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Keynote Paper

On fundamental issues in texture evaluation and texturization—A view[☆]

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Abstract

Irrespective of the geometry and other factors, the human motor sensory system creates and processes signals in a manner that is qualitatively different from those produced by stiff mechanical testing machines. This is primarily because the tissues own deformability and rheological properties play a major role in the stimulus generation. Consequently, and unlike in man-made machines operating in their designed load range, the sensory sensitivity depends on both the rheological properties of the tissues involved and those of the specimen. Also, the sensory response to a mechanical stimulus is non linear and can be affected by adaptation and fatigue. Sensory evaluation and material science have different vocabularies and many sensory textural attributes are difficult to express in universal mechanical terms. It is, therefore, proposed to deepen the involvement of material science in texture studies and to relate the distribution of sensory responses to well defined and measurable mechanical properties like stiffness, toughness, elasticity and brittleness.

Since textural differences are frequently accompanied by other organoleptic differences, hydrocolloids offer a unique way to create and control the mechanical properties of model and real foods with minimal effect on their flavor and color. Such foods, at least in principle, can reveal how mechanical properties are perceived. They can also help establish the human sensitivity to various mechanical properties thus helping the food industry not only to create and control desirable textural characteristics, but also to establish rational tolerance margins to the mechanical properties of its products.

Keywords: rheological terminology; psychophysical relationships; ‘soft machines’; mechanical stimulus; texture perception; sensory evaluation; hydrocolloids

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1. Introduction

Much of the research into the textural properties of foods and their sensory perception has been done in academia and in industrial laboratories. The goal of many studies has been to develop instrumental, or ‘objective’, methods to quantify textural properties. These methods, so it has been hoped, would help in the manufacturing of food products with desired and controlled textural characteristics. In many fresh commodities, fruits and vegetables in particular, texture serves as a ripeness measure, which determines the time of harvest and/or release to the market. Texture also plays a major role in food process engineering. It is a major factor in the choice of a handling method and the type of cutter or grinder for example. Foods' texture has also been studied in relation to dental and oral medicine (Lucas, Prinz, Agrawal, & Bruce, 2002) but this area will not be addressed in this communication. The focus of the discussion will be the definition of mechanical properties, how they are measured instrumentally, how they are assessed sensorily, and how hydrocolloids can be used to solve some of the outstanding problems in texture studies. Foods' structure and texture have been two fertile fields of research (Eads, 1994). The results are summarized in several books (e.g. Moskowitz, 1987; Aguilera & Stanley, 1999; Bourne, 2002) and discussed in numerous reviews and research articles in general and specific food journals, notably the Journal of Texture Studies. The purpose of this communication is to highlight certain fundamental problematic issues whose resolution, in the author's opinion, is essential to progress in the field. What follows is a personal statement based on research done in the Physical Properties of Foods Laboratory at the Department of Food Science of the University of Massachusetts. The presentation is not a review and no effort has been made to cite pertinent works published by others, irrespective of whether they are in line or contrary to our views on the subject.

The term ‘texture’ has different meanings, as every dictionary will testify. For our discussion, ‘texture’ will mean

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the assortment of mechanical–structural–acoustic properties that humans perceive as a food's distinctive physical characteristic. The emphasis will be on solid foods. Again, what constitutes a 'solid' is not always clear from the rheologist's point of view. Therefore, the term will be used loosely, as in everyday parlance, i.e. a body having a considerable stiffness and rigidity and hence does not flow under its own weight.

2. The problems

The results of numerous texture studies are in the form of graphical or tabulated relationships between instrumental, or 'objective', parameters and the sensory evaluations of the attributes which they are supposed to represent (Fig. 1). In experimental psychology, they are called 'psychophysical relationships', and in most cases, can be described by a power expression known as Weber's law (Stevens, 1975; Falmage, 1985; Gescheider, 1985), i.e.

$$\text{Response intensity} = \text{Constant} \times \text{Stimulus intensity}^n \qquad (1)$$

where n is a power characteristic of the sensed physical or chemical property.

Or, as shown in Fig. 2,

$$\log[\text{Response intensity}] = \text{Constant} + n \log[\text{Stimulus intensity}] \qquad (2)$$

For mechanical stimuli n has values on the order of 0.4–2 (Harper & Stevens, 1964; Moskowitz, 1977; Moskowitz, Seagrs, Kapsalis & Klutter, 1974). It is self evident that Weber's law cannot be extended indefinitely (Fig. 2). At a sufficiently high stimulus level the response will be pain (Stevens, 1975; Gescheider, 1985) or saturation (Peleg & Campanella, 1988). Either way, one can get a different slope depending on the region of the log response intensity vs. log stimulus intensity plot examined and the data scatter.

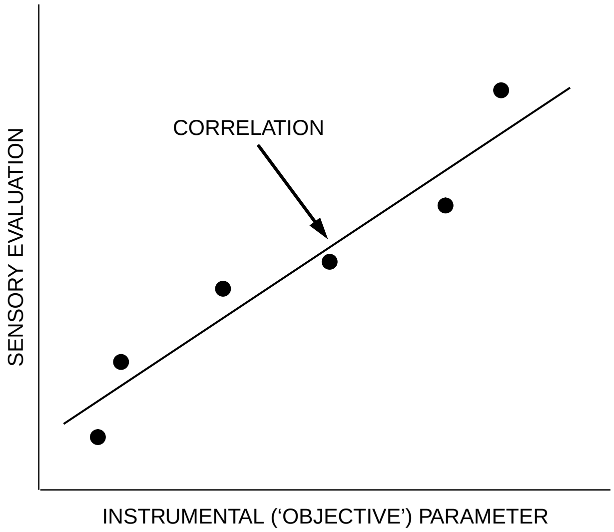

Fig. 1. The correlation—a traditional source of information about the relationship between mechanical properties and their sensory perception.

