

Integrated Sensory Response (ISR) Modeling: A New Methodology to Understand and Predict Sensory Attributes in Terms of Physical Properties

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ABSTRACT

The goal of this study was to develop and evaluate a tool that can assist in physical understanding and predictability of sensory from physical properties. Intriguing results have been obtained of graphical and mathematical ways of relating physical and perceived texture properties of several categories of baked foods with and without crispy layers. This led to a new methodology called integrated sensory response (ISR) modeling that integrates the whole set of receptor and brain responses on physical stimuli, all essential for a given sensory attribute, by delivering a quantitative, multivariate, multiplicative Stevens model of the sensory attribute in physical terms: $\text{Sensory attribute} = a \times \text{Phys1}^b \times \text{Phys2}^c \times \dots \times \text{Physn}^n$. The multivariate approach allows description of the more complex sensory attributes in terms of instrumentally measured physical properties where one-to-one relationships fail. It also allows description of how rather different physical properties may lead to the same sensory score. ISR modeling does not derive models from an exact physical analysis and mathematical description of oral processes and physical stimuli, nor from a theoretically derived psychological sensation

scale. Instead, it identifies a few physical parameters that appear to dominate sensory perception, in this case quantified in terms of texture attributes. The decision by (a segment of) consumers about their sensory perception of a given product set is the integrated result of many interactive, parallel, and consequential psychological, physiological, and physical processes. The physical parameters identified and validated as dominating a given sensory attribute are likely to characterize product effects in those physical processes that have dominated the quantified perception. This implies that other product properties and other physical processes are less relevant to study and optimize for the product category and consumer group investigated. Thus, a better focus in product development is obtained. ISR models provide understanding of a sensory attribute valid for a given set of products and panelists, not in terms of a complete mechanistic explanation, but in terms of knowledge about the relative importance of different physical properties and, through this, about the relative importance of different physical processes and mechanistic elements.

Within the food industry, continuous efforts are devoted to the exploration and development of new ways to vary the physicochemical properties of food products. For product development, it is crucial to understand how the consumer would perceive these variations. Ideally, the understanding would lead to prediction of the sensory properties of new products that have been only physicochemically characterized. Alternatively, the understanding could lead to a prescription of the physicochemical product properties to be obtained for a desirable sensory perception. In this context, the aim of the present study has been to develop and evaluate a tool to physically understand and predict sensory properties. As main result, this article describes a seven-step methodology to relate physical and sensory properties. To illustrate separate steps, visual representations are given of physical and sensory effects of ingredients and processing conditions for different categories of baked products. The methodology does not derive information from a product level (ingredients, processing conditions) but identifies physical parameters dominating sensory perception. The rules to vary these physical parameters by changing ingredients or process conditions will be left to product developers, who will know which physical parameters to concentrate on after applying the ISR methodology. These physical parameters could differ from traditional ones measured to assess product quality, as for example, specific volume (SV), but would be most relevant to essential quality: the sensorially perceived attributes relevant to consumers.

The perception of sensory properties of food products by consumers takes place at home during consumption of a branded product. The effects of the home situation and branding on sensory perception are very relevant and interesting, but outside the scope of the present study. We concentrated on the understanding of sensory properties perceived in laboratory testing by panels during unbranded food intake. To illustrate the modeling approach developed, results have been used of studies on the oral texture properties of baked products, both with and without crispy outer layers.

Relationship of ISR Methodology to Product Innovation

Oral food perception is the outcome of many interactive psychological, physiological, and physical processes (Christensen 1984; Hutchings and Lillford 1988; Guinard and Mazzucchelli 1996) (Fig. 1). Many product innovations generate at least one new or changed oral physical effect (physical stimulus) followed by a changed balance between all the processes determining the perception. If the size of this physical effect is critical to an oral perception element relevant to repeated consumer choice (intrinsic cue perception) (van Trijp en Schifferstein 1995), awareness and understanding of the effect will considerably hasten the innovation process and increase the chance of long-term business success. This awareness is crucial for the whole modeling approach, actually crucial for the sensory analysis as such. For commercial reasons, it does not make sense to measure, model, and understand sensory variations with no influence on repeated consumer choice. To make best use of research funds and to maximize effectiveness of sensory research results, the first element in any sensory modeling methodology should be to assess the consumer relevance of the sensory attributes to be modeled.

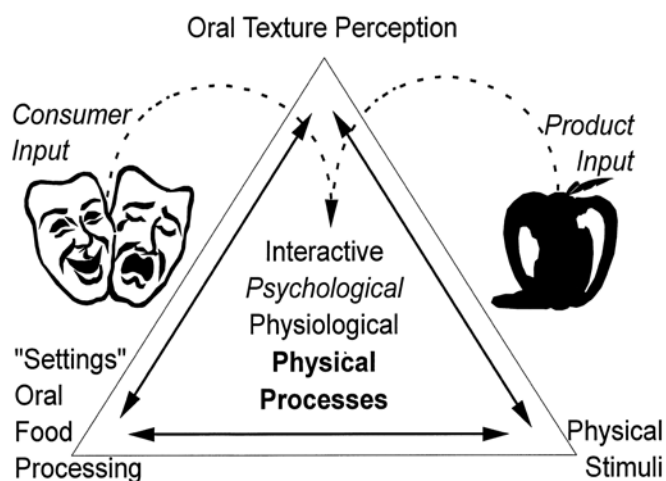


Fig. 1. Factors leading to oral texture perception.

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Characteristics of ISR Methodology

The ISR methodology has seven steps: 1) assess the consumer relevance of the sensory attributes to be modeled; 2) develop a qualitative analysis of the physical processes operating during stimulation; 3) define physical parameters characterizing these processes; 4) develop methodology to quantify these physical parameters; 5) measure physical parameters and sensory attributes for a relevant range of products; 6) derive quantitative models and to identify parameters dominating sensory perception; 7) fine-tune and validate these quantitative models.

The methodology delivers quantitative, multivariate, multiplicative Stevens models of sensory attributes in physical terms (sensory attribute = $a \times \text{physical parameter}^b$) (Stevens 1975). The multiplicative Stevens approach has been used because it offered one of the simplest possibilities to integrate several nonlinear responses on physical stimuli, all essential for the sensory attribute. It also offers the possibility of an easy first screening of models using linear regression on the logs of the measured values ($\log \text{Sensory attribute} = \log a + b \log \text{Phys}_1 + c \log \text{Phys}_2 + \dots + n \log \text{Phys}_n$; $\text{Phys}_1 \dots \text{Phys}_n = \text{physical parameter 1} \dots n$). The same approach has been adopted by Meullenet et al (1997, 1998), modeling texture attributes of a wide range of foods using texture profile analysis (TPA) and alternative instrumental measures. The multivariate approach is generally required as the parameter space of sensory attributes and the parameter space of instrumentally measured physical properties is so different that one-to-one relationships fail to explain major parts of the sensory response (interactions).

