that this peaked function is the same as the decreasing strength of response as levels of a stimulus fell below or rose above the value that was followed by reinforcement in experiments on animal learning. The slope on either side of this learnt peak is known to behaviourists as the intradimensional stimulus generalisation gradient (e.g., Hearst, 1968; cp. Booth, Lovett & McSherry, 1972, for levels of sweetness in a drink). Booth, Thompson and Shahedian (1983) unfolded this peaked function of a sensed material feature of a familiar food against the individual's ratings of distance from ideal and obtained a linear psychophysical function when the physical values were logarithmically scaled (for likely equal discriminability). The personally learnt value of the ideal point could be estimated by interpolation. McBride and Booth (1986) established the same principle using the classic Method of Constant Stimuli on a familiar beverage. They compared the intensities of test stimuli with a standard physical stimulus or with the mental standard (norm) of memory of the most preferred intensity. The two comparisons gave identical values both for the standard level and also for 50% discrimination between physical levels, i.e., the "just noticeable difference" interpreted as objective performance (Torgerson, 1958). Implicit standards have recently been found to yield better discrimination than physical standards in visual psychophysics (Morgan *et al*., 2000; Nachmias, 2006).

The initial work on discrimination from norm of features of familiar objects was carried out mostly with salty, sweet, sour and bitter tastants in foods and drinks. Nevertheless, norms were measured in the same way also for food aroma (Booth *et al*., 1995, 2010; Kendal-Reed & Booth, 1992), colour (Conner *et al*., 1994) and even verbal labels (Freeman *et al*., 1993). The present experiments apply normed discrimination scaling to the multisensory complexities of the physical break-up of foods manufactured in bakeries. Indeed, this study demonstrates the independence of the approach from sensory modality by taking the case of crunching a biscuit. It now seems likely that the resulting rapid variations in pressure between the food and the teeth are both heard (Vickers, 1984a,b) and sensed by touch (Trulsson *et al*., 2010).

Eaters' conceptualisations of biting a biscuit

The present experiment also departs radically from usual practice in the evaluation of texture by using consumers' words from their experiences of eating, instead of vocabulary that investigators have tried to train panellists to use in the way that interests them (*cf*. Dan *et al*., 2008). The task for the participants has been simplified further by tying the life-trained vocabulary to the main initial steps of grasping a biscuit between the teeth – splitting off a piece with the front teeth (Johnsen *et al*., 2007) and the first closure of the side teeth around that piece, plus initial pressure into the surface of the biscuit at both those steps, from which the sense of touch might pick up movement of the teeth from resistance to compression before audible cracking begins (Johnsen & Trulsson, 2003). That is, the task of quantitative judgment of the texture of a biscuit has been conceptualised as initial haptic perception (active appreciation by grasping), rather than as passive sensing throughout the chewing of a mouthful (Brown & Braxton, 2000; Varela *et al*., 2009).

Method

Participants

Forty-four untrained volunteers agreed to take part in an assessment of varieties of shortbread biscuit. The participants were mostly undergraduates in the age range 18 to 21, plus eight others aged 20 to 28 years. If feasible, the test session was held shortly before lunch, although sometimes it ran during the afternoon.

Materials

The experimental samples were variants of a short-dough cookie recipe intended to crack in diverse patterns when bitten while not being unacceptably deviant in texture, taste, aroma or appearance. The three-point breaking force (3PBF) for each biscuit was measured by resting the biscuit on two bars and bringing down a third edge from above to press on the biscuit until it broke completely into two pieces and recording the maxmum force required. Three other instrumental values were obtained using cone penetrometry (Booth *et al*., 2003b,c). The patterns of force produced by sub-millimetre fractures (cracks) during the crushing of a cookie by the teeth were simulated by pushing a needle with a 10º cone at the tip into the biscuit at a constant rate of 0.6 mm/sec, to a depth of 4.5 mm. The variations in force as the cone penetrated the biscuit were recorded and analysed for successive trough to peak heights, in the unit Newton (N), 1 $kg.m.s^{-2}$, the weight of about 100 g. Three numerically independent parameters were extracted from these force-distance profiles: low-force cracks, the percentage of mini-fractures (cracks) between 0.03 and 0.05 N (%LFC); high-force cracks, the percentage of cracks above 1 N (%HFC); and frequency of cracks, the total number of mini-fractures over a distance of 4.00 mm of cone penetration and a time of 6.67 seconds (FreqC), excluding those below 0.03 N.

