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Perceiving the Texture of a Food: the Biomechanical and Cognitive Mechanisms and their Measurement

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1. Introduction

Perception is the objective achievement of acquiring knowledge about the environment through the senses. Therefore, measuring a consumer's perception of the eating quality of a sample of a food requires the scientific use of information produced by the eater to recover sensed information generated by the food material.

This information-transmitting performance by an individual consumer can be indicated by selecting foods for eating, whether at the table, in the kitchen, from the menu at an eating place or off the shelves in a shop. However, by themselves these choices among foods tell us nothing about what in the foods was perceived that produced the observed selection: in order to study sensory perception, there must also be evidence that distinguishes among the many possibilities of stimulation to the senses from the material. That is, the influential physicochemical characteristics of the available foods have to be known before consumers' choices among foods and their expectations about food quality can be used to measure their perceptual achievements on the materials.[1-3]

Thus, sensory description is not the perception of materials, nor does the mapping of sensory scores onto hedonic scores (or preference votes) model the perception of quality. Neither can sensor readings or other instrumental parameter values serve as quality criteria without having been validated objectively on the perception of sensed quality by representative consumers.

The science of objective perceptual performance is psychology. The sciences of the senses also include neuroscience: this ranges from the molecular neuroscience of the outer membrane of the sensory receptor cell, through the neurophysiology of discharges in the axon from the receptor to the first synapses in the brain, to the functioning of the networks to, among and from the cells in cerebral cortex whose activity is influenced by stimulation of particular types of receptor - activity which can be summed up crudely in event-related electrical waves or nuclear magnetic resonance of oxygenated blood flow. However, the way in which any part of this neuronal machinery contributes to perception can only specified by analysis of the overall information-processing performance of the individual who has the senses, brain and muscles for stimulation and responding. False-colour brain images may look very pretty but they tell us nothing about the perception of food unless differences in brain activation are related in a mechanistically interpretable manner to differences in the performance of the individuals whose heads have been scanned.

This processing of information in the mind of the life-taught consumer (or of the laboratory-trained sensory panellist) is like any other type of causal process invoked by scientists: it can only be inferred from observations by use of theory that has been confirmed by long periods of empirical testing of critical hypotheses derived from plausible speculations. The transmission of information from the senses to actions can be regarded as going through communication "channels". All types of mental process, conscious or unconscious, tend to be referred to by psychologists these days as "cognitive". Thus calculations to diagnose the sorts of channel(s) or perceptual processes that are in use as an assessor evaluates a set of samples of a food can be called cognitive models of the food's quality.

2. Preference and quality are objective perceptions

The perception of material characteristics of a food is not fundamentally different from the perception of the food's quality with respect to those characteristics. The implications of that psychological fact can be disconcerting. For example, the notion that sensory scores are objective while hedonic scores are subjective arises from scientifically invalid analysis of the numbers generated by the assessors.

Dispositions to select foods having certain characteristics rather than others, i.e. preferences among foods, can be expressed very precisely and economically in words and numbers. The word used for the attitude makes little or no difference – liked, pleasant, just right, preferred, likely to be chosen, good quality etc. The way the numbers are generated matters little either, so long as the test sample (not a magnitude of sensation) is placed at a point between the highest preference possible (ideal, perfect, always choose) and a lack of quality that borders on the unacceptable.

Such quantitative judgments (ratings) can also be used with descriptions of foods in more or less particular terms, e.g. "runny" or "thick" on a line from "not at all" to "extremely." These descriptive ratings can include the degree of liking or dislike for the particular level of the named characteristic in the food sample, e.g. "so runny that I'd never choose it" or "exactly as thick as I like it." That is, sensory description and hedonic evaluation do not have to separated but can be incorporated into a single score.[2-6]

Traditionally, however, the descriptive assessments in sensory panels are supposed to have been emptied of attitudes. This intention is rooted in the mistaken view that preferences cannot measure sensed characteristics. On the contrary, judgments of the preferred of two levels of a sensed food property can discriminate those levels just as well as the traditional profiling scores. Indeed, the preference-based descriptive judgments have the bonus of specifying the individual assessor's ideal point too when related to values of a receptor-stimulating physicochemical parameter.[7]

This error of regarding hedonic, affective, preference or overall quality judgments as "subjective" was corrected 20 years ago.[8] Yet the implications are still not generally recognised. A consumer's scores of liking or choice come to a peak at the personally ideal level of any sensed property of a food. Hence, before averaging such data across the individuals in a panel, a lack of preference below the ideal point must be given the opposite sign to a lack of preference above the ideal point. These unfolded scores are as comparable among assessors as the plain descriptions are.