The methodology does not derive oral response models from an exact physical mathematical description of oral processes and physical stimuli, nor from a theoretically derived psychological sensation scale such as the Fechner models in Baird and Noma (1978): $\text{Sensory attribute} = a \times b \log \text{PhysParam}$, but identifies a few physical parameters which, together, empirically and statistically relevant, appear to dominate sensory perception both in calibrating and validating experiments.

As the decision by a panel about their sensory perception of a given set of products is the integrated result of many interactive, parallel, and consequential psychological, physiological, and physical processes, the physical parameters identified and validated to dominate this decision are likely to characterize product effects in physical processes that dominate the quantified perception. If this sensory perception would be relevant to consumer choice, it would suggest that other product properties and other physical processes would be less relevant for study and development. If product properties and related physical processes are not relevant to consumers, product optimization could then be led by arguments of cost saving or advertised claims. Thus, a better focus on behalf of product development is obtained.

Another implicit consequence of the methodology is that the understanding of sensory properties that is generated by ISR models does not provide an explanation of the sensory attributes in terms of a full and quantitative mechanistic description of all the numerous mechanical, physical transport, and phase behavior phenomena involved during consumption of food products (not to mention the mechanisms of the numerous physiological and psychological effects in perception initiated by these physical phenomena). In most cases, the complexity common to food products inhibits this complete mechanistic description. Instead, the methodology provides knowledge about the relative importance of different physical product properties. Through this knowledge, information is obtained about the relative importance of different physical processes and mechanistic elements. This information is valid within the sensory space of the product set investigated and within the constraints of the panel or consumer group used.

Many studies have been reported on the physics behind the oral texture perception of liquid and semisolid foods (Dickie and Kokini 1983; Kokini 1985, 1987; Takahashi 1991; De Bruijne and Bot 1999). These studies all have in common that oral food processing did not require biting or chewing. Thus, oral texture perception could be physically related to premouth rheology and mechanisms of break-up (de Bruijne et al 1993) in salivary flow. In studies of foods like baked products, the oral processes are strongly driven by chewing (Heath 1991). Reduction of particle size and of resistance against food deformation are the main goals of the chewing process. Only when perceived resistance is sufficiently low and particles are sufficiently small and lubricated, will a bolus composed of crumb particles be swallowed (Prinz and Lucas 1997).

The need for chewing creates options for sensory variations (deficits, challenges, innovations) that are different and additional to the options without chewing (Heath and Prinz 1999). Another consequence of chewing is that different and additional consumer specific settings of the oral food processing machine will influence oral physics and perception. Perceived resistance from the moment of intake until the moment of swallowing, combined with perceived particle size, deformability, and lubricity-stickiness as a function of time, gives an oral fingerprint of the food system.

In the examples given below, this fingerprint varies with composition and quantifies product quality. Different physical methods will be presented that have been performed to quantify (indirectly) elements of the overall fingerprint. For instance, in our farinograph experiments, resistance is measured in time during kneading at 35°C of cubes of product and adding artificial saliva after 2 min of dry processing. The elements of this instrumental bread-spread fingerprint may have a relationship to bolus mouthfeel. In texture evaluations, panelists are asked to split the fingerprint up into a

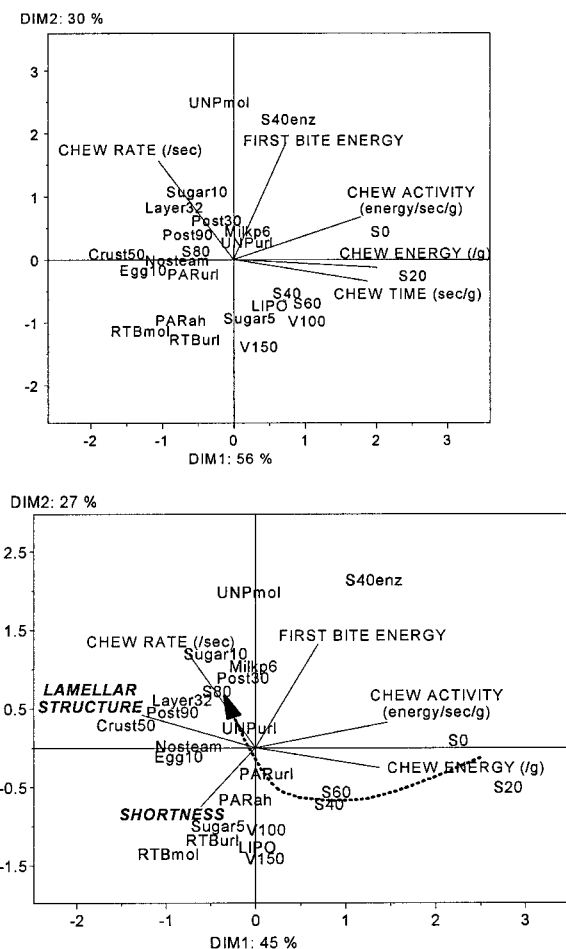


Fig. 2. Biplot representations (see Explanation of Biplots) of effects of fat reduction (arrow in right figure) in baked products + crispy outer layer type 1. Chewing properties (muscle activity) vs. perceived shortness and lamellar structure. Abbreviations are related to product formulation and are used as product codes indicating the position of the product in the two-dimensional space.

few sensory attributes. The different elements of the overall fingerprint will have a different weight factor per attribute. Our modeling combines those physical parameters (proposed to represent fingerprint elements) that give the best description per attribute. The significance of the combinations indicate how well the physical measurements represent fingerprint elements. Furthermore, the combinations demonstrate which measured elements of the overall fingerprint appear to dominate each attribute. As these elements are measured for all products (structures, fat levels, etc.) their identification allows quantification of product effects on mouthfeel in a physical sense. This could help to reduce product deficiencies as elements of the final models will provide 1) the identity of the physical parameters driving the sensory profile; 2) the extent to which they describe this profile; 3) the relative effect of these drivers. The models will also predict the sensory profile of commercial products and guide research to obtain more preferred or cheaper products with a target and benchmark sensory profiles.

Explanation of Biplots

Biplots are used to demonstrate the main messages in the data while keeping the presentation of complex data simple. The properties of the products (attributes) are represented on the map by vectors which point in different directions out from the center, or origin, of the map. The relationship between the vectors can be deduced by the angle they form at the origin. A small angle indi-

cates a high level of correlation. Attributes going off in opposite directions have a high level of negative correlation. The length of a vector is an indication of the amount of variance of that particular attribute.

