REVIEW PAPER

PSYCHOPHYSICAL MEASURES OF TEXTURE

HOWARD R. MOSKOWITZ
Pioneering Research Laboratory, U.S. Army Natick Laboratories, Natick, Mass. 01760, U.S.A.

and

BIRGER DRAKE and CAJ ÅKESSON
Swedish Institute for Food Preservation Research, Goteborg, Sweden

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Abstract. Psychophysical measurement seeks functional relations between instrumentally measured quantities and subjective perceptions. The review concerns the sequence of operations needed to construct meaningful scales for dimensions of perceived texture. Initial investigations require delimitations of the range of texture description in order to select 'fundamental' perceptual dimensions. Once dimensions such as subjective hardness or viscosity are selected, the next step is to develop an appropriate scale of magnitude. Placing products into verbal categories or into an ordinal arrangement cannot provide the necessary scale. However, when a scale is set up so that differences or ratios of scale values are meaningful, then an equation can be chosen to describe perceptual strength as a function of physical intensity. By constructing valid scales of perceived texture, it is possible to expand the applications of sensory scaling to encompass the optimization of products and the quality control of food materials under development.

1. Introduction

Sensory evaluation of texture in foods, as well as in other products such as textiles, belongs to the domain of psychology known as *psychophysics*. Psychophysics directly concerns the correlation of sensory experience with physical measures. Its ultimate goal is to establish mathematical equations or relations that permit the scientist to predict the sensory characteristics of materials from the physical measurements, and vice versa. Psychophysics does not seek to explain the basis of sensation, but instead searches for orderly relations between the subjective realm and the physical world. Much has been written about the development of machines to quantify the physical characteristics of food that give rise to 'texture' as perceived by the human judge. However, machines cannot appreciate texture like a human being. Psychophysics of texture thus has two goals: a description of the relevant physical characteristics of materials that are implicated in the perception of texture, and an analysis of subjective-objective correlations to relate one or more physical characteristics to the ultimate percept experienced by the human judge.

The present review provides a foundation for the psychophysics of texture by indicating and discussing the available sensory scales that may be used by the human

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observer. Traditionally, psychophysics has viewed the human observer mechanistically, as a machine that transduces physical information supplied by the environment into sensory and perceptual information experienced by the subject. Sensory scales in this context provide the scientist with a transfer function, which allows him to determine how quantitative relations between physical measures are translated into relations between subjective percepts.

Prior to introducing the types of scales used by psychophysicists, it is relevant to discuss the theory of measurement. Two major problems have been considered by philosophers and psychologists interested in quantifying sensory experience: the problem of *representation*, or how can one assign numbers to sensory phenomena, and the problem of *uniqueness*, or the degree to which the numerical assignment is unique or unchanged when transformations are made on the scale values (Suppes and Zinnes, 1963). The representation problem is a problem of modelling, i.e., if the physical domain to be represented permits meaningful intervals and ratios (e.g., distance), the psychophysical representation of that domain (namely scales of subjective distance) should also permit intervals and ratios. The uniqueness problem pertains to the often-noticed fact that one may transform measures but yet continue to maintain the scale. For example, distances may be measured either in feet, inches or miles, but the measurement is unique to the size of the unit. A constant multiplicative factor will relate distances in inches to distances in miles. In addition, the ratios of the distance between – for example – Argentina and Bolivia to the distance between Hungary and Austria remains the same, whether the distance is expressed in inches, feet or miles. Psychophysical scales must always be subjected to scrutiny with these two analyses in mind. Quite often the scientist may lose perspective and fail to model the most appropriate physical relations on his scale. He may also lose sight of permissible transformations which will not change the quantitative, formal properties of the scales.

2. Dimensions of Perceived Texture

Empirically, both subjective and objective (instrumental) assessments of texture are multidimensional in nature. No single instrument reading can fully characterize the rheological properties of a food material, and even untrained observers will report a complex of sensations that occurs when they chew and swallow a food. Keywords such as 'sliminess', 'firmness' and 'unctuousness' may be sufficient to elicit quite different responses from the observer as he samples a pudding. As attention focuses on different subjective attributes of texture, the importance of physical characteristics shifts so that some become more relevant and others diminish in importance.