An even more basic scientific fact about perception has been neglected since the beginnings of sensory evaluation over 50 years ago. This neglect has diverted an enormous amount of effort into developing descriptive vocabulary without any criteria for determining what the words describe. Indeed, the numbers generated in descriptive profiling can never identify what the raters have perceived in the rated samples of food. Even if the panellists have been trained with standard materials to illustrate the meanings of the descriptors, as recommended for sensory analysis of texture,[9] the information transmitted by each descriptor is seldom if ever identified as specific to a source of stimulation to the senses from foods of the sort to be descriptively profiled, let alone calibrated on chemically or physically measured levels of the specific property.

Very recently it has become fashionable to replace the traditional phrases containing the word "sensory" by the term "perception." This makes the scientific mistake even worse, by claiming the one thing for sensory data which is logically impossible for them to provide - evidence on what sensed material properties of a food are reflected in a point on a panel's profile of scores.

In short, numerical scores of descriptions and/or preferences, however sophisticated their statistical modelling, by themselves tells us nothing about the science of what has been sensed in the food. The theoretical nature of a descriptive or 'hedonic' rating is a social communication, not any sort of surrogate chemical assay or physical measurement. Ratings cannot be related successfully to sensed physicochemical properties until we have evidence as to what information from the food was actually processed through the senses to produce the observed attitude or ascription.

Hence a science of sensory perception has to integrate the cognitive science of the perceivers' language with the physical and chemical science of materials.

3. Food psychophysics

The traditional name in psychological science for the relationship between a graded assessment of various samples of a particular material and a graded physicochemical property of those samples is the *psychophysical function* (Figure 1).

This graph specifies the transformation achieved between input through the senses from patterns in the environment and the output of patterns of action on the environment. This transformation is a causal process in the mind of the assessor, totally dependent both on neural processing in the person's brain and on social processes in the person's culture but not reducible or deconstructable into either.

Perhaps the most familiar practical example of a psychophysical function is a plot of ratings of how sweet a solution is against various concentration of sucrose or some other sugar or sweetener in a beverage, i.e. in water also containing some or all of other tastants, aroma volatiles, colourings, gelled macromolecules and suspended, emulsified or colloidal particles (solid, liquid or gaseous). Unfortunately, academic psychophysics got caught up in a chase of the will of the wisp of a general equation for intensity scores from stimulation of supposedly single types of sensory receptor from undetectable levels to saturation. This abstracted from its context the well learnt perceptual process (e.g. judging how sweet a food is, relative to some familiar or preferred level) and produced the bizarre enterprise of rating preference for pure solutions of sucrose or saccharin and unreal claims that there is a universal innate preference for 10% sucrose.

In fact, very precise psychophysical functions can be obtained if the amount of a particular source of stimulation is varied (regardless of which or how many types of receptor are stimulated) around the amount that is familiar to an assessor. The test samples should otherwise be fairly similar to the usual form of the food and either vary little in other ways or vary substantially in one or more other sensed features but independently of each other -- that is, no two factors substantially correlated.

The way that psychophysical data are talked about often fails to allow for the logical necessity that data from only one input variable and one output variable are insufficient to provide evidence for or against any one type of mediating process in the mind. The perceptual performance could have been achieved by sensory processes close to the receptors, by linguistic processes close to the descriptive or attitudinal response or by a phenomenological process such as a sensation or an emotion. That is to say, there is no scientific justification for regarding the construction of a psychophysical function from merely one response and one stimulus as the estimation either of subjective magnitudes (the fallacy of direct scaling) or of firing rates in afferent nerve fibres (the fallacy of neural reductionism).

When there are two or more observed patterns of output, on the other hand, it may be feasible to specify the type of mental process involved. Such covert functions are certainly diagnosable when there are also two or more observed patterns of input. These indirectly evidenced functions represent mental processes (either conscious or unconscious), otherwise known as cognitive mechanisms (that account for observed performance) or perceptual channels (of communication through the perceiver). The relationship between an observed stimulus and an observed response can be regarded as the limiting case of a mental process, one that is totally evident in overt performance.

4. Dependence of precision on context

Theoretically, a psychophysical function follows the intersection of a vertical plane with the surface of a cone (Figure 2). Sensed amounts of a characteristic are perceived as further away from the standard amount (at the cone's peak) as they go farther below or above that level, e.g. away from best quality towards "too little" or "too much" respectively. When scores for amounts above the usual level are plotted above the score for the highest quality level, the peaked curve becomes the familiar monotonic function (Figure 1).

When the test samples are all of the highest quality (or are maximally preferred by the individual assessor when rating is relative to ideal) except for variation in one characteristic being investigated, the intersecting plane goes through the apex of the cone. Then the distances from the apex form an isosceles triangle and the "unfolded" function is a straight line. However, if the basic preparation is of lower quality (or not personally ideal), the folded function will be a conic section, having the formula:

$$R = m\,(S^2 + D^2)^{-0.5} + c$$

where R is the response score to a sample, S is the level of the varied stimulus in that sample, D is the size of the defect(s) in the preparation. (If the score for top quality of ideal is set at zero for analysis, then the constant disappears and the slope becomes the proportionality between response units and stimulus model units.)