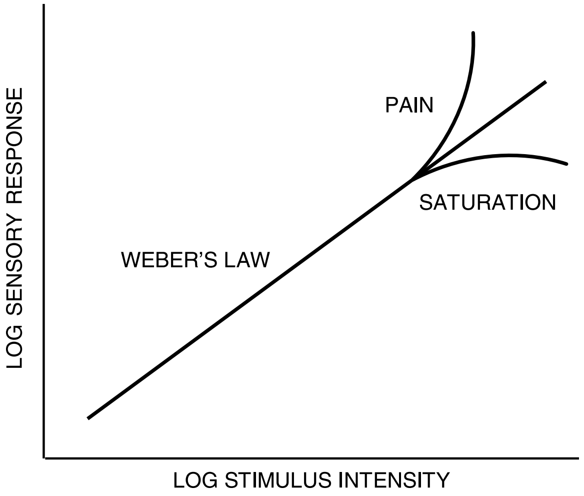

Fig. 2. Weber's law. Note that in reality power law relationships cannot continue indefinitely; strong mechanical stimuli can lead to pain (Stevens, 1975; Grescheider, 1985) or saturation (Peleg & Campanella, 1988).

One of the prerequisites of a proper interpretation of any experimental results is to understand what the instrument actually measures and how sensitive it is under the pertinent operational conditions. In a relationship represented schematically in Fig. 1, the results of two 'instruments' are compared. A human or a group of humans, provide the ordinate and a mechanical device produces the values along the abscissa. In food research, commonly, the experiment's goal is to produce a 'calibration curve', which will enable to 'predict' the sensory response of consumers from instrumental measurements of the particular food's texture.

Let us examine how these two instruments are constructed and function and how their different modes of operation affect their response to a given input or 'stimulus'. It has been generally assumed that most, if not all, people have basically the same sensation of 'hardness', for example, and that a selected group of suitable individuals can be trained to sense it. The training starts with the introduction of a prescribed 'definition' of the property in question and the candidate is judged by his/her ability to conform to the consensus, which had already been reached by the trained 'expert panel'. The questions that arise are whether 'hardness', 'cohesiveness', 'fractureability', 'springiness', and the like, are really 'universal properties' similarly perceived by different individuals, and whether even 'trained panelists' have the same *sensitivity* to these attributes. It is the author's opinion that there is no credible evidence that these questions can be answered in the affirmative (see below).

The 'instrumental scales' also needs re-evaluation. In the popular 'texture profile analysis', or TPA for example, the assignment of textural properties to the 'instrumental parameters' is obviously unwarranted. Most of the supposedly textural parameters produced by this method are expressed in force units, i.e. without adjustment to the specimen's area volume, or mass. Consequently, if the method is taken seriously, a cylindrical piece of cheese 2 cm in diameter let us say, must be about twice as hard as a piece of the same cheese of same height only 1 cm in diameter. Working with a standard specimen size and a fixed displacement will not remove this logical inconsistency. This is simply because there is no reason to believe that there exist characteristic specimen dimensions, let alone that they are the same for all foods. Obviously, adjustment of the specimen size so that the results will fit the panel's evaluation, as was done in the past, is not a permissible option. Solution to these problems as will be listed below is to express the specimen's mechanical properties in terms having universal units, like strength or stiffness (stress units) work per volume, maximum deformability (dimensionless), etc.

One can envision that when the discrimination ability of humans and machines are compared there can be three situations; that they both have exactly the same sensitivity, that the machine is more sensitive than humans or vice versa. Surprisingly, this issue, which needs to be settled *before* any textural evaluation takes place, has rarely, if ever, been investigated. Also, mechanical testing machines, operating at their designed load range, have a constant mechanical sensitivity, but this is not necessarily true for humans (see below).

Can a mechanical stimulus be perceived in isolation, i.e. without being affected by chemical, thermal and acoustic signals? Can statistical procedures be used to resolve this issue? And mentioning statistics, is a significant difference by a statistical criterion the same as a practical difference? These are only a few issues, that have yet to be fully resolved and whose possible implications in the interpretation of texture studies ought to be reassessed. The approach that we advocate here is by no means novel or unique. It may not even bring about a satisfactory solution to all the mentioned problems. But its re-introduction will demonstrate that a fresh and critical look at how texture analyses are performed is timely and clearly needed.

3. Rheological and sensory vocabularies

Mechanics and material science are mature and well-established scientific disciplines. Like in every physical science, they deal with entities that can be measured and in most cases quantified unambiguously. The mechanical properties of solid materials, biological and food materials included, are usually described by one of the following terms (Reiner & Scott Blair, 1967):

- Hardness— Resistance to penetration, scratching, abrasion, or impact loading. [Three different properties determined by different instruments and expressed in different units.]
- Strength— The stress (force per unit area) that a specimen can sustain before failure. [Materials have a different tensile, compressive and shear strength.]
- Deformability— The amount of deformation or strain [relative deformation] that a specimen can sustain before failure.
- Brittleness— The tendency of a solid to fail abruptly after a very small deformation.
- Ductility— The ability to deform indefinitely without failure [e.g. chewing gum].
- Stiffness— The resistance to deformation. [Expressed in terms of a modulus having stress (force per unit area) units.]
- Toughness— The ability to absorb mechanical energy before failure. [Expressed in terms of work per unit volume.]
- Rigidity— The resistance to shear stresses. [Expressed in terms of modulus-stress units.]
- Elasticity— The capacity to return to the original dimensions after the deforming load is removed.
- Plasticity— The tendency to sustain permanent deformation after the deforming load is removed.