An appropriate first step in the development of psychophysics of texture is to classify by suitable methods the linguistic descriptions that are most relevant, and then to specify how these terms may be used to denote unambiguously the salient characteristics of texture. Two general approaches have been made in this direction to extract the underlying 'dimensions' important to the observer. The first is psychological in nature and seeks to extract fundamental dimensions of texture perception without necessarily referring to instrumental measures. The second begins with an assumed set of basic dimensions believed to characterize subjective perception of texture and then seeks analogues in physical measures.

Yoshikawa *et al.* (1970) presented a multivariate analysis of Japanese descriptive terms for texture, and showed how these terms applied to a selected group of named foods. Multivariate analysis (Harman, 1967) condenses the different descriptive terms to basic dimensions presumed to be independent of each other. The large array of words uncovered by Yoshikawa *et al.* appeared to be composed of different weightings of the following basic underlying dimensions: hard-soft, cold-warm, oily-juicy, elastic-flaky, heavy, viscous and smooth. Each descriptive term for texture could be described by a linear combination of the dimensions, but the fundamental dimensions were assumed to be pure. No attempt was made as yet to correlate these dimensions to instrument measures.

Multidimensional analysis provides a useful technique for uncovering the existence of simple geometric representations of texture perception. The goal is to represent the attributes of subjective texture as a series of axes in multidimensional space (a space of seven dimensions for the Japanese analysis). A given texture term may then be expressed as a linear combination of these fundamental dimensions. More powerfully, however, the texture of a food may be represented by assigning that food to a point in the multidimensional space, whose coordinates provide the relative weights of each of the seven dimensions. A consideration of multidimensional representation of texture measures ought to be made for representation of instrumental measures in terms of fundamental rheological principles, much in the same way as was done for subjective attributes.

Szczesniak and her colleagues (Szczesniak *et al.*, 1963) have provided an illustration of the basic psychophysical approach to classifying texture attributes. The system is based upon an appreciation of instrumental measures of texture, as well as ancillary dimensions that may participate in and influence the perception of texture. Each dimension is selected in order that it may be related to an instrumental measure, and assessments may be effected either by a panel of observers or by an appropriately constructed machine.

Scott Blair (1966) has also considered the construction of texture scales based upon instrumental measures. In one series of studies in which observers were instructed to judge 'firmness', he noted that their judgments could best be predicted by a combination of physical dimensions in a manner not permitted by physical principles. These 'intermediate entities' as he called them, suggest that a psychophysical approach to characterizing the dimensions of texture ought to consider the possibility that observers may combine rheological dimensions in a manner not consonant with standard physical principles.

An intensified study of psychophysical approaches deserves as much interest as measurement techniques, for it may provide to the instrumentalist a systematic and relatively straightforward way of reducing texture to analyzable components in terms of subjective percepts. The future of these approaches, however, depends critically upon the continued refinement of psychological methods to extract the nuances of texture perception.

3. Scales of Magnitude in Texture

For the past 150 years psychophysicists have struggled with the problem of quantifying experience, and the subjective attributes of texture are no exception. A list of relevant attributes or dimensions is only part of the task of describing sensations. Two food materials may possess the same set of characteristics, but yet may seem entirely different because the characteristics are present to different degrees in each food. A short history of the attempts of psychophysicists to construct intensity scales is relevant for an appreciation of those commonly used today.

In the early part of the nineteenth century, E. H. Weber (Boring, 1942) reported the results of his studies on the discriminability of stimuli. In a study of the resolving power of the touch sense, Weber discovered that two stimuli were reported to differ in sensory magnitude only when the more intense one exceeded the weaker one by a relatively small, but fixed, proportion of physical intensity. For example, two weights appeared to differ in heaviness if one was approximately 10% heavier. If they differed by a smaller ratio, they were reported as being equally heavy. In order to represent this critical fraction, Weber chose the expression $\Delta I/I$ (later called the 'Weber Fraction') to signify the smallest fractional part by which a stimulus had to be increased in order to render the two stimuli just noticeably different.