Thus, a rounding of the preference triangle to an inverted U shape diagnoses an unrealistic set of food samples (characteristic of hedonic scores for plain sugar water). Even if all the experimentally varied factors are at the perfect level, an otherwise defective food preparation will not be of the highest quality.

It is of fundamental importance that the triangle, the two-feature cone and the multiple-features "hypercone" are each defined by their apex; there is no particular base to the cone. Furthermore, there are limits to the linearity of the function at the extremes of stimulation below and above the level at the apex. As that sort of stimulus becomes hard to detect, the line steadily decreases in slope, changing from a logarithm of physical values to the square root.[10] At high levels (probably beyond anything that can be incorporated in food), the slope will also decrease as receptors approach saturation. More relevantly to perception of foods, as the level of a sensed property deviates further from usual levels, so the whole formulation becomes less familiar and may even change in character. So preference will be reduced to the limit of acceptability and different factors of unacceptability will operate increasingly.

Thus the folded function is shaped more like a omega than a delta in Greek capital letters.

These limits on tolerance of deviations from the norm invalidate a key assumption made 30 years ago by the psychologists who developed the multidimensional scaling of preferences are now widely used in sensory statistics (e.g. MD-PREF). In these calculations, all potentially peaked data are fitted to a quadratic function. Yet the set of samples to be assessed are not selected for familiarity to or tolerance by each individual assessor in the panel. Hence the data far from the ideal or familiar are non-monotonic and the theoretical function has inflections at its extremes (something like an omega): therefore the data should be fitted to cubic or quartic functions, not a quadratic.

On the other hand, these limits on the unfolded linear function provide a hard mechanistic basis for the use of fuzzy logic in analysis of psychophysical data that have been collected with regard for individuals' ranges of preference. The non-linear extremes correspond to two-value logic and the linear phase between them carries all the useful information, albeit in far from fuzzy form.

5. "Tasting" and texture perception

The descriptors for sensory ratings that are thought to be strongly influenced by the purely physical characteristics of liquids or solids are generally called *textural* terms. "Texture" is commonly taken to be delimited by mechanical properties sensed by touch, i.e. usually "mouthfeel," or possibly by kinaesthesis (senses of the muscles, tendons and joints).

However, the cracking of hard solids can be heard; indeed, there are no mechanoreceptors known in the mouth that are sensitive to frequency. In addition, the spatial distribution of (near-)surface reflectance by liquids and solids can be sensed by eye (textural appearance). Therefore experiments on perception of the physical properties of foods must not assume that textural information is purely tactile.

Furthermore, the physical properties of foods sensed in the mouth are often related to their sensed chemical composition and, in addition, can greatly affect the release of solutes and volatiles, generating respectively gustatory, irritative (pain) and astringent (texture) stimulation during mastication, as well as retronasal olfactory stimulation during swallowing. The mouthfeel of dairy creams is strongly confounded by the release of lipophilic volatiles, with "creamy" aroma signalling fat content at least as strongly as apparent viscosity does.[11] The barely describable tastes of sodium chloride and lactose in the aqueous phase may also be important in preserving a genuinely dairy feel at high fat contents against an unnatural "oily" impression.

Appreciation of the sensed material quality of a food or beverage is commonly termed "tasting," whether during deliberate sampling of the material or incidentally to eating or drinking it. Thus the "taste" of a food includes the effects of volatiles as well as solutes and may well extend to aspects of stimulation from spatiotemporal patterns of force or displacement generated by the food in the mouth. For example, chocolate may "taste" smooth as well as sweet, bitter and chocolatey (aroma). The "flavour" of a food may also extend to textural aspects, such as the feel of cream perhaps. However, it may be too strong to speak of an illusion that texture is taste in the mouth, in the way that retronasally sensed aroma is normally confused with oral gustation in the combined flavour of a food.

6. Perception of particular characteristics

It follows that mere differences in wording do not provide evidence for perception of distinct characteristics of a food. Indeed, when sensory profiling scores are tested by factor analysis or multidimensional scaling, they are often found to be full of redundancies. This shows that the panel was incapable of using the vocabulary to distinguish among most of the chemical or physical properties which investigators tend to assume that the words to refer to.

There is however a far more basic reason why descriptive profiling does not work and cannot ever work as it has been practised over the decades. The samples presented are never designed to make it logically possible for any method to distinguish among the effects of different chemical or physical characteristics of a food or a type of food or beverage.

This is a requirement on any sort of investigation of a whole material. The effects of apparent viscosities at low and high rates of shear on passage through a pipe, pouring into a pot or setting as a shape cannot be separately measured unless samples are prepared in which these two characteristics vary independently of each – that is, the two sets of values are uncorrelated. Otherwise, the effects of the two factors must be confounded and ratings on highly specific descriptors (or different physical measures) cannot give distinct results.