These are all 'macroscopic properties', that is they are an overall manifestation of structural and micro-structural features, as well as the expression of inter-atomic and inter-molecular interactions. A mechanical property determination, therefore, is based on monitoring the total effect of events that take place over very different time and length scales. In many types of materials, notably metals, concrete, polymers and ceramics, the relationship between mechanical properties and microscopic features is well understood. This has led to the development of numerous man-made materials for a large variety of engineering, medical and domestic applications. A similar trend exists in food research, albeit on a much more modest scale (Eads, 1994; Aguilera & Stanley, 1999; Peleg, 2002). The texture of foods, however, is rarely described in the terminology of material science. Instead, there is a special sensory vocabulary, which includes terms like 'cohesiveness', 'springiness', 'hardness' (defined by some as the 'force exerted by the molar teeth on one side of the mouth to deform or crush a standard piece'), 'firmness', 'fractureability', 'softness', 'adhesiveness', 'crispiness', 'crunchiness', etc. None of these is clearly defined, and their 'objective determination' is usually based on tests, which are performed under arbitrary conditions. The underlying concept is that they represent universal attributes and hence can be quantified and used to produce a calibration curve based on different foods (Fig. 3). In reality, if such attributes can be quantified at all, the resulting numbers or ratios would only pertain to the particular panel that had developed the scale. It is self evident, that a biscuit is harder than cheese. But this does not imply that the sensory 'hardness scale' among biscuits and cheeses is the same, and hence that one can construct a calibration curve by connecting the biscuit and cheese scores as shown in the figure (Peleg, 1983). As modern semantics teaches us, there are situations where it only makes sense to talk about 'contextual meaning'. Thus, if the above example is a case in point, then 'biscuit hardness' and 'cheese hardness' need not be even the same property. It is surprising that despite many years of research, this aspect has not yet been fully clarified. Similarly, the problem of overlapping meanings has not been satisfactorily resolved either. Are 'hardness' and 'firmness' exactly the same properties? Can one say a 'firm boiled egg'? Is a 'firm peach' softer than a 'hard peach'? In English, the opposite of both 'firm' and 'hard' *is* soft! Whether, such terms have exactly

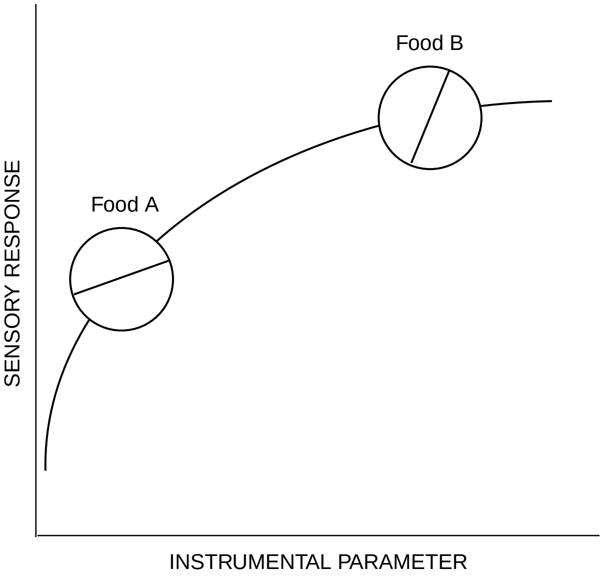

Fig. 3. Schematic demonstration that a psychophysical relationship (or 'correlation') derived from different foods need not correspond to that which may exist within any particular food (Peleg, 1983).

the same meaning in different languages is of course another issue altogether.

Vocabularies of texture terms in various languages do appear occasionally in the food texture literature. But that the perception of the corresponding properties exactly matches those which are implied by the translated term is not at all certain.

A way to avoid this semantic confusion is to drop the attempts to correlate the results of arbitrary tests with sensory ratings altogether. One should determine the mechanical properties of the food in question in the same manner as a material scientist would determine those of engineering materials, expressing the results in the same universally accepted mechanical terminology. Once determined, the *distribution* of the sensory responses to these properties should be recorded. For example, if a material has a certain degree of stiffness, expressed in terms of a modulus, then one should record the percentage of people who call it 'stiff', 'hard', 'firm', 'rigid', etc. A certain degree of overlap with other attributes will most probably emerge. But this should not be a reason for concern. On the contrary, it will be a reflection of the fact that sometimes, and unlike man-made testing machines, humans can only provide a fuzzy evaluation of textural properties regardless of whether they are experts or not.

Many of the published 'significant correlations' between sensory scores and instrumental parameters have been obtained with foods of considerably different texture. It can be argued that in such cases almost *every test* will reveal the differences. But the pertinent question is not whether humans can distinguish between unripe and ripe fruits, uncooked and cooked vegetables or, once more, biscuit and cheese. The issue is whether they can rate, or distinguish between fruits picked at different orchards, vegetables after 2 and 3 days of storage, biscuits produced on different dates and cheese samples from different batches. That either the current instrumental or sensory methods are always adequate to deal with these problems is again not at all obvious. To resolve the issue one may need to distinguish between a statistical difference and a practical difference, a topic that will be addressed later.