Subsequently, in the middle of the Nineteenth Century, a German physicist G. T. Fechner (Boring, 1942) suggested that a sensory scale could be constructed by adding units of discriminability in a differential equation. The result was a logarithmic function $S = k \log I$ that could be used to relate the sensory magnitude S to the physical intensity I. The logarithmic relation was an attractive conjecture since it set forth a simple and tractable mathematical transformation to relate increments in physical magnitude to those in perceived magnitude.

A complete method, based on Fechner's assumptions, is tedious since it involves adding together many units of subjective discriminability in order to span the range of sensation from 'barely perceptible' to 'extremely strong'. Fortunately, more direct and simpler methods have since become available, and their use has gained for psychophysics a new appreciation of the utility of intensity measurements.

Psychophysicists in the past fifty years have suggested that sensory measurement be approached in a direct fashion, by requesting the observer to report his perceived magnitude for a given stimulus along an appropriate response scale. In this way, the judgments of an observer are treated as would be the output of a measuring instrument, and the technique of arriving at data is simple and immediate. Because the observer carries with him the experience of a lifetime in making informal judgments of magnitude, several caveats must be followed. Often the order of stimuli in a sensory test can influence the outcome of the measurement, as the observer recalls the judgments he had made for previous stimuli. Many observers exhibit peculiar number behavior and consistently refuse to use the extreme portions of the scale, even to describe intense or faint stimuli (Stevens and Greenbaum, 1966). Perhaps the most important caveats to follow are that the observer be aware of the dimension to which he is instructed to attend and to judge, and that he report his judgment in a manner appropriate for the response scale that has been selected.

Three major methods have been used to arrive at measures of magnitude: ordinal scaling, interval scaling, and ratio scaling. The method of ordinal scaling may be dismissed immediately, because it provides only an indication of the relative position of stimuli along an intensity continuum. No information is forthcoming about the relative separation of different stimuli and, therefore, no equations or functions relations can be derived. Interval and ratio scales provide this information.

4. Interval Scales of Texture Perception

Scales of perceived texture may be developed by partitioning an appropriate sensory continuum into a series of ordered categories (e.g., 1–9, 1–100), and then instructing the observer to assign to each physical stimulus a category rating by selecting the category that best describes the perceived magnitude. For example, a 1–9 scale of perceived 'hardness' may be of interest. At the low end of the scale (category 1), the anchor word 'very soft' may be used, whereas at the high end of the scale (category 9) the anchor word 'very hard' would be appropriate. For each sample to be judged, the observer selects the most appropriate category. On occasion, intermediate verbal anchors may be inserted at one or another category to aid in making judgments.

Interval scales rely upon the concept of sensory 'distances'. In order to use the scale properly and to apply statistical tests to the subjective responses, the differences between adjacent categories in the scale must be equal. Thus, for example, the subjective hardness difference between categories 3 and 4 must be equal to the hardness difference between categories 4 and 5. If this criterion is met, the scale values for different textural attributes may be analyzed by the methods of inferential statistics to determine whether or not the two materials differ significantly in hardness (e.g., by the t test, or for more samples by the technique of Analysis-of-Variance). It is appropriate to conclude that two samples are separated by 4 units on the hardness scale when the category values for these samples are 6 and 2, respectively. Because the zero point is not fixed, however, one cannot conclude that the harder sample exceeds the softer one by a factor of 3. Thus, differences between category (interval) scale ratings convey information about intervals, but proportions or ratios cannot be obtained.

The 'Texture Profile' (Szczesniak *et al.*, 1963) comprises a series of category scales for the subjective dimensions of hardness, brittleness, chewiness, gumminess, adhesiveness and viscosity. Each attribute is represented by a scale containing a series of ordered categories, although the number of categories is not the same for each dimension. There are nine categories of hardness, eight of viscosity, seven each of brittleness and chewiness, and five each of gumminess and adhesiveness. Each scale is anchored by a series of representative standard products that illustrate the intensity gradations for the subjective magnitude on that dimension.