This is a matter of basic logic, not of statistics. It has to be addressed first by a fundamental examination of the hypotheses to be tested. If a breakfast drink is made up at different strengths without dissociating the concentrations of sugar from those of acid, no experimental design or statistical modelling can ever distinguish the effects of sugar and acid, or of sweetness and sourness, on aroma strength (for example) or anything else (such as shelf-life or sales). (The switch to examples from taste has no scientific significance: it is merely a move to clarify the point by use of well understood examples of stimuli and responses.)

Food scientists are aware of an aspect of this issue as a statistical problem, to be solved by blocked experimental designs. However, regression is a much more economical measure of the strength of an effect, such as in the slope of a psychophysical function. With only two levels of each factor whose effect is to be investigated, it needs only eight samples to disconfound seven factors (Table 1). Four samples exhaust the possible combinations of two factors, of course, and eight samples cover the dissociations among three factors.

Another great advantage of regression over ANOVA, in fundamental as well as applied research, is that the value of a factor's level does not have to be identical in replicate samples. The higher value can be a range of values in the different samples, so long as it does not overlap with the low range of values. The correlation coefficient will not then be zero; nevertheless, as long as $r < 0.3$, then over 90% of the variance in the results will in practice be separately attributable to one or other of the two factors.

7. Sensory continua and complex characteristics

A sensory characteristic that combines two or more simpler features behaves quite differently from a simple characteristic. Even after a contextually appropriate level for a simple factor has been learnt, there is still a continuum from too little through just right until too much. However, two characteristics have to be in balance in order for a complex characteristic composed of them to vary in strength. The quantity may still change if the ratio changes but the quality certainly changes.[12]

Thus, for example, it is far from certain that there is a genuine continuum of creaminess. Over a range between two familiar milks or creams, ratings of creaminess ratings are very closely related to judgments of fat contents: indeed, creaminess explains estimates of fat content.[13] However, the balance of features in double cream is likely to differ qualitatively from that in high-fat milk. Thus fat content may be judged by deciding which are the closest two familiar creams, estimating the distances of the test product from each of them and interpolating a believed content of fat.

One of the greatest difficulties in research on complex materials is to estimate the nature or even just the relative importance of the effect of a factor that has not been tested. For example, Stanley[14] did not vary droplet sizes, only oil fraction, in her study of the physical bases of creaminess. This may explain why she estimated that aroma and taste each contributed over 40% of creaminess, viscosity about 15% and fat only about 3%. Distance between droplets can have major effects on viscosity. At high oil fractions, droplet size is likely also to have a serious impact on viscosity. Furthermore, colloid and emulsion particles might affect the sense of touch independently of their influences on viscosity, as we shall see (section 10).

8. Model systems

For a model to be of scientific value, it has to be sufficiently similar to reality to provide opportunities for advancing the understanding of actual systems. This criterion is not met by colloids or emulsions in which the particles are of size or shape outside the range found in the real food system. The effects of particles ten times the size of dairy cream droplet may not be relevant to the texture of dairy creams.[15] The effects of plates are unlikely to relate to those of globular particles.[16] The effects of cellulose granules may be quite different from those of dextrin granules.[17]

This point applies equally to the measurement rigs. Frictional effects between wet surfaces in the mouth are not well modelled with dry leather.[18,19] Even now, there is no instrumental model for the smoothness of creams.[20]

So-called fat replacers are generally mere thickeners that totally fail to mimic the smoothness aspect of creaminess. Indeed some starches have a graininess and gelling agents an elasticity that bear no relation to a milk product. Consumers looking only for a fruit flavour and a slightly acid dessert may not care about the absence of creaminess. As a result, consumer quality standards are changed (some might say degraded) by the products that they get used to eating.

9. Real foods and their simulation

The sets of samples used in published sensory profiling studies are typically rather heterogeneous collection of foods, rather than variants of a single type. In such sample sets it is fallacious to assume that a single descriptor has a single physical source. There may be many different forms of roughness and smoothness (and indeed of thickness or body). Indeed, if two or more physical parameters contribute to a single descriptive term or conscious sensation, then the “balance” between/among them may vary with examples of smoothness or creaminess.[11] This would show in a different cognitive model of microstructural factors in creaminess of, say, whole milk and single cream, let alone of milk, yoghurt or crème caramel.

Yet a diversity of products is needed in order to get interesting pictures out of the statistical modelling that continues to dominate food sensory research. This is yet another feature of sensorimetrics that prevents that approach from contributing to scientific understanding of the perception of food. The only way that psychological science can begin to investigate the sensed physicochemical bases of food quality is by focusing studies on ranges of products without qualitative divergences in character.