Two sets of biscuits were selected from a batch of 18 variants made for this study. The attempt was made to minimise the correlations between the values of each pair of the four fracture characteristics of the biscuits in a set, while at the same time keeping as many values as possible either below or above the value of the standard shortcake biscuit with which each biscuit was to be compared. (This is necessary to disambiguate the position of the peak of the normed function.) One set (7 samples including the standard biscuit) had values of each fracture parameter that were higher than the those of the standard but the break forces and proportions of high-force cracks were highly correlated, *r* = 0.81 (Table 1). The other set (8 samples including the standard biscuit) had values of two fracture parameters higher and two fracture parameters less than those of the standard, with shared variances of little more than 20% at most between fracture parameters (Table 1). The sets were evaluated by 23 and 21 assessors, respectively. The data from the two sets are combined where that does not confound interpretation.

Table 1 about here

The first sample to be tested (placed on the left of the row of samples) was of a recipe close to that usually marketed in the U.K. The 6 or 7 other test biscuits were arrayed to the right in an order randomly assigned to each assessor from the lines of a Latin square.

Procedure

Participants were randomised between the two sets of samples of short-dough cookie and evaluated the assigned set at a single session. The test procedure was identical overall in the two sets, with some variations between sessions within each set of biscuits (see below).

Two of each variant in the set to be assessed were presented in a row on a tray, each covered by a piece of opaque paper on which a meaningless code of two letters was written. The assessors was required to use a disposable glove on the non-writing hand to uncover and pick up the biscuit, in order to prevent tactile detection of differences between biscuits in the fine grain of the surface. After the assessment of each biscuit, it was covered from sight before another biscuit was exposed to the eye.

A cup of water was provided for the assessor in order to rinse the mouth whenever wished. Additional samples of the standard formulation were available for reference at any time. At the end of a session before lunch, the assessor was given a sandwich and fruit to eat as the remainder of lunch for that day.

A sample of the standard formulation was bitten in the assessor's normal manner and the layout for ratings was introduced. In 'initial overall' texture judgement, assessors first tested the first sample (standard biscuit) as a texture reference, and then assessed how good was the texture of each sample in the set of test formulations, by placing a mark as rapidly as they could on a line divided into twelve equal distances with one end labelled as "Texture exactly like usual biscuit" (scored as zero distance from norm).

Then the assessor used three haptic concepts elicited in a pilot study to judge the distance of each test variant from the standard biscuit, using the covers and glove to go through the samples in the same order as before. Each act of denting, breaking or crushing the biscuit was rated as promptly as possible by placing a mark on a line on which there were two anchors, with space available for marking outside each anchor also. One anchor on all three lines was the phrase "Exactly like a top-quality shortcake biscuit" (scored zero). The other anchor was "totally rock-hard" for denting, "crisper / less doughy" for breaking and "less crunchy" for crushing (scored nine).

At the end of the session, 27 of the 44 participants evaluated the overall texture of the test samples as they had done at the beginning. Data from these assessors were used to compare cognitive processes in overall texture judgment before and after ratings under the haptic concepts.

Psychophysical measurements

This early version of multiple discrimination modelling required the unfolding of any psychophysical function that spanned a peak in responses (Coombs, 1964), as follows. In a majority of cases, initial and final judgments of overall texture and of crunchiness showed a peak when plotted against values of an instrumental parameter. The peak mechanical value was taken to be that given the highest rating that was also nearest that of the standard biscuit. Then the ratings of all samples above that peak value (i.e., less than the highest rating on the right-hand side of the regression plot) were unfolded by multiplying by -1 all of the ratings with higher instrumental values than that of the peak-rated sample (see Figure 4 in Booth, Earl & Mobini, 2003a).

As a result of this unfolding, a rating could be positive for one mechanical characteristic (at a higher value than in the standard biscuit) and negative for another (lower than the standard) of the same biscuit. However all the data for modelling must have the same sign. Therefore, a sample's data were excluded from the regression if there were two unfolded ratings. If three of the four ratings were unfolded or not unfolded, the disparate sign of the fourth rating was reversed. The resulting number of test samples (*k*) was the same for the cognitive analyses of initial and final overall ratings in one assessor, although it varied between 3 to 6 samples across assessors.