The value of category scales such as the 'Texture Profile' lies in the possibility of describing functional relations between perceived magnitude along the subjective scale and instrumental measures. Szczesniak *et al.* (1963) present six graphical functions that relate the perceived intensity of texture to instrumental readings of the General Foods Texturometer. In all cases but one (subjective viscosity), the category scale arrived at in the profile could be described either by the simple linear function $S=kT+b$ (S=subjective rating, T=Texturometer reading), or a logarithmic function $S=k\log T+b$.

5. Ratio Scales of Sensory Texture

Many physical scales of magnitude possess the convenient property that ratios of measures convey meaningful information about proportionality. For example, 2 miles represent twice the distance of 1 mile, and 40 grams represent five times the weight of 8 grams. Category scales lack this ratio property, and although category scales can be very sophisticated in their usage, they nonetheless must be considered inadequate when proportionality is of interest.

During the 1940's, Beebe-Center and his colleagues (Beebe-Center and Waddell, 1948) developed four scales for the primary tastes of salty, sour, sweet and bitter. They used a technique entitled 'fractionation', which was as follows. A top concentration of a representative taste compound (e.g., sodium chloride for 'salty') was selected, and the observer was instructed to sample that aqueous concentration, and then to select from a series of comparison samples the solution tasting half as salty. Successive applications of this procedure produced an array of concentrations of NaCl that appeared subjectively to correspond to the numbers 100:50:25:12.5 etc., (equally 2.5:1.25 etc.). A later report (Beebe-Center, 1949) listed nine standard concentrations of chemicals for each of the four primary tastes. The 'gust scale', as Beebe-Center called it, set the stage for numerous subsequent investigations of other sensory and perceptual continua.

In a study of subjective roughness and smoothness, Stevens and Harris (1962) instructed their observers to assign numbers in proportion to the perceived intensity by the technique of *magnitude estimation*. In essence, the observers acted as meters to generate numerical output, with the assumed property that ratios of numerical assignments to stimuli corresponded to subjective ratios of perceived magnitude. Subsequent studies investigated the sensory functions for many other senses (Stevens, 1960). Other experiments directly relevant to the psychophysics of texture are those by Ekman *et al.* (1964), also on the perception of roughness and smoothness as well as on the acceptability of those sensations.

Harper and Stevens (1964) studied the relation between physical hardness of rubber (measured by the degree of indentation of a weight on the rubber sample) and perceived hardness. They reported that a power function with an exponent of 0.8 related the subjective magnitude to the objectively measured degree of hardness. Subjective perception of viscosity was studied by Stevens and Guirao (1964) who instructed their observers to either stir a viscous silicone oil while blindfolded, stir it while looking, or simply turn the solution over in an enclosed container. Moskowitz (1972) also investigated subjective viscosity and fluidity, but with twelve vegetable gums made up in solutions of different concentrations.

The techniques that provide ratio scales are simple to use and give reproducible results across different laboratories. Over a period of about two decades, beginning in 1953 (Stevens, 1953), there has been a continued and increasing interest in appropriate equations to relate sensory and objective (instrumental) measures. Consistently, equations of the form $S=kI^n$, the simple power function, appeared adequate to describe the results of these direct scaling experiments, whereas the simple linear, logarithmic or exponential functions appeared to be unsatisfactory.

A major problem that arises in direct scaling of any type, and especially in ratio scaling where functional relations are of extreme importance, is the validity of the scale. How can one assert that the texture scales arrived at by magnitude estimation truly obey the properties of a ratio scale wherein proportionality statements are meaningful? In a validation study, Ekman *et al.* (1960) demonstrated that the technique of magnitude estimation provides essentially the same scale as is obtained when the observer is asked to judge directly the ratio of intensity between every pair of stimuli in the set (monochromatic wavelengths in that case). Although individuals may possess idiosyncratic ways of handling numbers as measuring instruments, and there appear to be systematic biases resulting from the selection of the initial stimulus to serve as a standard and the initial judgment to serve as a modulus (scale unit), the outcome of these direct experiments is a robust scale that can be replicated in different laboratories.