The practice of testing diverse foods can lead to totally erroneous conclusions. A key piece of evidence for the tribological theory of creamy smoothness[18,19] is plainly an artefact of including a sherbert and a frozen orange juice. These serve as outliers and are solely responsible for the claimed relation between normalised frictional force (from lubrication in a leather-surfaced rig) and panel-judged smoothness. There is clearly no correlation at all between instrumental values and panel scores among the ten samples of various dairy emulsion samples.[18] (In any case, it is difficult to see how oil-in-water emulsions could vary in lubricating effect in the mouth. The tissues surfaces are all thoroughly wetted already. Furthermore saliva contains mucins that make it extremely slippery.)

The moral is that samples must be selected so that they each exemplify one of at least two different values of an hypothetically sensed material factor, unconfounded by correlated variation in any other potentially sensed factor. Such a subset of samples may not exist in the market. Indeed it is in principle likely that sensorily influential factors are varied together during formulation because they arise from the same constituent. An example for creamy texture might be rises both in release of oil-soluble aroma volatiles and also in the apparent viscosity at modest rates of shear as the oil fraction was increased in a dairy emulsion. Hence advances in scientific understanding depend on designing at least some artificial samples with formulations that break up the confounding of factors across the set of samples that are tested by an assessor.

Yet the nature of the scientific problem requires that these artificial samples are perceived as natural, or at least are sensed to be close enough to the familiar form of the product to permit accurate quantitative judgements of differences from normal in overall quality or in described characteristics. This is not a requirement that the samples are "palatable". The requirement is that each sample is recognisable. When this requirement is met, none of the samples presented to an individual consumer goes outside that person's range of tolerance for deviations from familiar or even preferred levels of any sensed characteristic - not just the factor(s) being investigated. In short, it is crucial to the linearity of each psychophysical function that all tested samples are recognised as the same food as is familiar from marketed variants.

10. A microstructural source of texture

Relatively rigid macrostructure obviously is important to the texture of solid foods, together with its destruction in the mouth by processes such as compression between the teeth and wetting by saliva. Particles at the millimetre scale within semi-solids are important to the character and quality of a food, in size, shape and/or hardness, ranging from the lumpiness of cereal grains, through the graininess of potato granules, to the smoothness of sufficiently milled cocoa solids in chocolate.

It is widely thought that particles have to be tens of micrometres (um) in diameter in order to be felt. Nevertheless, undetectably small particles may help to make chocolate feel smooth. Furthermore, a clearly gritty feel is produced by particles of only 10 um in diameter if they have sharp points on them, such as the mineral particles serving as abrasive in toothpaste.

Nevertheless, the fingertips are capable of detecting particles with diameters as small as one micrometre as asperities on otherwise smooth plates.[21] It is therefore theoretically conceivable that colloidal particles and emulsion droplets as small as, say, half a micrometre could influence texture if the fluid were pressed between tactually sensitive tissue surfaces sufficiently thinly for the two surfaces to press the monolayer into each other.

This microstructural hypothesis of a creamy smoothness, distinct from thickness, was supported by an increase in consumers' "creamy" ratings halfway from "high-fat milk" to "single cream" of dairy emulsions when the fat content was raised, the emulsion homogenised and thickener added.[13] Not only did viscosity have to be raised but also the number of fat droplets increased and their sizes reduced and narrowed in distribution. Homogenisation of fat droplets and of gas bubbles is now widely used to improve the creamy smoothness of dairy products and brewed stouts respectively.

Preliminary tests of samples in which dairy and plant-fat emulsions were varied independently in viscosity and in sizes and spacings of droplets supported the hypothesis that droplet size and/or distance between droplets as well as viscosity contributed to rated creaminess.[22] That pilot work is now being replicated and extended in an attempt to assess the contributions of droplet size and inter-droplet distance to the rated smoothness and creaminess of realistic artificial creams, and possibly also differences in shear-thinning behaviour and/or in low-rate viscosity or yield stress, as distinct from the known contribution of apparent viscosity at high rates of shear to rated thickness and creaminess.

Only two of the possible types of cognitive interactions were calculated for the initial publication of that preliminary work.[22] The same data have now been analysed for all cognitive models, using algorithmic calculations. The evidence indicates that the processes that explained the raw data best involved perceptual integration -- that is, information from at least two measured physical features (Tables 2 and 3). Viscosity contributed to creaminess in 5 of the 6 assessors but was a dominant factor in only 3. The width of the distribution of droplet sizes contributed more that viscosity in the 5 assessors who were influenced by it, while spacing between droplets occasionally contributed when viscosity did not.

A packet creamer consists of uniformly sized globules of vegetable fat suspended in maltodextrin: the dilution of this carbohydrate and the dispersion of the lipid particles in a drink of coffee can leave only a rather slight rheological effect at most, and so the intensely creamy mouthfeel of the coffee (if it can be distinguished from creamy aroma and slightly sweet taste) seems to depend on the size and spacing of these minute 'ballbearings.' Presumably microparticulate egg protein[23] worked in the same way. These considerations encouraged further pursuit of a microstructural hypothesis of creamy smoothness.