Least-squares linear regression through the monotonic data was used to estimate each psychophysical function. The function's slope and its sign were used to measure the strength and direction of relationship between the fracture parameter and the descriptor rating. In accord with the formula for the JND (Booth *et al.*, 2003b,c; Conner *et al.*, 1988a,b; Torgerson, 1958), the mean square error around the regression line ($1 - r^2$) was divided by the slope and multiplied by twice the z score for 25% to give the assessor's half-discriminated disparity (HDD) in the instrumental values by the ratings on the concept. An individual's data were omitted from further analysis when $r^2 < 0.10$ (to avoid outliers in values for norms or discrmination) or the slope had a sign opposite to that of the group mean for that function (to avoid anomalous sets of data).

To generalise about the discriminative acuities of the concepts in this task, the number of participants with the lowest HDD in each haptic concept across the three concepts was counted up for each fracture parameter. Also, in order to assess the strengths of influence of an instrumental parameter of fracturing on the ratings, the lowest HDDs for each parameter across the four fracture parameters were counted for each of the concepts.

Cognitive measurements

Each assessor's raw data for a session were entered into an interim version of cognitive modelling from multiple normed discriminations (Booth & Freeman, 1993), programmed in Microsoft Access 2.0 (Platts & Booth, 1999). The values of the instrumental parameters, break force (s1), high-force cracks (s2), low-force cracks (s3) and frequency of cracks (s4), were used as estimates of the strengths of patterns of physical stimulation. The scores for hard (r1), crisp (r2) and crunchy (r3) were used to estimate the strengths of analytical concepts that might influence the modelled response, which was the score for overall texture (r0).

The first round of calculations estimated discrimination (Weber's fraction) and norm (the physical value interpolated to the anchor point for the standard biscuit) for each possible relationship between a stimulus variable and a response variable observed in the individual's session (Booth & Freeman, 1993; Booth, Earl & Mobini, 2003a). The stimulus variable was then rescaled from instrumental values to number of discriminations below or above norm. Discrimination and norm were also calculated for each relationship between a response variable and another response variable: the response of which the concept was taken to be the influence on the other response was rescaled too in discriminations from norm. When the response affected was overall texture, these discrimination-scaled functions were termed elemental models, directly stimulatory (s) and response-conceptual (r) respectively (Booth & Freeman, 1993). Finally for this step in the calculations in Access, the discrimination-scaled s and r functions that did not have overall texture as the response were each tested as influences on overall texture and then discrimination-scaled to give indirect or covert descriptive (s/r) and reasoning (r/r) models.

Within each of these four types of simple one-dimensional model of overall texture (r0), all possible combinations were tested for factors in common by summing their discrimination-scaled distances from norm (Booth & Freeman, 1993). That step generated complex 1D models, e.g., the predictor s1 + s3 + s4, or perhaps s2/r3 + s3/r3.

These simple and complex 1D models were then tested for integration into overall texture of their distinct aspects. Distinctions between processes are orthogonal to each other and so the combination rule follows Pythagoras's Theorem (which generalises from two dimensions to three and more) – that is, the square root of the sum of squares of each element's discrimination distance from norm (using capital gamma, Γ, to represent a right angle). For example, integration of two differently sensed instrumental parameters gives a 2D model, s1 Γ s2. If those two parameters had distinct aspects as well as an aspect in common, then there would be support for the 3D model, s1 Γ s2 Γ (s1 + s2). The program in Access (Platts & Booth, 1999) provided r^2 values for models having up to four dimensions. The model of overall texture with the highest value of r^2 was the best estimate available from the data of the cognitive processes performed consistently by that assessor during that session.

Statistical analyses

The group means of HDDs across ratings or mechanical parameters were compared by one-way analysis of variance. The hypothesised relationships between fracture parameters and descriptor ratings were tested by comparing group mean slopes in one sample *t*-test. The reliability of variations in frequencies among conditions was estimated by χ^2 or Fisher's exact probability as appropriate. Changes in cognition were evaluated by the Wilcoxon paired ranks test.

Results

Perceptual channels

Each individual's half-discriminated disparity (HDD) for each fracture parameter was compared among the three haptic concepts. The most acutely discriminative (lowest) HDD for break force was achieved as expected by their ratings on the term "hard" in 14 of the 44 assessors. However, a similar number of other assessors achieved their lowest HDD for this fracture parameter rating for "crisp" or "crunchy" (Table 2, row 1).

Table 2 about here

The HDDs for low-force cracks were lowest (best) by ratings on the terms "crisp" and lacking in "give," as had been hypothesised, in only seven of the 44 assessors (Table 2, row 2). A much larger proportion of the panel achieved their lowest HDDs for this mechanical parameter using ratings of “crunchy,” two-tailed exact $P = 0.06$ against random.