4. Problems with the 'instrumental' scale

An ideal material property is independent of the method and instrument of its determination. And more importantly, it is also independent of the physical dimension of the sample examined except for very special cases (see below). Very few food technologists will accept, or endorse, a method to determine the sugar contents of a certain fruit juice, let us say, if the result it gives is 10% in a 100 g sample and 15% in 200 g. But this is exactly what happens when one uses the already mentioned TPA, and needless to say the Kramer Shear press, the Warner–Bratzler blade(s), the 'back extrusion' cell and many other devices used in food research and quality control. In all these, the blade dimensions and/or number of blades, as well as the specimen and cell size and geometry play a decisive role that determines the outcome of the test. The only times these methods 'work', are when the differences between the compared samples are very large. But in such cases, as already mentioned, the rationale for carrying out the test at all may become a debatable issue. Again, 'a standard instrument' and 'standard procedure' are not a solution to the problem. This is because the results' dependence on the test conditions and geometry can vary widely among food materials (Szczesniak, Hambaugh & Block, 1970; Peleg, Gomez, & Malevski, 1976), for example.

There are, of course, non-trivial cases where the textural differences to be monitored are indeed large. The agar used to culture microorganisms is a good example. Agars from different sources produce gels of very different strength at a comparable concentration. If all that is needed is to monitor and document the differences, the simplest test will do, e.g. penetration with a cylindrical plunger.

There are also cases where the test results' dependence on the specimen geometry is not an artifact but a textural characteristic by itself. Fruit flesh, where compression induces juice extraction is a case in point (Peleg et al., 1976). Similar considerations should apply to fibrous and flaky foods, meats, fish and their analogs in particular, where the material may also have different mechanical properties in different directions (Kuo, Peleg & Hultin, 1990; Aguilera & Stanley, 1999; Peleg, 2002).

Traditionally, the result of an instrumental texture evaluation is reported as a mechanical parameter's mean value with a corresponding standard deviation. But, only rarely, is the scatter further analyzed to reveal whether it is primarily a reflection of the test's reproducibility or evidence of real textural variability within and among the specimens tested. Again, whether this variability is actually sensed by humans is not always clear. Whether averaging the instrumental measurements is equivalent to an 'averaging process', which must take place during a sensory evaluation and in the food's normal consumption is again largely unknown.

The testing rate is another aspect that needs a closer scrutiny. Most instrumental textural evaluations are performed at rates, which are considerably lower than those imposed on foods during their mastication. It can be shown that, theoretically at least, there can be situations where the machine will show rate sensitivities that do not exist at rates that are generated during mastication, or vice versa, depending on the rheological properties of the examined food—the shortest relaxations time to be exact (Peleg & Normand, 1982).

The same can be said about the deformation level. Whether the dynamic tests, now in vogue, which are based on the specimen's response to very small strains, indeed produce information that is relevant to what happens during sensory evaluations is yet to be convincingly demonstrated.

5. Texture evaluation as a process

A sensory texture evaluation produces a rather complicated stress history with a continuously changing geometry, and in mastication, because of saliva secretion, a changing composition as well (Lucas et al., 2002). The sensation of the mechanical events involves activation of mechanoreceptors in tissues *at and around* the contact area. Some are *pressure sensitive* and others respond to the local *pressure rate*. How the neurons firing pattern in response to these *temporal stimuli* are integrated, translated into a sensory assessment and then expressed verbally as a set of textural attributes is not yet fully understood. Studies of how the sensory response intensity changes with time have been reported in the food literature. But how fatigue in mastication and the mechanoreceptors adaptation affect textural perception is not at all clear (Roy, 1989; Peleg, 1993). The same applies to the inclusion or exclusion of the simultaneous response to chemical, thermal, acoustic stimuli, and the integration in the brain of stored information.

6. The mechanics of soft machines

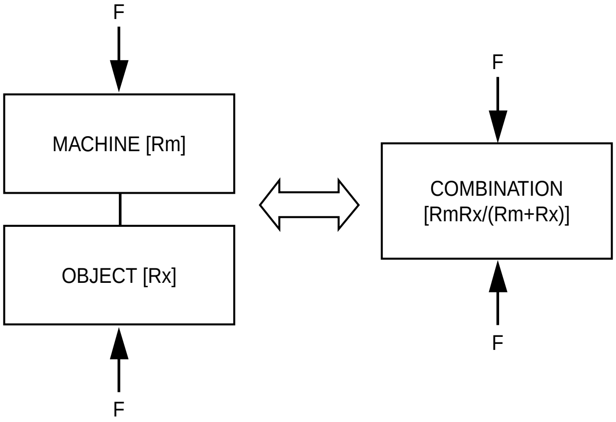

Fig. 4. Schematic view of the mechanical array formed during a specimen testing by a machine. Notice that when the mechanical resistances of the sensor and specimen are in series (Rm and Rx, respectively) the array is equivalent to a single resistance RmRx/(Rm + Rx) (Peleg, 1980; Swyngedau & Peleg, 1992; Peleg & Campanella, 1989).