Other groups, however, have found very small effects of fat droplets. However, weaknesses in experimental design can be adduced. An early study[14] estimated the contribution of fat to be only about 3% but only droplet spacing was varied (and over an unspecified range), not droplet size. More recent studies[24,25] may show an effect of homogenisation to smaller droplets over a narrower range when viscosity is appropriately high; however the critical data are hidden in the wide ranges used. Another study[26] showed a small effect of homogenisation but whitener was needed to bring it out.

A microstructural theory of texture falls at the first post if consumers cannot sense differences in droplet sizes or spacing. Preliminary work confirms that some consumers can discriminate distances between droplet centres, even in the mouth (Table 4). However, differential acuity ("suprathreshold" sensitivity) is poor at best.

Also, descriptive vocabulary is problematic. Even "thick" may not be totally unambiguous in its use to describe a dairy emulsion: ratings on this term are more sensitive to droplet spacing than are smoothness ratings (Table 4). "Smooth" may be even more ambiguous. Some assessors rate closer spacing of droplets as smoother (as predicted by the "ball-race" model). Others use the word in the opposite sense. Aggregation of droplets may be evaluated as lumpy or rough, not just as oily.

Nonetheless, there are signs that viscosity strongly controls thickness while droplet spacing more strongly controls smoothness. Table 5 illustrates the characteristics of such a double dissociation from one assessor's data. This pattern of findings will have to be replicated within and across assessors before we have real evidence that thickness is rheological while smoothness is structural.

The microstructural theory of creamy smoothness faces a conundrum. It is conceivable that droplet sizes and spacings are sensed through the dynamic spatial distributions of forces generated by complex variations in shear. The closeness of droplets and similarity in size could affect the streaming of the emulsion as its bolus is squeezed into a thin layer between rounded (and rough) surfaces of sensing tissues. This is a challenging task to be tackled by computational rheology.

Experimentalists face a severe challenge in attempting to vary rheological properties independently of each other in sets of realistic emulsions. The asymptotic value of apparent viscosity that is approached with increasing rates of shear (such as 50 s^{-1}) has to be dissociated from viscosity at very low rates that may approximate a yield stress. In addition, both these parameters need to be disconfounded from the rate of shear-thinning, measured for example as the difference in apparent viscosity between a very low rate and a modest rate. If each of these rheological parameters can be dissociated in its effect on creaminess of a familiar product from the effects of distances between droplets, diversity in size of droplets and the central tendency of droplet size, this would keep a microstructural theory alive.

Mental integration of these two sorts of physical information can be investigated by cognitive modelling of interactions among percepts based on either rheological or microstructural sources of tactile stimulation. However, only the investigation of the physical chemistry can determine if complex rheological interactions mediate the effects of microstructure. In addition, the sensing of effects of structure could be mediated by interaction between the droplets of fat and the saliva.

Concluding remark

It is beginning to be appreciated that the applicable scientific understanding of food requires realistic and precise quantitative evidence on how consumers build knowledge through the senses. Physicists and chemists have long recognised the need for a deep understanding of the mass forces arising from molecular interactions within the material as it moves through the mouth. An implication of the present work is that neither of these two fields of science can be fully effective in their research into foods without close collaboration. Chemical physics and cognitive psychology will always retain large areas completely separate but where they overlap, in psychophysics, some theoretical unification may be necessary in addition to experimenting jointly.

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Table 1. Formulation requirements for sets of 8 samples of a food in which up to 7 sensed characteristics vary independently in strength and thus their effects can be measured separately. "Hi": values in a higher range. "Lo": values in a lower range. To avoid serious confounding, the two ranges must not overlap. To study interactions of mental processes in perception, both ranges in the factors studied must all be either above the top-quality point or below it. Lo and Hi ranges may be reversed without altering the disconfounding. For fewer than 7 factors, any set of 2-6 columns may be chosen. This may allow all or at least some of the eight variants to be selected from already existing formulations after their factor levels have been measured.

	Sensed characteristic to be varied						
	A	B	C	D	E	F	G
Food variant							
S	Lo	Lo	Lo	Hi	Hi	Hi	Lo
T	Lo	Lo	Hi	Hi	Lo	Lo	Hi
U	Lo	Hi	Lo	Lo	Hi	Lo	Hi
V	Lo	Hi	Hi	Lo	Lo	Hi	Lo
W	Hi	Lo	Lo	Lo	Lo	Hi	Hi
X	Hi	Lo	Hi	Lo	Hi	Lo	Lo
Y	Hi	Hi	Lo	Hi	Lo	Lo	Lo
Z	Hi	Hi	Hi	Hi	Hi	HI	Hi

Table 2. Perceptual interactions in ratings of dairy emulsions relative to "gold top" (high-fat) milk or single cream (full analysis of data preliminarily presented by Richardson *et al.,* 1993). The physical parameters varied among the milk samples were: V = Viscosity at a shear rate of $50s^{-1}$, representing rheological factors; S = Size (mean diameter) of lipid droplets, fitting into tissue anisotropies; W = Width ('span') of droplet sizes – the (un)evenness of the monolayer; and I = Inter-droplets distance (mean) – the spacing (packing) of the monolayer. The models differentiate the sum of distances from the norm (+) from the square root of the sum of squares of distances from the norm - the hypotenuse of a right-angled triangle (¬).