The relationship between a product and an attribute vector can be interpreted by drawing a perpendicular line to the vector. Products found near the origin of a vector have less of the attribute represented by that vector than products found further out along it. It is also possible to extend the vector backwards beyond the origin in the opposite direction.

The primary axes which divide the map into quarters, are the first and second dimensions. The horizontal axis, the first dimension (DIM1), is the one responsible for the maximum amount of perceived difference between the products. It takes its meaning from the attribute vector or group of attribute vectors that are at the smallest angles to it. The vertical axis, the second dimension (DIM2), is the dimension responsible for the next highest amount of perceived differences between the products. Note that the primary axes have no meaning of their own but take their meaning from the major discriminating attributes.

The coordinates for the origin are calculated by taking a mean score across all products for each individual attribute. That means for a product to lie at the origin it would need to have these overall mean scores for every one of its attributes; it would be, in a sense, an average product.

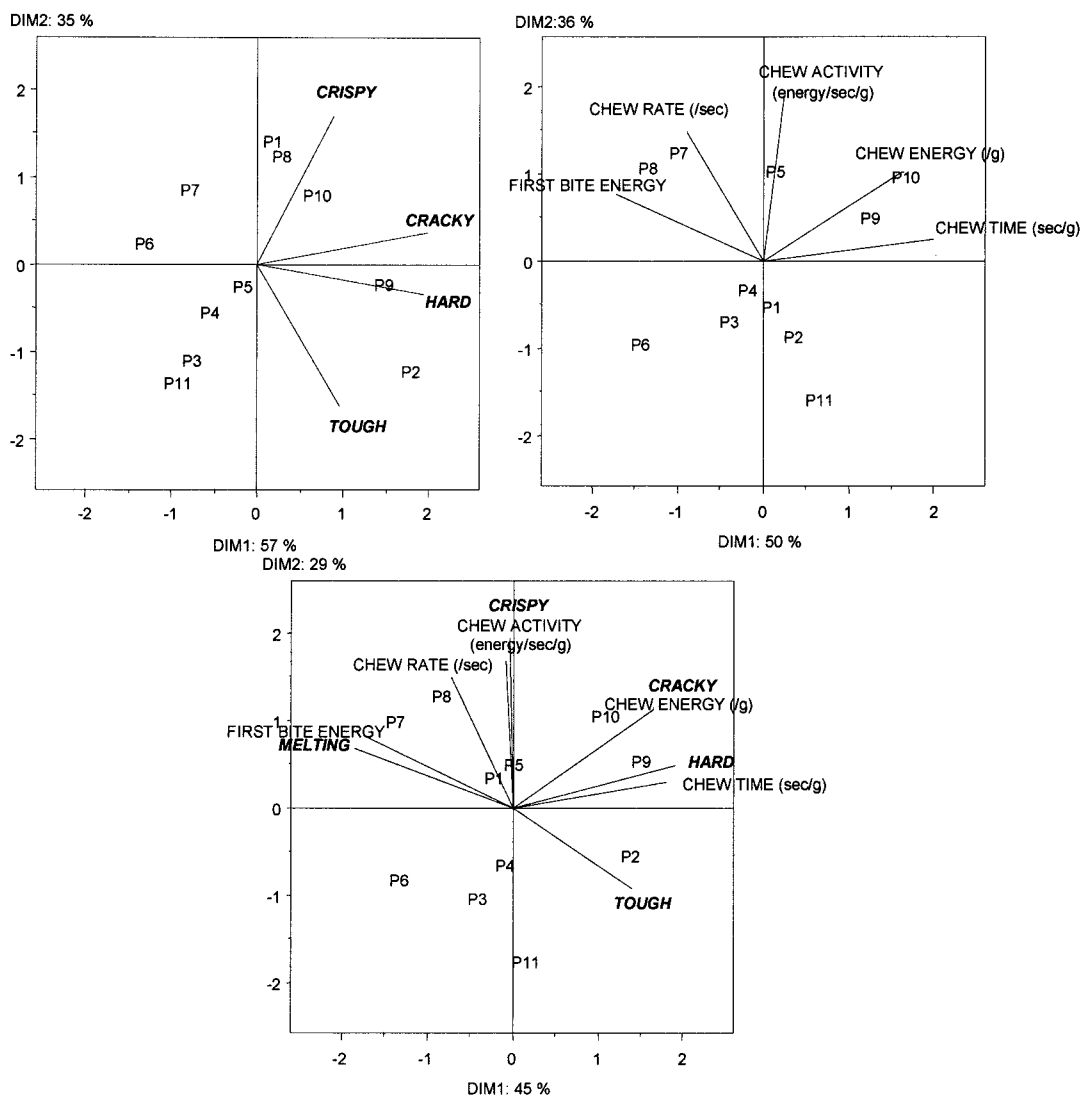


Fig. 3. Biplot representations (see Explanation of Biplots) of sensory and chewing (EMG) properties of baked products with crispy layer type 2.

RESULTS AND DISCUSSION

Step 1

Step 1 assesses consumer relevance of sensory attributes. This step requires qualitative information about the sensory drivers of consumer preference or complaints. Generally, this information leads to commercial project briefs stating sensory targets. However, additionally, this first methodological step preferably should also deliver quantitative information about the relationships between consumer repeated choice; consumer home liking and perception of product variations in a branded context; consumer laboratory sensory blind liking and perception of the product variations; sensory data obtained by the panels used as the measurement instruments in our laboratories (Bech et al 1997; Mioche and Martin 1998).

One element of these relationships needs to be stressed in this context. Figure 1 illustrates how texture perception will be influenced by the settings of the oral food processor (chewing rate, saliva flow rate, amylase activity, chewing efficiency, swallowing threshold etc.). Differences in these settings will cause different physical stimuli due to product differences but also to differences between individuals. In the latter case, oral biovariability may cause different persons to generate different physical stimuli after taking in the same product. These differences in physical stimuli generated with the same product might very well lead to differences in sensory perception consuming the same product, and thus to a different relationship between physical (in vitro) product properties and the in vivo properties sensorially perceived. This aspect has been

studied by Brown et al (1994, 1996a–c, 2000) and Braxton et al (1996) and could lead to different models being valid for different people. This might be one of the reasons consumer segmentation of sensory liking is found frequently, and also one of the reasons why results obtained with sensory panels sometimes may have limited relevance to the sensory perception of real consumers. In many sensory panels, differences in perception are being trained away, even if they would have physiological or physical meaning related to the individual.

The relationships above, including sensory effects of oral biovariability, may have both business and scientific relevance, but are subject of further studies and are outside the experimental scope of the present study.