The present main use of power functions is to index how rapidly sensory magnitude grows with increases in physical intensity. For example, values of n equaling 1.0 indicate a linear relation between sensory and objective measurements, so that doubling the physical intensity in turn doubles the subjective impression of magnitude. Line length viewed on a wall (Stevens and Guirao, 1963) is such a continuum. On the other hand, when n is less than 1.0, as is the case for subjective loudness with $n=0.64$ (Stevens, 1966), or subjective viscosity with $n=0.4$ (Moskowitz, 1972) or $n=0.5$ (Stevens and Guirao, 1964), the subjective magnitude grows more slowly than the physical intensity, and the range of subjective intensity is narrower than that measured physically. An example is provided by the viscosity exponent of 0.5. If two gums are dispersed in water and their viscosities are 1000 and 100 cps respectively, then their apparent viscosities lie in a ratio of 10:1. The observer, however, in judging the subjective viscosity of these two gums will tend to rate them as a ratio of only $(10/1)^{0.5}=$ 3:1 (approximately). Finally, n may exceed 1.0, in which case the opposite effect occurs, so that the subjective magnitude grows more rapidly than the physical intensity and the subjective range of magnitude exceeds the physical range. The smoothness of sandpaper is governed by a power function with an exponent of 1.5, when grit size is used as the instrumental measure (Stevens and Harris, 1962). Thus, when the grit of sandpaper is increased tenfold, the sensory effect is a 'jump' of apparent smoothness by a factor of $(10/1)^{1.5}=30:1$ (approximately).

The power function of sensory magnitude provides a simple index of perceived magnitude for different aspects of texture. The exponent n is independent of the units of instrumental and subjective measurements, so that instrument readings that vary by a multiplicative factor (i.e., change of unit) will still yield the same power function exponent when correlated with subjective judgments. In addition, n also remains unaffected when the observer multiplies all of his judgments by a constant factor, although on occasion the size of numbers that an observer selects will tend to bias his judgments. Some observers feel comfortable using small numbers, and may not make an equivalent multiplication for all of their judgments when changing their scale to large numbers. The intercept k is, however, extremely sensitive to changes in the size of numbers used by the observer.

6. Applications of Sensory Scales of Magnitude

One aim of sensory scaling is to replace the instrumental measure with the human observer, or vice versa, to replace the human observer with one or more instrumental measures. Two of the most important areas that can benefit from developments in quantification of subjective perception are the fields of quality control and of product development.

Quality control can delimit the physical characteristics of products so that only acceptable and safe foodstuffs are offered for consumption. No one wishes to eat rock-hard hamburgers or mushy apples, and our decision to accept or to reject these items is based upon the measuring capacity of our senses. Knowledge of psychophysical relations, whether based upon interval (category) or ratio scale methods, may provide improvements in quality control.

Continued research by Kramer (1965, 1969) represents a fertile avenue of application. An illustrative study is provided by the experiment of Fox and Kramer (1966), who attempted to predict the overall quality and flavor of cooked and raw green beans. Their instrumental measures were the shear press, the qualitometer and other 'objective' indices, while the sensory evaluations were provided by both trained and untrained panelists. Their interest was to determine an equation that could predict with high accuracy the sensory judgment (S) as a function of the instrumental measures. The technique of 'multiple regression' (Efroymsen, 1960) was used to arrive at the following linear relation between sensory magnitude (S) and instrumental readings $X_1, X_2 \ldots X_n$

$$S = k_1X_1 + k_2X_2 + k_3X_3 \cdots + k_nX_n .$$

The independent, *ad hoc* predictor variables, $X_1, X_2, \ldots X_n$, were weighted by multipliers $k_1 \ldots k_n$, respectively, in order to maximize the predictability of the sensory response (S).

Kramer's equations are designed to provide a statistically satisfactory prediction of subjective responses to texture, but are not focused upon any theoretical model of human responses to texture variables. A valuable contribution to the psychophysics of texture perception would be a combination of Kramer's technique with standard psychophysical scaling, such as the Texture Profile. That combination would bring together the analytical techniques with statistical prediction theory, and would provide a firm basis for the study and employment of sensory and instrumental texture measures.