The frame of universal testing machines is built from very stiff materials, and the sensor, a load cell or LVDT, is especially designed so that the deformation it undergoes, relative to that of the tested specimen is negligible indeed. Consequently, it can be safely assumed that when the machine operates at its designed load range all the displacement is sustained by the tested specimen. Also, at the designed load range there is a linear relationship between the sensor's output and the actual force exerted. [This is not true when the tested specimen is short and stiff, in which case compensation for the machine's own compliance is needed.] In comparison with man-made instruments, the human motor and tactile sensory systems can be considered as a 'soft machine' shown schematically in Fig. 4 (Peleg, 1980; Campanella & Peleg, 1988; Peleg & Campanella, 1989; Swyngedau & Peleg, 1992). It also has a non-linear and 'adapting' output. [One of the manifestations of adaptation is that the response to a stimulus of a constant intensity decays or even completely vanishes after a time—see below.] When we squeeze a loaf of bread or a fruit with our fingers to assess their texture, the deformation the fingers undergo is comparable to that sustained by the assessed object. A similar situation exists when we chew a hard material such as a nut, bite into a dry biscuit, or press a highly viscous semi liquid food against the palate with our highly deformable, and compressible tongue. This characteristic of the sensory system has two major outcomes:

(a) The force – time relationship is that of the food-finger, food-jaw or food-tongue system and not of the food alone (Fig. 5).

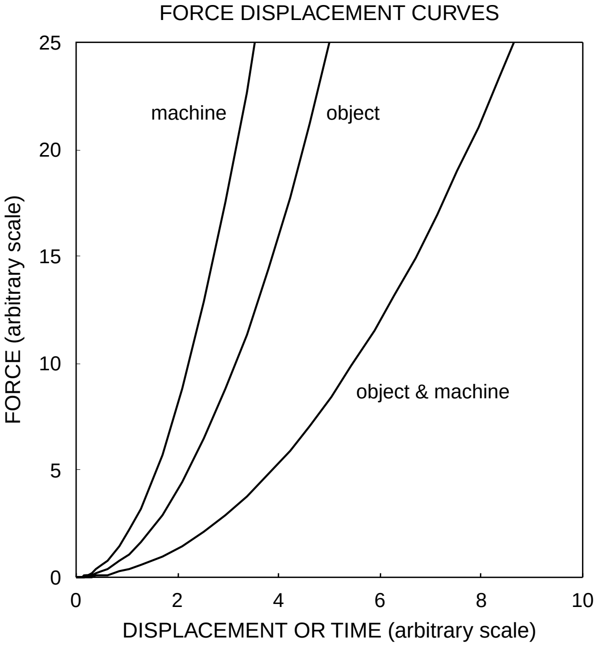

Fig. 5. Schematic view of the force–displacement curves of a 'soft machine', a tested food, and they are in series array. Note that the deformation at a given force is always additive. The actual shape of the curves is determined by the rheological characteristics of the 'machine' and tested food specimen (Campanella & Peleg, 1988; Swyngedau & Peleg, 1992).

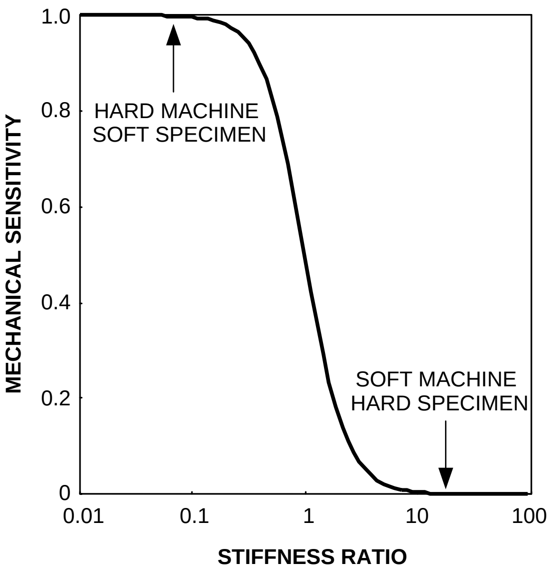

Fig. 6. The mechanical sensitivity of a testing machine as a function of the relative stiffness of the tested specimen. The shown curve is for the case where both are constant and force independent. For more complicated cases, e.g. a compressible finger and a yielding or compressive food see Peleg & Campanella (1989).

(b) The mechanical sensitivity of the sensory system becomes a function of the ratio between the stiffness of the tissues involved and that of the tested object. If the ratio is sufficiently large the mechanical sensitivity may disappear altogether (Fig. 6).

It can be shown that the mechanical sensitivity of the sensory system to hard objects is practically zero. But because the applied pressure is high, we perceive them as hard. Hence, humans can easily identify hard foods but they cannot discriminate between them on the basis of a mechanical stimulus alone. Similar considerations apply to very soft materials. The mechanical sensitivity is close to one, but the stimulus is too weak to allow for a reliable discrimination. These features of the sensory systems are shown schematically in Fig. 7. The exact nature of the generated force–time relationship (the stimulus) and the loss of sensitivity (defined here as the ratio between the change in output intensity and the change in input) depends on the rheological properties of both the specimen and the tissues involved (Campanella & Peleg, 1988; Swyngedau & Peleg, 1992; Peleg & Campanella, 1989). Since the rheological properties of the different components of the sensory system, jaws, fingers and tongue, are not the same, one must suspect, on theoretical grounds, that they produce a different response to the same object. The same applies to individual humans. Since their fingers, tongue and jaws are unlikely to have an identical stiffness, a scatter in their evaluations of the same object is expected even if for this reason alone. One must conclude that *irrespective of geometry and other dissimilarities*, the stimulus processed by the sensory system is qualitatively different from the signal produced by a man-made testing machine. To add to the complexity, the tissues involved in sensory evaluation are viscoclastic and hence undergo mechanical relaxation. This, combined with the simultaneous adaptation of the receptors due to electrochemical processes, causes that the sensory response to a constant external stimulus decays with time. [For the same reason, we stop feeling our clothes, watch and jewelry soon after wearing them.] Since some mechanical receptors are activated by pressure rate rather than by pressure, the sort of motion generated during the evaluation must affect the nature of their firing pattern and hence the intensity of the temporal sensory response. Obviously, the information that the brain receives in the form of a sequence of electric pulses generated by the receptors is not even remotely simulated by a machine that operates at a low and constant displacement rate.