Steps 2 and 3

Steps 2 and 3 develop a qualitative analysis of the physical processes operating during stimulation, and define physical parameters characterizing these processes. This analysis will be based on observations made during consumption of a range of products including those demonstrating relevant physicochemical variations. These observations may include data obtained using sensory methods, physiological methods like electromyography (Brown et al 1994, 1998a) deriving chew parameters from measured muscle activity patterns during chewing, or a combination of both (Brown et al 1998b). Examples from our work obtained for three different types of crispy cereal products are represented by the biplots in Figs. 2–4. These figures give the positions of products (identified by the

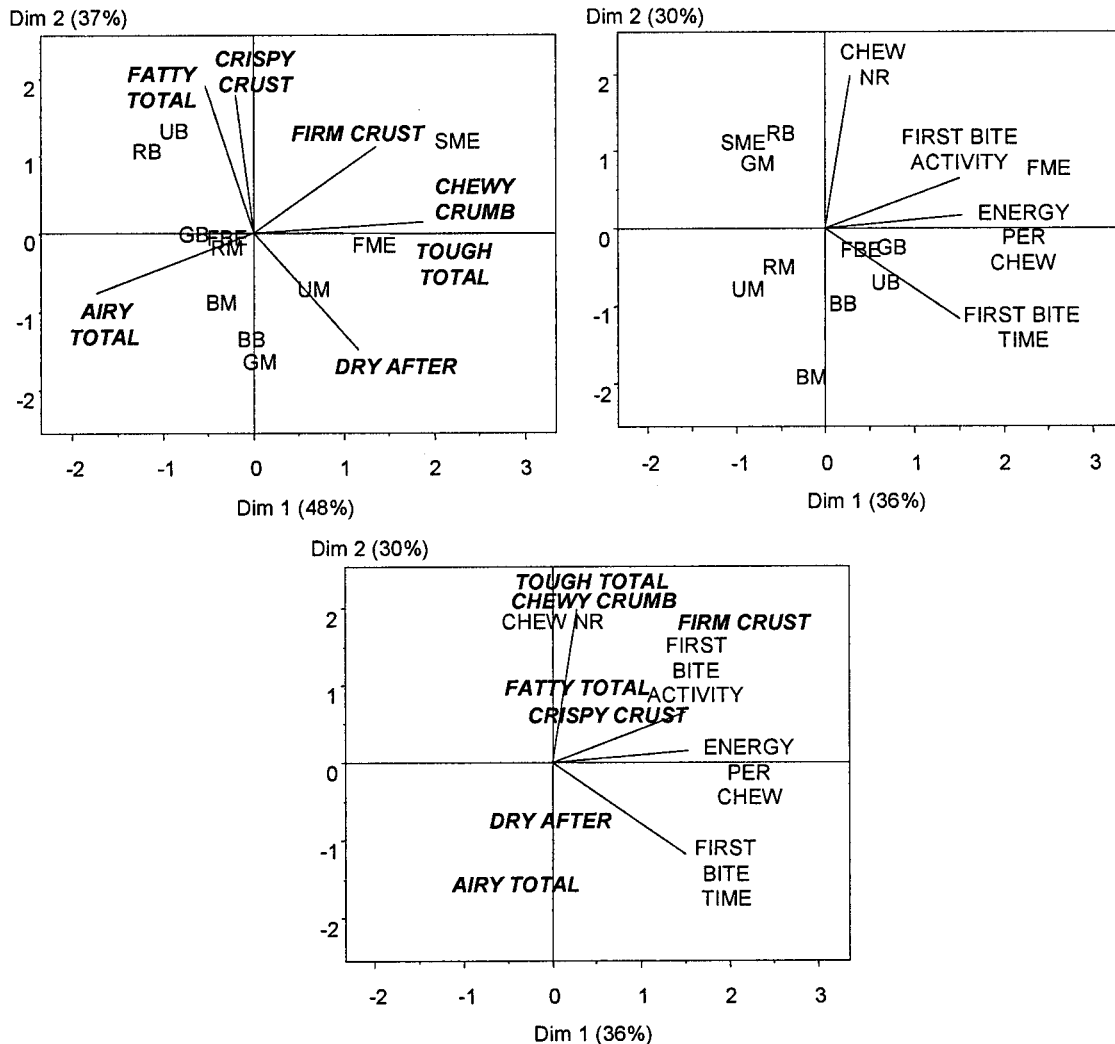


Fig. 4. Biplot representations (see Explanation of Biplots) of sensory and chewing (EMG) properties of baked products with crispy layer type 3.

different codes in each figure) in the first two-dimensions (DIM1 and DIM2) of the multidimensional space defined by the physiological and sensory properties given as vectors. [Explanation of biplot representations were given above.] The sensory attribute “cracky” as used in these examples is a translation of the Dutch word “krokant” which also relates to crunchiness.

In the examples given of consumption of baked products, biting and chewing are responsible for a range of physical processes in addition to those effective during consumption of more liquid type foods. These processes give many opportunities for perception in relation to physical stimuli. Especially during the first bite, iterative fracture events cause manifestations of crispy and cracky food structures, with more or less shortness of bite. After this first bite, chewing combined with saliva and enzyme effects cause reduction of particle size and lessen resistance against food deformation. After a process characterized among other things by chew rate, energy, and time, the perceived resistance is sufficiently low and the bolus composed of crumbs is swallowed.

Inventory of Physical Processes Relevant to Texture Perception of Baked Products

An inventory of physical processes playing a role during eating could be derived from a qualitative analysis of the consumption of baked products. After identification of these processes, for each of them one, if relevant, more physical parameters could be defined to characterize the process.

Process 1. Many baked products pass through pretreatment processes like microwave defrosting, toasting, final baking, coverage with a lubricating layer like butter, or soaking in tea. As all these processes have a significant effect on product physics and texture perception, sensory variations should be preferably related to physical variations measured on products pretreated in the same way as for the sensory evaluation. Moreover, very common pretreatment processes like covering a baked product with a lubricating layer of butter or margarine will cause many additional physical processes that operate during oral processing and are related to interactions between the baked product and the modifying, lubricating, or softening product. Although these additional processes are very relevant to practical situations, they are not discussed here.

Process 2. First bite fracture of the product leads to separation of an orally manageable sample size from the bulk of the product. This process, requiring muscle force and jaw movement, is characterized by the fracture mechanical properties of the product before saliva wetting and will play a role during the rest of the chewing process until saliva penetration gradually changes these fracture properties.

Process 3. Heat transfer between the product and the oral tissues changes the temperature of the pretreated baked product from the initial preoral value into the orally effective temperature. This process will, depending on the initial temperature, lead to sensations of coolness or heat. It could be characterized by parameters quantifying the heat flow at changing the product temperature from preoral to oral values.