Assessor	Anchor term for ratings of "creamy"	
number	"Gold Top" milk	"Single Cream"
1	W ¬ S ¬ (S + V)	W ¬ S
2	V + W	(V + W) ¬ (W + S)
3	W ¬ I	W
4	(S + I + W) ¬ (S + I)	V ¬ W
5	I	V ¬ I
6	W	V ¬ W

Table 3. Contributions (%) of rheology and microstructure to the perceptual interactions of Table 2.

	Anchor term for ratings of "creamy"							
	"gold top" milk				"single cream"			
Assessor number code	Viscosity	Droplets Size	Droplets Width	Droplets Intercentres distance	Viscosity	Droplets Size	Droplets Width	Droplets Intercentres distance
1	32	0	38	30	0	2	97	0
2	59	0	40	0	33	22	32	13
3	0	0	60	39	0	14	50	37
4	0	39	6	55	44	28	28	0
5	55	0	0	45	66	0	0	33
6	0	0	100	0	51	0	48	0
Mean %	*24*	*7*	*41*	*28*	*32*	*11*	*43*	*14*
k	*3*	*1*	*5*	*4*	*4*	*4*	*5*	*3*

Table 4. Tactile sensing of rheology and microstructure by fingers, lips and tongue-on-palate: panel median acuities (50%-discriminable differences) of cream descriptors for high-shear rate (50 s^{-1}) viscosity (**V**), correlated with low-rate viscosity, or mean inter-centres distance between droplets (**I**). About 0.1 ml of butter-fat emulsion was pipetted onto the lower tissue surface (unseen), the assessor wiped it once against the upper surface and then immediately made the three ratings.

	Fingertips (dry)		**Dry lips**		**Wet lips**		**Palate / tongue**	
	V	**I**	**V**	**I**	**V**	**I**	**V**	**I**
"thick"	$>10^{-9}$	0.13	26	0.16	$>10^{2}$	0.7	14	0.20
"smooth"	$>10^{-2}$	0.44	69	0.27	$>10^{2}$	0.3	$>10^{2}$	0.53
"creamy"	$>10^{-2}$	1.18	17	0.42	$>10^{4}$	0.5	$>>10^{2}$	0.63

Table 5. Relative specificity of "thick" to rheology and of "smooth" to microstructure: an illustration of evidence from double dissociation of the thickness / viscosity function from the smoothness / spacing function in perceptual measurements of butter-oil emulsions during eating (assessor 57 4/03). Acuity (50%-discriminable difference) for uncorrelated variations in viscosity and droplets-spacing in cream-like samples. Note that the lowest value in a row is the finest acuity (best discrimination), which is the same thing as that physical paramter's most strongly controlled rating.

	Rating relative to "double cream" of how		
	"**thick**"	"**smooth**"	"creamy"
Apparent **viscosity** (50 s^{-1})	<u>0.08</u>	2.02	0.36
Oil fraction (*pp* inter-centres **distance**)	1.5E+3	<u>1.01</u>	7.1

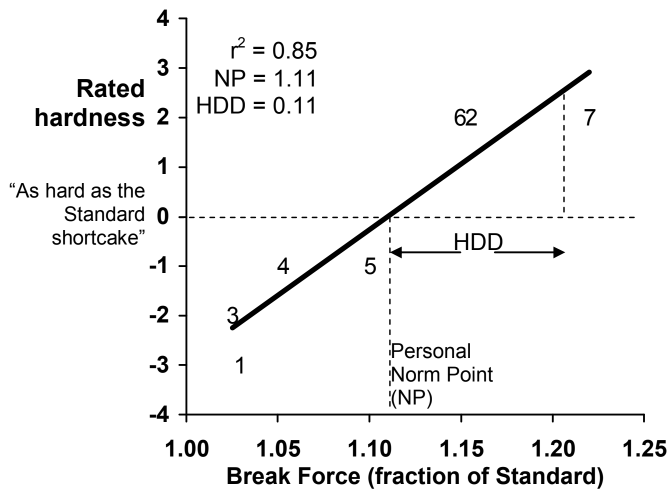
FIGURE LEGENDS

Figure 1 The psychophysical function: an example of raw data on the texture of a highly heterogeneous food (shortcake biscuit) from one assessor rating seven samples in a single session. (It is not known if breaking force is sensed by audition, touch, kinaesthesis or some combination.) When the samples are not too dissimilar from what is perceived as top quality for that food (the personal Norm Point: NP, in this case 11% higher in 3-point break force than the Standard biscuit, as marketed), the rated intensities of a described characteristic (positive numbers = increasingly harder than Standard; negative numbers = less hard) are linear against the amount of a stimulus to that response (semi-logarithmic for material stimuli, i.e. ratios of amounts).[2] r^2: variance accounted for by the regression line. HDD: Half-Discriminable Difference between amounts of the stimulus. Data points 1-7: sequence of presentation of the sample biscuits (1st to 7th).