Nevertheless, the main pair of hypotheses was well supported: “crunchy” meant high in amplitude and frequency (Table 2, rows 3 and 4). High-force cracks were most acutely discriminated by ratings on this term in half of the 44 assessors. The HDDs for high-force cracks by ratings of “hard” or “crisp” were the best in considerably fewer assessors (Table 2, row 3), exact $P = 0.48$ and 0.11.

Finally, in accord with hypothesis, the HDD for frequency of cracks was the lowest for ratings of “crunchy” in 24 of the 44 assessors, with far fewer assessors finely discriminating between frequencies of crack by ratings on the terms “hard” and “crisp” (Table 2, row 4), $P = 0.009$ and 0.062.

To sum up the specificities of the three haptic concepts, in the majority of these consumers, “crunchy” ratings were the most sensitive to differences in level of the stimulation measured by frequency of cracks and by proportions both of low-force cracks and of high-force cracks. Judgments of how “hard to break” each biscuit was, on the other hand, were most often the best discriminative of break forces and of high-force cracks. “Crisp” or lacking in “give” however was a concept without a clear relationship to the fracture patterns that were measured.

In order to test, conversely, which fracture characteristics had the most impact on a haptic concept, assessors’ HDDs for each concept were compared across fracture parameters. Very few assessors performed in accord with the hypothesis that break force had most influence (was best discriminated) by ratings of hardness (Table 3, row 1). The numbers of people with the lowest HDDs by ratings on this concept were considerably higher for each of the other three parameters, low- and high-force cracks and frequency of cracks.

Table 3 about here

Ratings on the term "crisp" (and lack of "give") most often had the lowest HDD for low-force cracks, as hypothesised, in a higher proportion of the assessors than "hard" but still more were influenced most by either high-force cracks or frequency of cracks (Table 3, row 2). Thus force patterns reflected in one or other of the three penetrometric parameters had a strong influence on ratings of crispness in the great majority of these consumers.

Consistently with hypothesis, the frequency of cracks dominated how "crunchy" the biscuits were rated to be, unlike how "hard" or "crisp" they seemed (Table 3, row 3). High-force cracks had the strongest influence much less often, although that would be the case if it were merely second to frequency.

The group means of the HDDs for each mechanical parameter (not shown) were consistent across the three haptic concepts, with frequency of cracks being the best discriminated (lowest HDDs) and break force the worst (highest HDDs). There was no reliable variation in group means of HDDs among the concepts rated within each mechanical parameter.

The slopes of the stimulus/response functions gave a somewhat clearer picture (Table 4), that accorded closely with expectations for relationships between fracture parameters and haptic concepts. The greater the force required to fracture a biscuit completely (break force), the higher a biscuit was in ratings of hardness, $t(28) = 16.1$, $p < 0.001$. Furthermore, the higher the proportion of low-force cracks, the more "give" (less "crisp") the biscuit was rated to be, $t(23) = 8.2$, $p < 0.001$. Finally, the more highly a biscuit was rated in crunchiness, the greater was the proportion of high-force cracks, $t(41) = 12.0$, $p < 0.001$, and the higher was the frequency of cracks, $t(28) = 5.4$, $p < 0.001$.

Table 4 about here

Cognitive processes in judgments of overall texture

Prior to any mention of describing the biscuits, most assessors' judgments of overall texture were dominated either by stimulation-driven processes (s models), or by stimulus/response relationships (s/r models in Figure 1). After eliciting an assessor's descriptions of the sensed effects of biting a biscuit, the proportion of the assessors using stimulus/response relationships to judge overall texture increased while stimulatory processing declined, $\chi^2(1) = 4.13$, $p < 0.05$. The drawing of attention to wordings for texture during biting did not increase the proportion of the purely conceptual control of overall evaluations of texture, either by the elicited verbal concepts (r models) or by their pairwise interrelations (r/r in Figure 1). That is, the change was not merely to thinking in words; rather, there was more use of words to analyse the sensory stimulation -- an increase in depth of processing.

Figure 1 about here

Of those assessors who changed their type of cognitive processing of texture after they had used haptic concepts, a switch from the processing solely of stimulation (s models) to the processing of stimulus/response relationships (s/r models) was made by eight assessors (30% of the total), whereas only two people (7%) switched from stimulus/response processing to stimulus processing, $\chi^2(1) = 3.57$, $p < 0.06$. This further indicates that the conceptualising of aspects of biscuit texture facilitated deeper processing, rather than merely switching attention from the physical stimulation to the verbal conceptualisation.