Process 4. Oral particle size reduction (increase of crumb surface area) of the baked product by mastication fracture is a physical process that is one of the basic goals of the chewing process. It will be influenced by the fracture properties of the baked product as a function of the state of interaction with saliva and by biophysical differences between consumers. This increase in crumb surface area will boost process 6 (saliva wetting of crumbs). It will also increase the need for process 10 (crumb lubrication or friction reduction). This process could be characterized by an average orally effective particle size.

Process 5. Surface coverage by mixing is oral enlargement of the contact interface area between the product and saliva, induced by mixing forces and influenced by crumb size and saliva rheology. This effect will be influenced by biophysical variations between consumers causing differences in shear rate profiles in the oral cavity.

At given oral conditions and amount of food intake, this process could be characterized by the physical parameter characterizing process 4.

Process 6. Saliva wetting of crumbs operates both through fast capillary suction and slow diffusion. It will be influenced by biophysical differences between consumers, their saliva productivity,

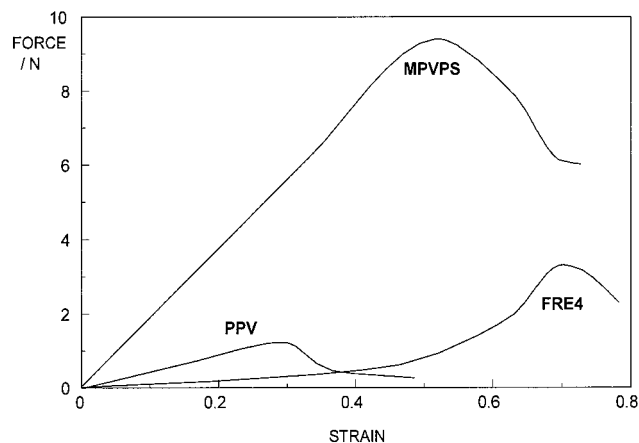


Fig. 5. Wedge penetration fracture analysis (WPFA) curves of baked products with crispy layer 2.

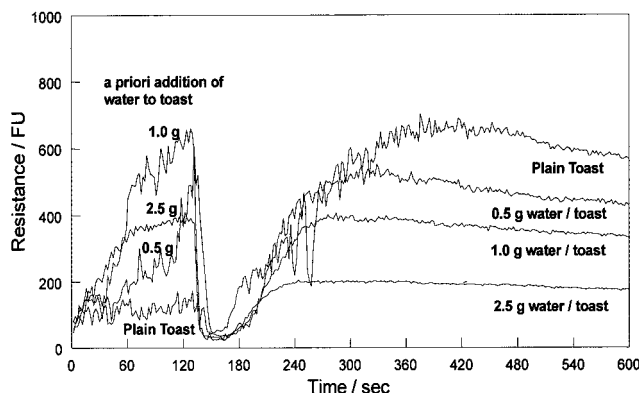


Fig. 6. Farinograph kneading at 35°C of toasted white bread (45 g of toast and water + 5 mL of artificial saliva without amylase added after 2 min).

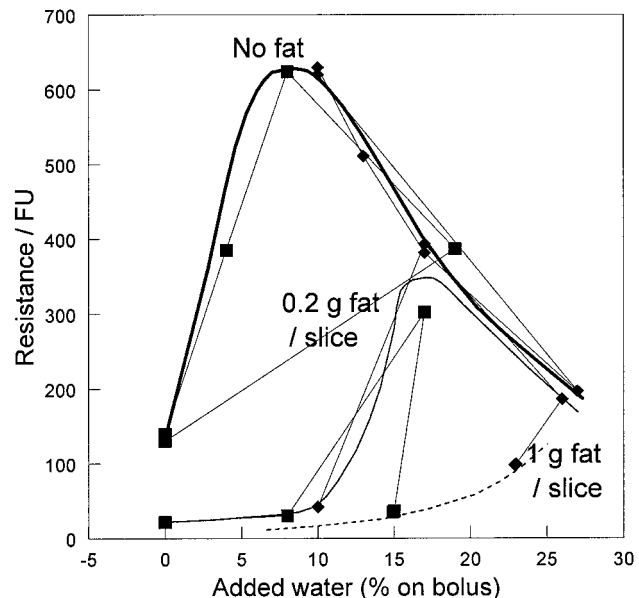


Fig. 7. Effects of water and fat on equilibrium of farinograph bolus resistance for toasted white bread (10 g/slice) measured at 35°C.

and properties (viscosity). This process counteracts process 10 (crumb friction reduction) and will be counteracted by process 11 (crumb gluing). After extreme baking regimes like severe toasting, the product may acquire a more hydrophobic character, thereby decreasing the speed or relevancy of this process. Also variations in fat level in the product may influence saliva wetting. The process could be characterized by parameters describing the kinetics of water uptake of the crumbs.

Process 7. Oral amylase action in most baked products will break down starch, decreasing crumb hardness and size, thickening the saliva, and possibly increasing the crumb glue (process 11). This process will be clearly influenced by individual differences. At given oral conditions, the process could be characterized by a parameter quantifying the effect of amylase presence on the resistance of crumb-saliva mixtures as a function of time.

Process 8. Crumb softening as a result of saliva wetting and amylase action increases the deformability of the final bolus consisting of the interacting crumbs. It could be characterized by a parameter quantifying the resistance against deformation of the bolus in equilibrium contact with saliva with or without amylase.

Process 9. Saliva thickening by dissolved molecules or dispersed small entities separated from the crumb could be characterized by the viscosity of the thickened saliva.

Process 10. Crumb lubrication and friction reduction by saliva increases the final bolus deformability. It will increase with decreasing crumb volume fraction in the bolus (more saliva inside the crumbs) and decreasing viscosity of the saliva phase between the crumbs. A poor crumb lubrication will cause stickiness (crumb gluing, process 11). The process could be characterized by a parameter quantifying an effective crumb friction coefficient.

Process 11. Oral particle size increase by crumb gluing is the collection of particles into a coherent bolus (Hiemae and Palmer 1999). The crumb surface area available for surface coverage by mixing will be decreased by glue properties of the initially wetted outer layers of the crumbs and by phases consisting of more or less thickened saliva. This process could be characterized in combination with process 4 by an average orally effective particle size.

Process 12. Loose saliva transport relates to processes 4 and 6 and will become more critical if large quantities of saliva have been used to wet and lubricate the crumbs and under conditions at which the saliva production induced by chewing is not sufficient to compensate for this and wet the oral tissues (causing dry mouth effects). At given oral conditions, this process could be characterized by the inverse of the parameters characterizing process 6: less loose saliva transport if more saliva has been taken up by the crumbs than can be compensated by the saliva production.