7. Brittleness

Foods, known as ‘crunchy’ or ‘crispy’, notably breakfast cereals and snacks, are notorious for their irregular and irreproducible force–displacement curves (Fig. 10). In most of these, preparation of a specimen with controlled dimensions is very difficult, if not utterly impossible, and consequently they ought to be tested intact. Nevertheless, it has been shown

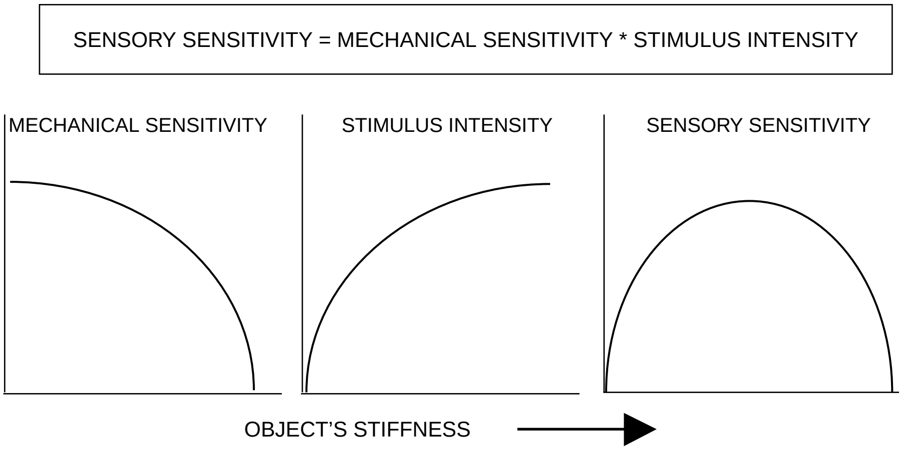

Fig. 7. Schematic view of how the sensitivity of the human system is determined. It demonstrates why humans can easily identify a stiff or soft material but have difficulty discriminating between objects in either extreme on the basis of their stiffness (Peleg, 1983; Peleg & Campanella, 1989).

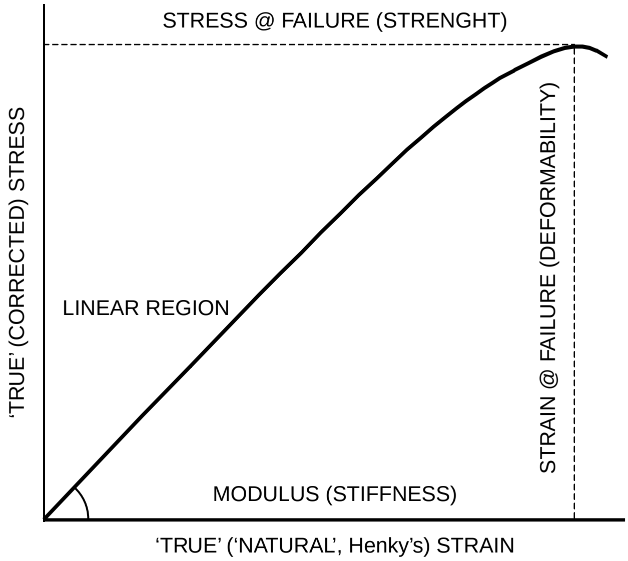

Fig. 8. A schematic view of the way stiffness, strength and deformability can be determined. Note that the area under the curve (having work per volume units) represents toughness.

that a good measure of their brittleness is the *degree of jaggedness* of their force–displacement curve, expressed as an apparent fractal dimension, for example (Peleg, 1997). It has been found that it is a fairly reproducible index and that the local failure events, which are manifested in the jaggedness of the force–displacement curve, are most probably the same kind of events, that produce the 'crunchiness' sensation. At least in some cereals and snacks, a moderate amount of absorbed moisture causes a simultaneous loss of brittleness and a measurable increase in 'stiffness' or 'toughness' (perceived as 'hardness' by untrained panelists). It has, therefore, been possible to show that, these two textural attributes can be perceived independently by humans, albeit not with the same sharpness as a mechanical testing machine (Suwonsichon & Peleg, 1999).

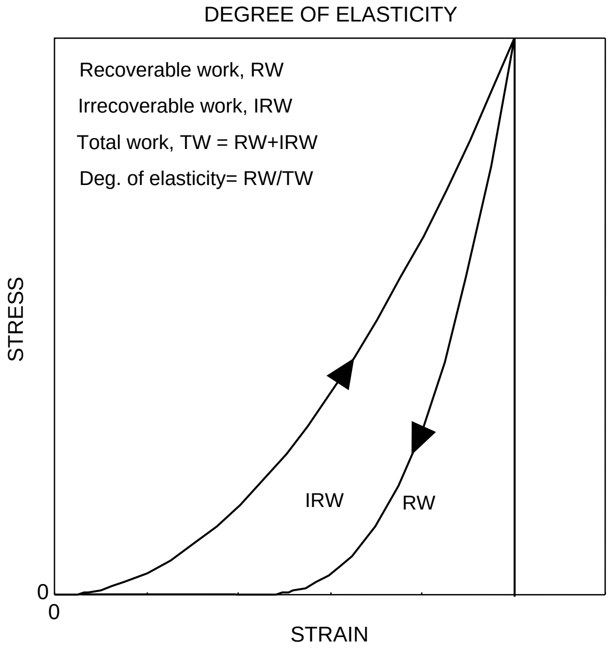

Fig. 9. A schematic view of how a 'degree of elasticity' can be determined. Note that the test can be improved by performing a series of compression–decompression cycles, but that the results may depend on the selected strain (Kaletunc et al., 1992).