For the great majority of participants (85%) after haptic analysis, the cognitive processing of overall texture involved at least one element of the same stimuli and/or responses as the initial judgements had done, with low-force cracks (s2) or crunchiness (r3) recurring in the largest proportions of the panel (22% each). For the other participants (15%), in contrast, cognitive processing of texture after concept elicitation involved a change of content. Almost all the assessors (90%) who used stimulatory processes in the initial evaluations of texture were driven largely by break-force (s1). After elicitation of wordings, however, all four of the measured sources of physical stimulation influenced the processing, and to almost the same extent, but much less frequently (15% of panel) than in the initial rating of overall texture.

The percentage contribution of each cognitive process to the individual's model of overall texture was similar in profile of group means to the frequencies of assessors using particular cognitive processes, described above. Prior to verbally explicit conceptualisation, processes driven by a physical stimulus (s elements) contributed more strongly to judgments of overall texture than did verbal processes (Figure 2a). Indeed, no assessor judged overall texture using the haptic concepts (r elements) before those wordings had been elicited. Nevertheless, some assessors used stimulus/response (s/r) and stimulus-driven (s) processes in judging overall texture from the start. In a few cases, judgments of overall texture were controlled at the start by relationships between concepts (r/r elements); the overt development of haptic concepts in these people may have narrowed attention to one or two particular concepts (Figure 2b).

Figure 2 about here

The data on central tendencies in cognitive processing were consistent overall with the findings for assessor frequencies in that, after conceptualising haptic aspects of texture, the primary effects were a decrease in the strength of contributions from stimulation-driven processing, Wilcoxon $Z = 1.94$, $p < 0.05$, and an increase in the strength of contributions from stimulus/response relationships, $Z = 2.14$, $p < 0.05$ (Figure 2).

For the initial ratings of overall texture, stimulation from break-force (s1) and frequency of cracks (s4) contributed most strongly on average (Figure 2a). In the final ratings, however, these two stimulatory elements were much weaker and high-force cracks (s3) made the strongest mean contribution among the weaker stimulation-driven judgements (Figure 2b).

The most strongly contributing elements to the final ratings of overall texture were the relationships of low-force cracks to crunchiness (s2/r3) and to hardness (s2/r1), of frequency of cracks to crunchiness (s4/r3) and of break force to crispness (s1/r2) (Figure 2b).

The percent contributions for the four hypothesised s/r relationships, break force/”hard” (s2/r1), low-force cracks/”crisp” (s2/r2), high-force cracks/”crunchy” (s3/r3), and frequency of cracks/”crunchy” (s4/r3), were each moderately higher in the final texture ratings than in the initial ratings, although none of these differences was reliable ($p < 0.2$).

Discussion

Cognitive integration of a biscuit's crunchiness

Each of the four types of cognitive process considered by Booth and Freeman (1993) were used by at least two assessors to decide similarity of overall texture to their personal standard, with one of the four types being seen in a majority of the panel (Figure 1). The asssessors varied greatly in their use of the instrumentally measured fracture patterns and the locally elicited haptic concepts. These variations were seen in the feature-specific discriminative achievements as well as in the features' contributions to the cognitive models of overall texture from interactions among the discriminative processes. It is widely recognised that assessors differ from each other and vary over time in their attention to different sensed features and verbalised ideas in a realistically complex situation, even when culturally framed sensory abilities are normal. This innovative approach exposes these idiosyncrasies in all their glory!

The testing of so many hypotheses on a modest number of data from one person at one session could be open to the dangers of overfitting. In other words, we need to evaluate the possibility that the model that best accounts for the data occurs at random. This issue has been addressed in various ways, including showing reasonable insensitivity to random changes in numerical values of the raw data (J. Brunstrom & D.A. Booth, unpublished) and improvements in fit over successive sessions, which indicate the reality of that cognitive strategy (Booth *et al*., 2008). The present findings contribute to the latter type of evidence. There was a systematic change after a manipulation, and that change was of a sort that would be expected theoretically. Being explicit about terms that are widely used in conversation about the texture of biscuits increased the incidence of processes that related those concepts to the measurements of the mechanics of texture.

Nevertheless, the main aim of the present report is to show that it is feasible to calculate detailed and specific characterisations of an individual's mental processes while tackling a complex multisensory task. Definite conclusions about the haptic perception of shortcake biscuits will have to wait for normed multiple discrimination analysis in full accord with theory (Booth & Freeman, 1993) of the data preliminarily analysed here. Then tests can be mounted of the specific hypotheses that emerge from such calculations about the processes of texture perception, both in general and as they vary among individuals and situations.