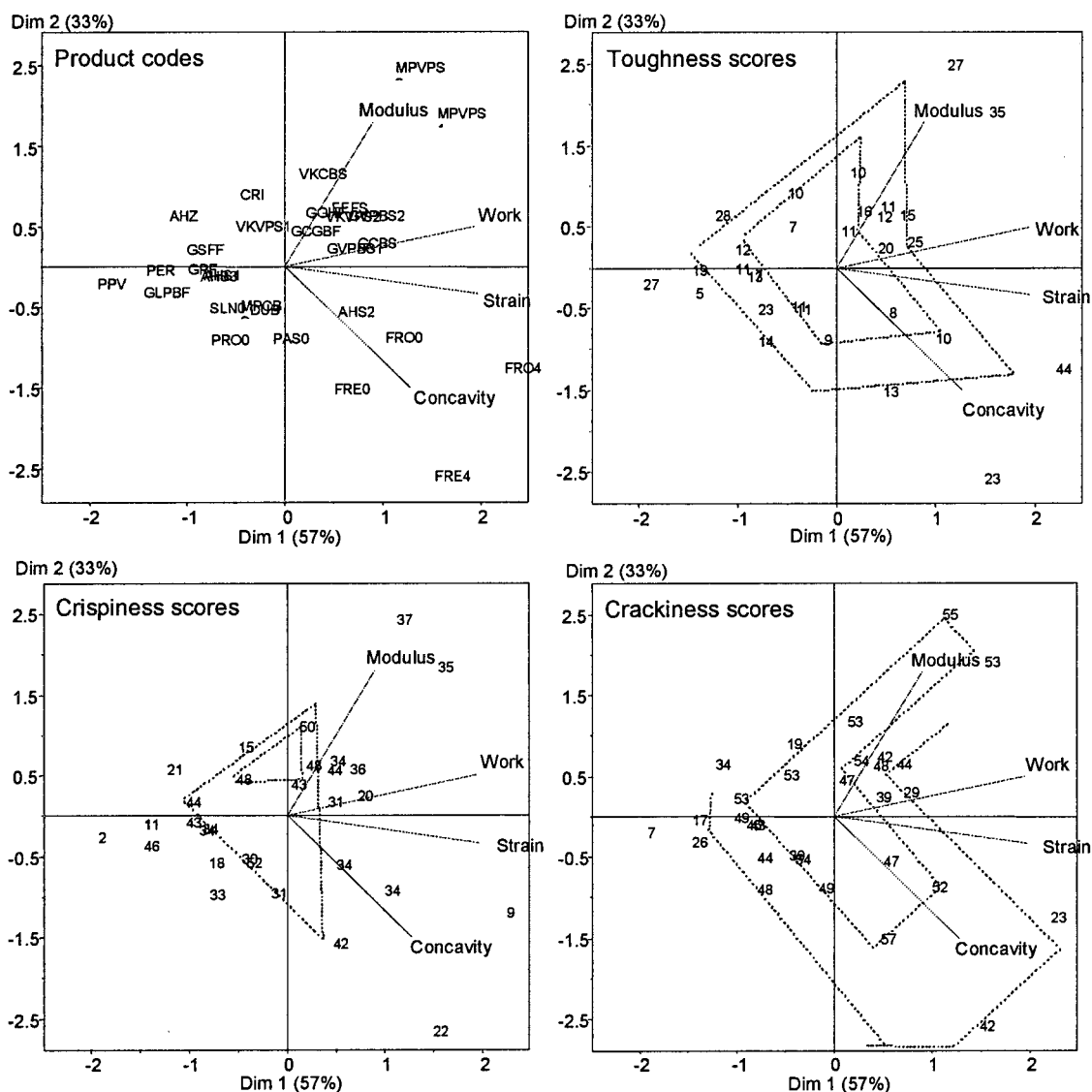


Fig. 8. Biplot representations (see Explanation of Biplots) of wedge penetration fracture analysis (WPPA) data from baked products with crispy layer type 2 related to sensory properties.

Process 13. Even if a bolus suffers from considerable internal friction or consists of crumbs that are strongly glued to each other, the outside of such a low deformable bolus could be well lubricated by a suitable saliva phase. Also, this effect would be very sensitive to biophysical variations (saliva flow rate vs. crumb saliva absorption rate). Expression of critical effects of this process would increase with increasing amounts of product taken in. This process could be characterized by the same parameter used for process 12.

Process 14. Swallowing is the physical transport of the bolus (or part of it) from the oral cavity into the esophagus. This process will take place after (unconscious) "green light" perception of the combination of bolus and crumb particle size, deformability, and friction properties. Analysis of bolus and crumb particle size, deformability and friction properties on boluses spat out immediately before swallowing, could lead to definition of the physical properties critical to swallowing for the research subject.

Process 15. Mouthcoating after swallowing is influenced by processes 9 (saliva thickening), 11 (collection of particles into the bolus), and 12 (loose saliva transport) and decreases to the extent that oral shear forces are able to scrape off layers adsorbed on the oral tissues. At given oral conditions, this process could be characterized by a combination of the parameters characterizing processes 9 (saliva thickening), 11 (collection of particles into the bolus), and 12 (loose saliva transport). Next to these physical processes, physicochemical processes related to the chemical product composition (like fat level) and the hydrophobic and hydrophilic nature of ingredients may play an additional role in sensory attributes related to mouthcoating (for instance chemical reactions, bilayer formations).

Step 4

Step 4 develops methodology to quantify the physical parameters identified in step 3. The following in vitro and in vivo methods have been applied and are further developed to quantify some of the parameters identified previously to be characteristic of oral processes relevant to the baked products we studied.

Wedge penetration fracture analysis (WPFA) of compression measurements using an SMS texture analyser has been applied to obtain the fracture properties relevant to process 2 (Vincent et al 1991). In this method, a rounded-off stainless steel wedge (included angle is 30°) penetrates the product at a speed of 1 cm/sec until a maximum strain of 90%. In Fig. 5, product PPV has the lowest fracture strain; product MPVPS has the highest fracture stress (proportional to force), fracture modulus (= fracture stress and fracture strain) and fracture work (area under the curve until fracture); and product FRE4 has the highest strain hardening or concavity of the stress-strain relationship. The fracture strain measured on these preoral dry samples could also be assumed to deliver an approximate quantification of effective oral particle size (process 4). Accordingly, product PPV in Fig. 5 would deliver smaller particles and product FRE4 larger particles than product MPVPS. Considering the chewing process to be largely strain controlled, a given chew would cause a standard strain, thereby causing more fractures in a material of low fracture strain than in a high fracture strain.