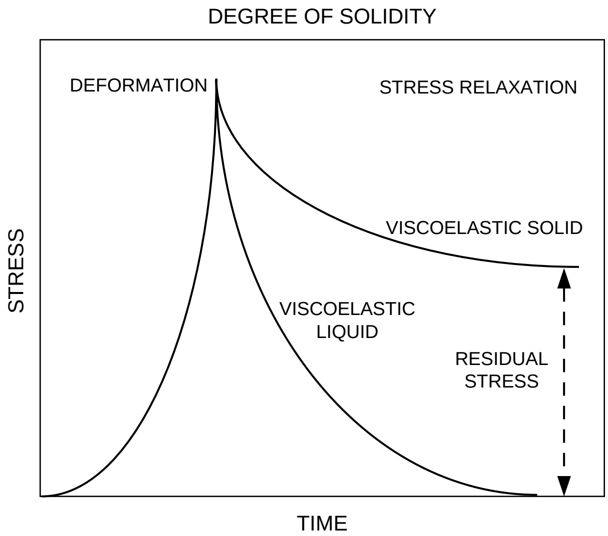

Fig. 10. A schematic view of how a 'degree of solidity' can be determined from a stress relaxation test. Note that this measure may depend on the selected strain, and that the character of the dependence reflects on structural changes that specimen undergoes during its deformation (Peleg, 1987).

8. Relating rheological properties to their perception

Stiffness, strength, toughness, degree of elasticity, etc. can be determined objectively (Figs. 8–11), although not always very accurately. One should also take into account that many foods are nonlinear viscoelastic materials and, that when

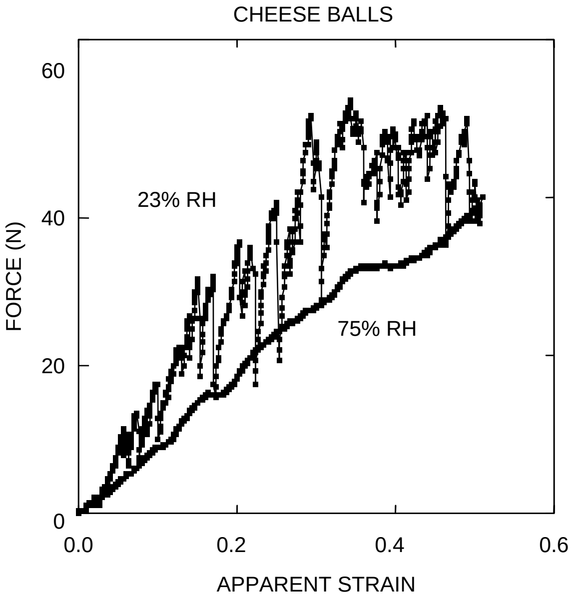

Fig. 11. The force–displacement curves of a cheese ball after exposure to two levels of relative humidity. Notice that the loss of crunchiness is also manifested in a smoother relationship (Suwonsichon & Peleg, 1998).

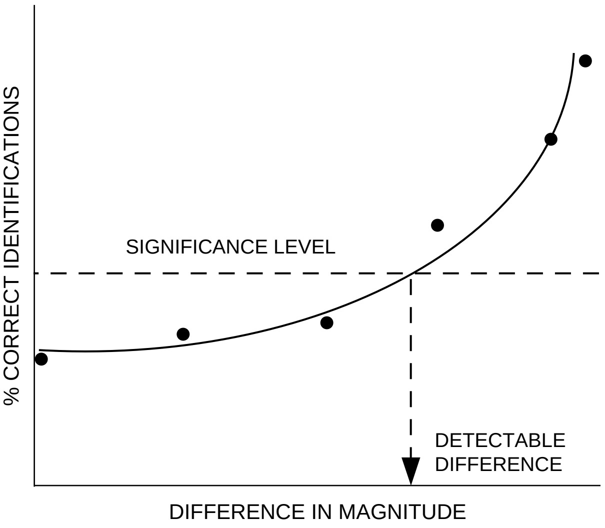

Fig. 12. Schematic view of how a ‘practically significant difference’ can be determined (Corradini et al., 2001; Chanasatru et al., 2002).