So far at least, the results are fully compatible with much evidence of a less individualised and cognitive sort, that the rate of crackling as a piece of biscuit is crushed dominates how crunchy that biscuit seems. Hence to the ears, crunchiness is the pitch of those noises, e.g. growly or squeaky. The force needed to snap a biscuit may also be judged by sound but kinaesthetic theories based on the off-loading of jaw muscle tension need further consideration (Svensson & Trulsson, 2009). If there were an initially viscous phase to biting into these biscuits, such denting would be silent. However, the matrix of the biscuits might 'give' so little initially to pressure from the teeth, that there is only a series of tiny fractures from the start. If that is so, either audition or vibratory sensing is remarkably sensitive to cracks of barely measurable force (less than half a gram in weight).

Illustration of multisensory normed discrimination

The purpose of this paper is to illustrate a new approach to cognition by applying it to the active multisensory task of appreciating the texture of a biscuit at the first two bites. Cognitive processes were measured while they occurred in an individual within a familiar situation. This causal analysis of mental processing is achieved by using variations in input to and output from the person among different examples of the focal object in that context, instead of using variations among individuals and situations. The influence of each input on each output is estimated from the discrimination between each example of the situation and the remembered usual situation, i.e. the personally acquired objective norm.

The introduction of individualised discrimination from norm was revolutionary in the measurement of an individual's state of appetite for a food in a situation where it is often consumed (Booth *et al.*, 1983). The hitherto artificially isolated psychophysical function was re-inserted into its natural context of the culture of material stimulation and conversational wordings. As a result, the measurement of the impact of merely a single sensed constituent on a person's preferences for a few foods and drinks yielded both fundamental gains in knowledge (Conner & Booth, 1988; Conner *et al.*, 1988b) and innovative practical techniques (Conner *et al.*, 1986; Booth, 1988).

However, the new approach was not limited to a single constituent or sensory receptor type. Any source of stimulation could be investigated within its usual context. Hence, the impacts of two or more sensed or symbolised factors on appetite can be measured simultaneously in the context of each other and of the wider situation (Booth & Freeman, 1993). That is feasible because the effects of the influences on a response to the situation are measured in the same unit of that action's discriminative sensitivity to any of the monitored factors (Booth, 1988, 2008; Booth & Conner, 1991; Freeman *et al.*, 1993). As a result, hypotheses about causal interactions among sensory and symbolic mental processes can be tested on any data from an individual involving at least two independently varying influences on a graded outcome, such as an overall judgment or disposition to act ('integration') or a highly specific concept ('descriptive analysis') of one aspect of a sensed or conceptualised influence (Booth, 2005; Booth & Freeman, 1993; Booth *et al*., in press; Freeman, 1996, cf. Freeman & Booth, 2010). This paper presents findings from an experimental design with four sensed influences and three partly analytical concepts, with one fully integrative rating explained cognitively from those seven variables.

As the number of influences and/or analytical responses increases, there is a combinatorial explosion of logically possible mental interactions involved in an integrative outcome. The initial generalisation of normed discrimination from one factor in context (Booth & Freeman, 1993) was implemented initially for up to four sensed influences (e.g. Booth *et al*., 1995, 2010; Freeman *et al*., 1993; Richardson & Booth, 1993). However, that first computational tool tested only user-entered hypotheses, omitting some potential interactions. Complete multiple discrimination analysis for up to five factors was carried out later by hand on data from interviews on components of a meal (Santos, 1998) but the first general calculator was implemented in a relational database (Platts & Booth, 1999), used in this paper. Even then, the interactions tested were limited to those among the same type of discriminative process and to a maximum of four dimensions, because of the time needed to compute all possible combinations in a high-level control language. The output serves to introduce the approach but full implementation of personal cognition requires an algorithmic simulation of this model of the mind. The first version of such software has now been built. Reports using that tool are under review or in preparation (cp. preliminary summaries by Booth *et al*., 2008, and Galea *et al*., 2008, for example).

Conclusions

An eater's mental processes of appreciating a biscuit's texture can be characterised from interactions between the effects of the forces generated by biting the biscuit on conversational concepts of that eating experience. Verbally conceptualising some details of texture tends to shift overall appreciation from a reaction to sensory input to use of the words to describe the patterns of force. These results illustrate how the human mind integrates linguistic culture with sensory biology.