Farinograph measurements have quantified properties of crumb and saliva mixtures related to several of the identified physical processes. The kneading resistance of cubes of baked product has been measured using a farinograph (Brabender type 8101), a machine developed to measure forces during kneading and development of dough. It consists of a mixing bowl in which two Z-shaped blades rotate in opposite directions at a constant speed. We used a 50-g measuring mixing bowl at 35°C, a mixer speed of 63 rpm, and a total kneading time of 15 min. Farinograph measurements are given in Fig. 6 for 5 mL of artificial saliva (Saliva Orthana ex Kemisk Fabrik, Kastrop, Denmark) added to 45 g of toasted Casino white bread after 120 sec of dry kneading. One of the observations based on these curves is that the time to reach equilibrium resistance after addition of artificial saliva decreased

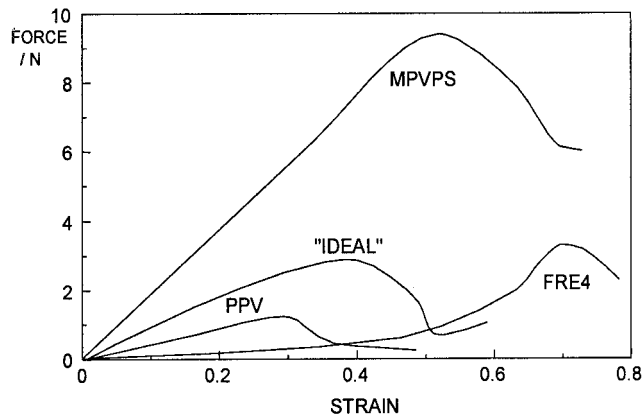


Fig. 9. Wedge penetration fracture analysis (WPFA) data of extreme vs. ideal baked product with crispy layer 2.

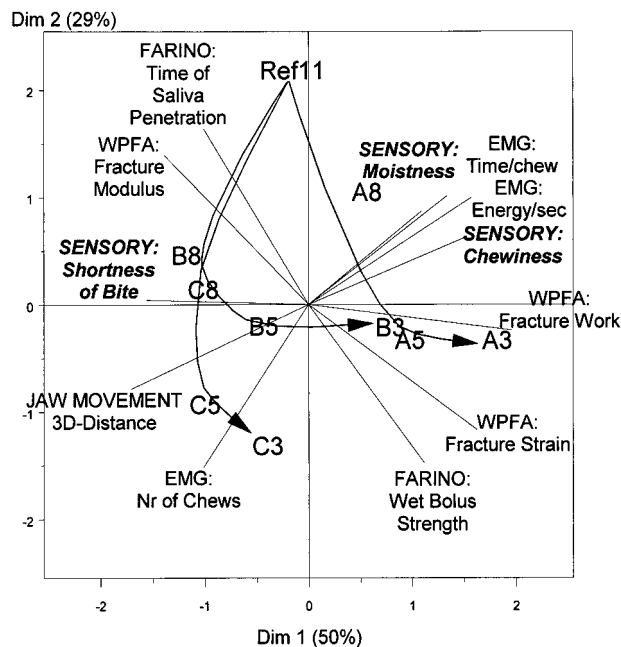


Fig. 10. Biplot representation (see Explanation of Biplots) of sensory and physical effects of three different fat reductions (A-C) in baked products without crispy outer layer. Numbers indicate fat level.

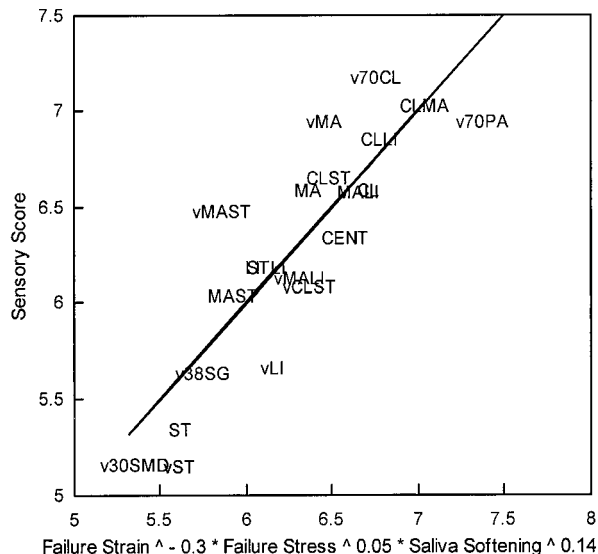


Fig. 11. Relationship between measured and modeled sensory scores obtained for calibration and validation (v) set of products.

from 119 sec for plain toast to 31 sec when 2.5 g of water was added per slice of toast before starting farinograph kneading. This time to reach equilibrium resistance will be related to the kinetics of water taken up by the crumbs and could be associated with process 6.

Differences between results of a farinograph experiment in which amylase has been added to the artificial saliva and such an experiment without amylase, could be associated with process 7. Equilibrium resistance after saliva addition could be associated with an integrated effect of processes 8, 10, 11, and 13. As the interface area of the kneading blades with the bolus formed in the farinograph is rather high, this equilibrium resistance appears to be very sensitive to processes 10, 11, and 13 (friction and lubrication effects). This is illustrated by the effect of adding small amounts of fat (molten at 35°C) to the equilibrium farinograph bolus resistance as function of water content (Fig. 7).

Electromyography (EMG) is a technique which uses electrodes positioned on the skin of the face to measure the activity of the muscles (masseter and temporalis) involved in mastication (Boyar and Kilcast 1986; Jack et al 1993; Brown et al 1994, 1995a–b, 1996a–c, 1998a–b, 2000; Duizer et al 1996; Agrawal et al 1998; Mioche and Martin 1998). From the muscle activity as function of chewing time, parameters like first bite energy (only first bite or chew), total chew energy (all chews), chew time, energy per chew, and chew activity (total chew energy/time) have been calculated. These parameters have been used to characterize elements of the processes 2 (first bite fracture), 4 (oral particle size reduction), 8, 10, 11 (crumb softening, lubrication, and gluing), and 14 (swallowing). In parallel with this technique, jaw movement (van der Bilt et al 1991; Kazazaglu and Heath 1991; Wang and Stohler 1991; Langley and Marshall 1993; Brown et al 1998; Kohyama 2000) has been measured. Parameters measured included average distances between the upper and lower jaws in the horizontal, vertical, and anterior-posterior direction of movement during chewing. The average three-dimensional distance between the jaws was calculated from these three values.

Step 5

Step 5 measures physical parameters and sensory attributes for a relevant range of products (identified in step 3). The products should include extremes and reflect a homogeneous distribution over the sensory space, as well as a minimum of variation on sensory attributes not to be modeled.