subjected to a large deformation, can undergo substantial internal structural changes. Notable examples are the yielding of deformed cheeses, and the compressibility of bread crumbs, which involves cell walls collapse and/or fracture. Consequently, the magnitude of parameters like a ‘degree of elasticity’ (determined by a set of compression–decompression cycles, Kaletunc, Normand, Nussinovitch, & Peleg, 1991; Kaletunc, Normand, Johnson, & Peleg, 1992), or a ‘degree of solidity’ (determined in terms of the asymptotic fraction of the un-relaxed stress, Nussinovitch, Kaletunc, Normand, & Peleg, 1990), usually depends on both the set strain level and the specimen’s rate history. But, at least in principle, one can find test conditions, especially a displacement rate regime, which will produce parameters that are pertinent to sensory evaluation. One can then ask what differences in the magnitude of these parameters are sensorily detected. The answer will not be based on the traditional ‘correlation’ between sensory and instrumental evaluations (Figs. 1 and 2) but on the relationship between the % correct identifications and the difference as shown in Fig. 12 (Chanastru, Corradini, & Peleg, 2002). To avoid interference from other stimuli, effort should be made that the examined specimens differ only, or primarily, in their texture but not in their appearance and flavor. In semi-liquid foods, this can be guaranteed by controlled mechanical disruption and evaluating the samples’ consistency by squeezing flow viscometry (Corradini et al., 2001; Chanasatru et al., 2002). Squeezing flow viscometry is currently the only method known to the author that enables testing a semi-liquid food specimen practically intact (Suwonsichon & Peleg, 1999; Corradini, Engel, & Peleg, 2000). In standard conventional viscometric methods, the food specimen, unless Newtonian, is inadvertently subjected to uncontrolled structural disruption during its insertion into the narrow gap of the sensor. Consequently, the test results do not faithfully reflect the consistency of the original material (Corradini et al., 2000). With solids, in contrast, it is much easier to ‘build up’, or strengthen the structure because almost certainly, the consequences of any mechanical abuse will be visibly evident or felt in other ways. Hydrocolloids are probably the most suitable texturizing agents to produce solid structures having a variety of rheological properties, with only minimal differences in their flavor and appearance.

9. Potential use of hydrocolloids in texture studies

Hydrocolloids—gums and proteins—can be used to create gels or gel-based texturized foods with different *specific* rheological characteristics, that is strength, stiffness, degree of elasticity, etc. Since relatively slight variations in a hydrocolloid concentration, or a hydrocolloids mixture composition, can produce substantial changes in a gel’s mechanical properties, it is possible, at least in principle, to modify the texture without significantly affecting other organoleptic properties especially taste and appearance (Kalentunc, Nussinovitch & Peleg, 1990). This would enable to determine if, or how, a specific rheological property is perceived, what the sensory sensitivity to this property is (measured in terms of % correct discriminations) and how its sensation is affected by other mechanical and non-mechanical properties. The latter can be achieved by producing texturized specimens with very similar rheological properties but with different flavor, color, etc. Similar methods can be employed in the study of ‘crunchy’ foods. Dried gels or foams of different formulations can be used as convenient model systems of cellular foods (Nussinovitch, Corradini, Normand, &, Peleg, 2000; 2001). The role of structural features, which would be determined by image analysis (Barret & Peleg, 1992), and that of the cell wall properties and density, can be studied almost in isolation. For example, one can produce freeze-dried gels of exactly the same composition with different cell size distributions by controlling the freezing rate. Such dry sponges can be used to learn how purely structural features affect texture perception. There are many ways to create structures (Peleg, 1993) and only the future will tell whether ‘texturally tailored foods’ will indeed provide the answers to the questions previously raised.

10. Concluding remarks

Despite great advances in the understanding of the neurophysiology of mechano-receptors and the operation of the sensory system and despite the existence of a large body of empirical data on texture evaluation, certain fundamental issues associated with texture perception still remain unresolved. Consequently, the creation of a desired texture in the food industry is still largely a matter of trial-and-error based on an accumulated empirical knowledge. There are, of course, helpful guidelines, but they are usually specific to certain products rather than general. There seems to be a wide spread confusion regarding the semantics of texture, an incomplete understanding of how specific textural attributes are actually perceived, and reliance on problematic empirical tests to characterize food texture instrumentally. Misinterpretations of the meaning of ‘correlations’ between sensory and instrumental evaluations is also not uncommon. At this time the proposed approach to base texture studies on material science principles is still largely speculative and may be over simplistic. But the need for a new direction in texture research can hardly be disputed. The most promising start is to define and measure the 'objective' mechanical properties of foods in the same way as engineering materials. Only then should it be investigated whether specific rheological properties are indeed perceived as such. The sensory response to a mechanical (or acoustic) stimulus should be expressed not as a characteristic 'value', i.e. as a mean relative or an absolute score, but as a *distribution of the terms* used by those who sense them. The implicit assumption that humans have a constant sensitivity like machines should be dropped. It can be shown that, theoretically, and most likely in practice as well, humans can identify very hard and very soft foods but they have no discrimination ability in both ends of the stiffness scale. There is a maximum sensitivity region in an intermediate stiffness level. But the exact location of the peak and its sharpness must depend on the rheological properties of the individual's sensory system as well as the food. This is a very important piece of information to the food industry and extremely valuable to setting tolerance margins for rheological attributes in a product's specification. What is a practically detectable difference can be determined by a combination of mechanical and statistical methods. Such differences, and not merely the standard deviation, should be considered in the interpretation of industrial quality control charts.

At least in principle, formulations containing different hydrocolloids and their combinations can be conveniently used to create model and real foods with controlled rheological properties. These in turn can be used to resolve some of the outstanding issues regarding texture perception by humans. In future research, hopefully, there will be more cooperation between scientists from different disciplines than now exists. Concepts of neuro-physiology, semantics, statistics, and behavioral sciences should supplement the principles of mechanics and material science in order to strengthen the scientific foundations of the discipline. This will not only widen the field's horizon as an intellectual endeavor, but will also provide the food industry with more effective guidelines concerning texturization and textural control of its products.

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