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Table 1. Product-moment correlation coefficients (*r*) among the instrumental measurement values of the test biscuits in two sets of sample biscuits. N = Newtons; % = percentage of cracks at all force levels observed; m^{-1} = reciprocal of metres travelled by the probe (spatial frequency).

	Break-force (N)	Low-force cracks (%)	High-force cracks (%)
Set one:			
Low-force cracks (%)	0.07		
High-force cracks (%)	0.81	0.07	
Frequency of cracks (m^{-1})	-0.35	0.04	-0.19
Set two:			
Low-force cracks (%)	-0.33		
High-force cracks (%)	0.43	0.26	
Frequency of cracks (m^{-1})	-0.46	0.18	-0.28

Table 2. Number of assessors in a panel of 44 with lowest half-discriminated disparity (HDD) among the three rated terms for each fracture parameter. The psychophysical functions with $r^2 \geq 0.10$ and a sign of slope identical to the sign of group mean are included.

Fracture parameter	Concept with lowest HDD		
	Hard	Crisp	Crunchy
Break force (N)	14	12	15
Low-force cracks (%)	7	7	23
High-force cracks (%)	14	8	22
Frequency of cracks (m^{-1})	4	7	24

Table 3. Number of assessors in a panel of 44 with the lowest half-discriminated disparity (HDD) among the four fracture parameters for each rated term. The psychophysical functions with $r^2 \geq 0.10$ and a sign of slope identical to the sign of group mean are included.

	Fracture parameter with lowest HDD			
Concept rated	Break force (N)	Low-force cracks (%)	High-force cracks (%)	Frequency of cracks (m^{-1})
Hard	3	11	14	12
Crisp	1	9	16	16
Crunchy	1	5	8	28

Table 4. Means (*M*) and standard errors (*SE*) of slopes with $r^2 \geq 0.10$ from the panel of 44. Data from individuals having slope values different from sign of the group mean were omitted.

Fracture parameters	Rated concept					
	Hard		Crisp		Crunchy	
	M	*SE*	*M*	*SE*	*M*	*SE*
Break force (N)	12.7	0.8	13.3	1.1	18.1	1.2
Low-force cracks (%)	-32.1	4.0	-33.1	4.0	57.8	4.4
High-force cracks (%)	27.1	2.1	29.9	2.0	40.6	3.4
Frequency of cracks (m^{-1})	-210	53	-220	47	311	57

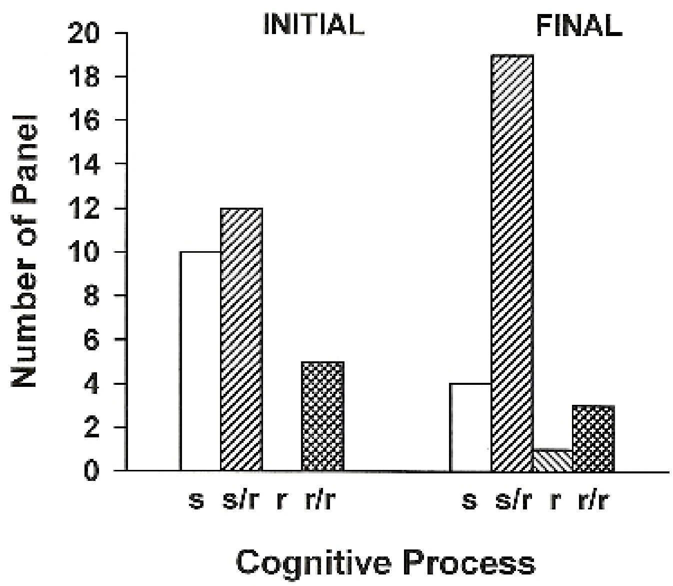
Captions to Figures

Figure 1. Number of assessors (N = 27) using a type of cognitive process to make the overall texture judgment before and after rating texture descriptors. Columns show stimulus (s), stimulus/response (s/r), response (r) and response/response (r/r) types of processing in control of overall judgments. The processing used by an individual in a session was identified as the calculation that accounted for the greatest proportion of the variance in that judgment.

Figure 2. Group means (N = 27) of the percentage contribution of each cognitive process to the ratings of overall texture judgment of shortcake biscuits in initial and final ratings. The columns show the contributing elements: s1 - break-force; s2 - low-force cracks; s3 - high-force cracks; s4 - frequency of cracks; r1 - “hard”; r2 - “crisp”; r3 - “crunchy.” The slash sign (/) on the x-axis shows a relationship between the instrumental values (s) and the conceptual responses (r) or between two responses. For example, the s1/r1 element shows that a relationship between s1 and r1 determined cognitive processing – that is, description of s1 by r1 played a key role.