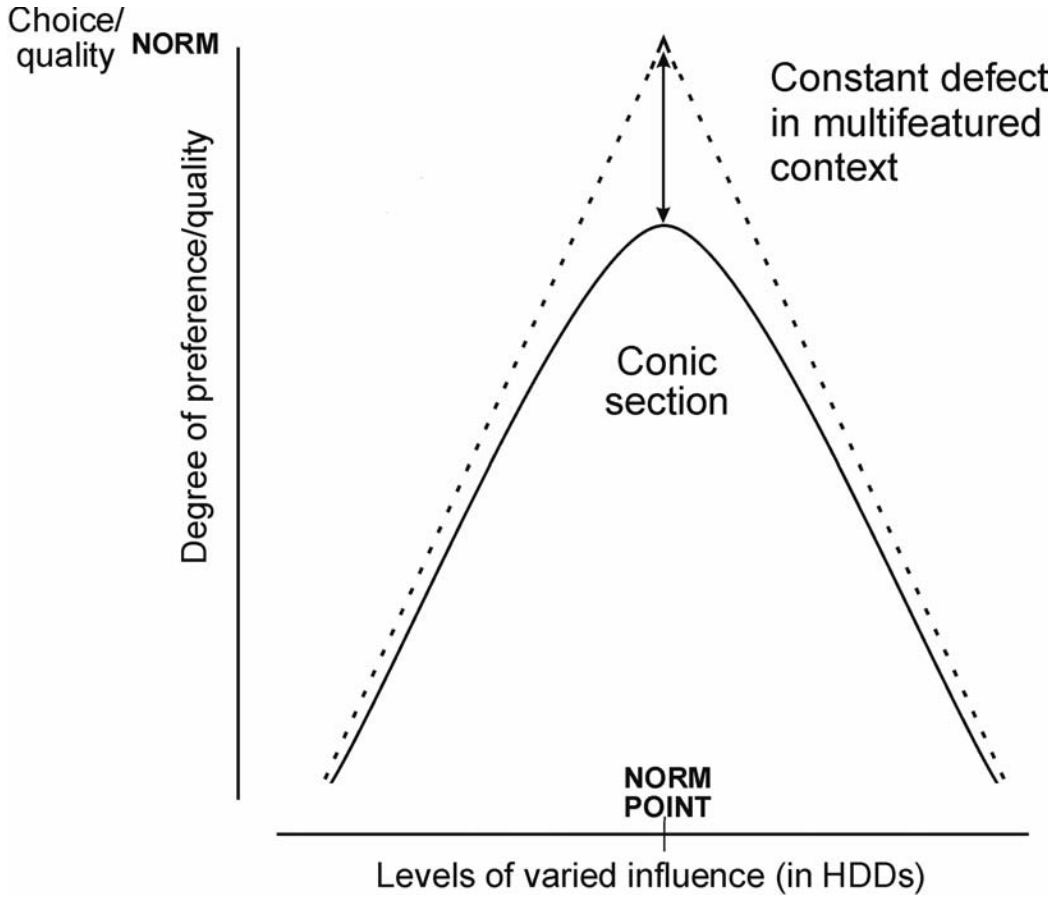
Figure 2 Cognitive theory of quality recognition: a single influence in its familiar context.[12] The effect of levels of the textural or other influence (scaled in half-discriminable differences) on a consumer's disposition to choose a food or perception of its quality (y axis) falls on the surface of a cone described by that influence (x axis) and the familiar context integrated from all other influences (z axis). When the context is less than perfect in any respect, then the function outlines a vertical section through the cone away from the peak along the z-axis, at a distance in HDD that measures the size of the contextual defect, and no level of the varied influence under test can create perfect preference or quality.

Figure 3 Cognitive theory of quality recognition: the simplest case of two distinct influences on perceived overall quality or personal preference. (More than two influences are represented by a "hypercone.") The cone is drawn through the ideal ranges of the two factors (A and B) under investigation that influence a consumer (when the context is perfect for that person): the ideal range is the ideal point (IP), or more generally the norm point (NP), plus and minus one half-discriminable difference or fraction (HDD, HDF).

Booth - Figure 1



Booth – Figure 2



Booth – Figure 3