As an example, Fig. 8 shows biplots of WPPFA data measured on baked products with crispy layer type 2, additional to the data of the extreme products given in Fig. 5. The first biplot in Fig. 8 gives the product codes on the WPPFA position of each product (determined by the four WPPFA vectors). The other three biplots give sensory scores on the WPPFA position of each product. The overlaying lines in these latter three biplots, containing the sensory scores, represent more or less isosensory lines, illustrating that quite different physical properties may result in an equal sensory score. In general, lowest toughness and highest crispiness and crackiness scores are located in the center of the biplot. These data allow a provisional construction of an ideal fracture stress-strain relationship, resulting in lowest toughness and highest crispiness and crackiness (Fig. 9).

As another example, Fig. 10 illustrates the sensory (moist, chewy and shortness of bite) effects of three different methods of fat reduction in baked products without crispy layer, in combination with effects measured by WPPFA, farinograph, EMG, and jaw movement. Chewiness appeared to correlate with EMG chew energy/sec, shortness of bite correlated inversely with WPPFA fracture work, and moist appeared to correlate inversely with jaw movement measured as 3-D jaw distance. Fat reduction, in general and quite logically, appears to result in a higher fracture strain and a lower fracture modulus correlating with a faster farinograph measured saliva penetration and a higher wet bolus strength (resistance after break-

down and saliva penetration). The latter illustrates the reduced lubrication properties of the low fat products. The relative size of the physical effects, however, differs between the three methods of fat replacement, as well as the sensory consequences thereof, which has been a very interesting observation on behalf of product development.

Steps 6 and 7

Step 6 derives quantitative models and identifies parameters dominating sensory perception. Step 7 fine-tunes and validates these quantitative models. Sensory scores can be modeled in terms of the physical parameters measured by linear regression using the log-transformed values, thus enabling initial screening of multiplicative Stevens models. Models thus obtained can be fine-tuned using nonlinear regression on the nontransformed values. The criteria that should be applied in the process of selecting physical parameters to enter into the models are: 1) maximum explained variance (max R^2); 2) minimum residual error per degree of freedom: minimum mean square error (MSE) or (even better) minimum prediction error after cross-validation; 3) significance of coefficients in model (significantly nonzero); 4) lowest correlation coefficients between physical parameters in one model; 5) total number of different parameters in all models obtained for the product set should be minimized.

Examples of models which have been obtained in this way, are given by Equations 1–4. These models suggest the sensory parameters firm crust, crispy crust, airy total, and tough total as determined for the product set given in Fig. 4 (croissants) to be dominated by the preoral (in vitro) WPPFA properties fracture modulus and strain hardening and the oral (in vivo) EMG properties first bite (FB) time, work and activity (work/sec), and total chew time, number, work/chew, and activity.

$$\begin{aligned} \text{Firm Crust} \quad (R^2 = 0.99) \\ (\text{Modulus}^{0.3} \times \text{hardening}^{1.4} \times \text{FB time}^{0.3} \times \text{chew activity}^{0.3} \\ \times \text{chew time}^{1.6})^2 \end{aligned} \quad (1)$$

$$\begin{aligned} \text{Crispy Crust} \quad (R^2 = 0.75) \\ (\text{FB time}^{0.4} \times \text{chew no.}^{-1} \times \text{work/chew}^{-0.6})^2 \end{aligned} \quad (2)$$

$$\begin{aligned} \text{Airy Total} \quad (R^2 = 1.00) \\ (\text{Modulus}^{-0.2} \times \text{hardening}^{-0.8} \times \text{FB time}^{0.8} \times \text{FB activity}^{0.6} \\ \times \text{chew activity}^{-1.8} \times \text{chew time}^{-2.5})^2 \end{aligned} \quad (3)$$

$$\begin{aligned} \text{Tough Total} \quad (R^2 = 0.96) \\ (\text{Modulus}^{0.2} \times \text{hardening}^{1.2} \times \text{FB work}^{-0.5} \times \text{chew activity}^{1.8} \\ \times \text{chew time}^{2.9})^2 \end{aligned} \quad (4)$$

Validation of these models would require production of a new set of products, intermediate to the ones in the modeled data set, measuring all sensory and physical parameters and testing the statistical significance of the relationships found. An example of such a validation obtained with a different category of products, is given in Fig. 11. With these products, the mathematical equation derived using the physical and sensory data obtained for the calibration set of products was used to predict sensory scores from the physical data obtained with a validation set of products (v prefix in Fig. 11). The relationship of these predicted values to measured sensory scores was statistically significant, which lead to the conclusion that the model derived was valid.

CONCLUSIONS

A new methodology has been developed defining seven steps to acquire 1) understanding and identification of the physics dominating sensory perception, and 2) predictability of sensory scores from physical properties. Understanding is provided not in terms of a complete mechanistic explanation, but in terms of knowledge

about the relative importance of different physical properties and, through this, about the relative importance of different physical processes and mechanistic elements (all within the constraints of the product set and panel or consumer group investigated).

Biplots of sensory and chewing parameters characterizing product differences measured during consumption of baked products have assisted in identifying physical processes relevant to texture perception of the experimental set. To characterize some of these processes both in vitro (WPFA and farinograph) and in vivo (electromyography and jaw movement) methods have been explored. Data have been obtained illustrating basic physical effects of fat reduction in baked cereal products like increasing fracture strain, decreasing fracture modulus, increased saliva penetration, and reduced lubrication properties, as well as the sensory consequences thereof. Different fat replacers appear to modify these effects in rather deviating ways (more or less interesting to product development), thereby delivering physical understanding of the routes to product optimization.

Biplots relating physical and perceived texture properties have demonstrated how different sets of physical properties may lead to the same sensory perception. To model this, a multivariate approach has been applied that explains the more complex sensory attributes from instrumentally measured physical properties where one-to-one relationships fail. This multivariate integrated sensory response (ISR) modeling integrates the whole set of receptor and brain responses on physical stimuli, all essential for a given sensory attribute by delivering a quantitative, multivariate, multiplicative Stevens model of the sensory attribute in dominating physical terms: Sensory attribute = $a \times \text{Phys1}^b \times \text{Phys2}^c \times \dots \times \text{Physn}^n$

Initial, unvalidated ISR models have been developed for the sensory attributes firm crust, crispy crust, airy, and tough in terms of dominating WPFA and EMG parameters. We demonstrated how an ISR model can be validated using an additional set of products.

As the decision by (a segment of) consumers about their sensory perception of a given set of products is the integrated result of many interactive, parallel, or consequential psychological, physiological, and physical processes, the physical parameters identified and validated to be dominant are likely to characterize product effects in those physical processes that dominate this perception. If this sensory perception would be relevant to consumer choice, it would suggest that other product properties and other physical processes would be less relevant to study and optimize within the constraints of the product category and consumer group investigated. Thus, a better focus in product development is obtained.

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