Setter: please move the “%” now placed outside the graphic for Figure 2 to a parenthesiss at the end of the label to the vertical axes, thus: “...texture judgment (%)” (also deleting the “e” between “g” and “m”).

Figure 1


INITIAL
FINAL
Number of Panel
20
18
16
14
12
10
8
6
4
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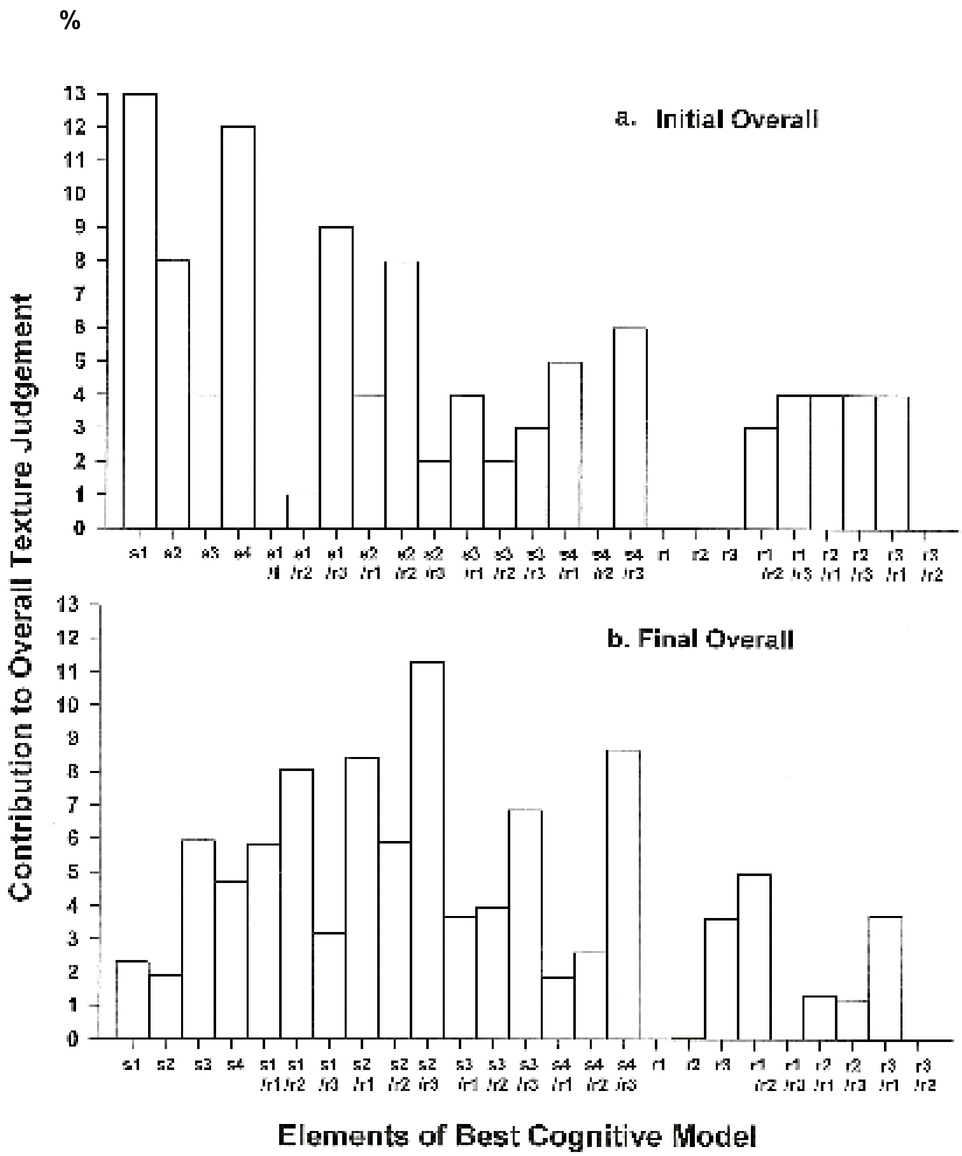
s s/r r r/r
s s/r r r/r
Cognitive Process

Figure 2


%
a. Initial Overall
b. Final Overall
Contribution to Overall Texture Judgement
Elements of Best Cognitive Model