Another challenging possibility is that acceptability limits in quality control may be expressible both in terms of instrumental measures and in units of sensory magnitudes. For example, under appropriate standardization of scaling techniques, one can assign to a tomato a firmness rating in proportion to a reproducible standard of firmness, as well as measure the 'instrumental firmness' by objective techniques. If the standard sensory firmness is called 10, and the tomato feels half as firm, then the tomato is rated as 5. Furthermore, if – on this sensory scale – acceptably firm tomatoes are rated between 4 and 9, with other ratings indicating tomatoes that are too hard or too mushy, then it is possible to set up equivalent limits of physical measurement and to define the region of acceptability in terms of instrumental measures. For example, if subjective firmness is governed by a power function of the form $F=I^{2.0}$ (i.e. subjective firmness F grows as the square of instrumental reading I), then the upper level of subjective acceptance (9) corresponds to an instrument reading of 3, and the lower level (4) to an instrument reading of 2. By this technique, it is possible to employ both instruments and human observers in the quality control process, and to make them interchangeable according to a transformation function between sensory and instrumental magnitude.

Product development work is another area that can use psychophysics of texture. Developing a product requires the close cooperation of food technologists who do the actual development work with psychologists who evaluate the consumer reaction to the product. The Texture Profile may be of great use in providing a system to characterize the salient texture dimensions of a food. For the past fifteen years the Hedonic Scale of food acceptability (Peryam and Pilgrim, 1957) has provided quantitative information which permits the development team to assess the prospective acceptability of their product. Neither procedure, however, possesses the capacity to assess both the dimensions of a food that need to be changed in order to improve acceptability, and the magnitude of change that should be effected. A combination of the Texture Profile, to focus attention on salient dimensions, with direct questions on the desired magnitude of change would provide the much needed approach towards more effective changes in the texture of newly developed foods.

A recent study (Moskowitz, 1971) has focused on this problem of 'optimizing' foods by instructing the taste panel to judge both the intensity of a sensory dimension (the subjective 'grind' of hamburger) and the degree to which the panel would like to alter that dimension (i.e. increase or decrease the subjective grind) in order to optimize the acceptability. The initial phase of the experiment concerned the relation between perceived 'chunkiness' (the subjective attribute) and the objective measure of grind. The relation could be described by a power function of the form $C=kG^{0.55}$ ($C=$ subjective chunkiness, $G=$physical measure of grind in inches). The panelists were then instructed to estimate the degree to which they would increase or decrease the grind of each hamburger in order to make the overall product maximally acceptable. Since a psychophysical equation was determined, changes along the subjective dimension could be related to changes in the physical degree of grind, and – therefore – the textural property of the hamburger could be altered in accordance with subjective estimates.

The work of Lundgren (1969) in assessing the 'hand' of textiles is appropriate in the application of psychophysics to the study of texture. According to Lundgren, textile hand is an integrated property of several sensory responses such as roughness, stiffness, bulk and thermal properties. In order to assess the appropriateness of these dimensions for a product, Lundgren proposes a multi-stage procedure, wherein the initial steps are to instrumentally measure magnitudes of each dimension, and to determine the response profile of the human tester. A combination of these two measures, one objective and the other subjective, is an index of how the tester responds to the specific textile characteristics. The outcome is a final profile of the product in terms of the acceptability of each dimension to the tester, with the profile serving as a quantitative index of which aspects must be changed in order to optimize the final acceptance of the fabric.

7. Outlook

Psychophysical scaling and sensory evaluation are in their infancy. The opportunities they present for providing scientific and technological information on ways to assess the dimensions of sensory texture are limited only by the ingenuity of the scientist and of the product developer. The pioneering work to assess intensity on many sensory continua by the method of ratio scaling (Stevens, 1960) as widely different as the loudness of noise, the hardness of rubber and the sweetness of sugar, promises that corresponding interest in food will also reveal important theoretical and practical functions in quantifying sensory responses.

One may, thus, look forward to the coming decades with confidence, as holding the promise of answers to many of the important questions in evaluating the subjective attributes of texture. Developing textures in accordance with consumer specifications, producing better descriptions of the salient dimensions of products, and finally arriving at precise sensory-instrumental correlations are all research areas that will no doubt profit greatly from the advancement of texture psychophysics.

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