DISCUSSION PAPER

VIEWS ON RELATING INSTRUMENTAL TESTS TO SENSORY ASSESSMENT OF FOOD TEXTURE. APPLICATIONS TO PRODUCT DEVELOPMENT AND IMPROVEMENT[1,2]

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ABSTRACT

Well-defined measurements of the mechanical properties of food and the reduction of sensory attributes to the fundamental primary entities, together with the definition of their correlation functions, provide the basis for the eventual development of instruments calibrated in terms of human sensory response and having a high probability of predicting the consumer reaction. Since mechanical measurements of most foods are time-dependent, the understanding of conditions prevailing during sensory testing (rate of shear, etc.) will aid in selecting the optimum conditions for instrumental testing. Recent progress in this area has been made with fluids and some solid foods. The method of magnitude estimation assists the researcher in discovering the underlying laws relating physical product changes to perceived textural changes. At the same time, magnitude estimation also aids the product developer to determine empirical, ad hoc relations between physical levels of mechanical variables and textural perceptions, even if the true, underlying relationships are not known. Ad hoc equations can be used (in conjunction with optimization techniques) to determine the combination of mechanical

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variables that (a) produce a specific sensory texture profile, and (b) maximize texture/product acceptability.

INTRODUCTION

In the recent 15 years a number of advances from research in several laboratories using different approaches have contributed to making food texture one of the most rapidly developing areas of Food Science. These advances include, among others, (a) the application of knowledge established in Material Sciences to the characterization of the mechanical properties of food; (b) the development of the Sensory Texture Profile which provides a basis for defining the sensory dimensions of food texture and for identifying its mechanical analogs; (c) work on the definition of processes involved in sensory testing (conditions in the mouth, testing by touch, etc.) with a view of optimizing the instrumental testing to reflect consumer response, especially in the case of fluid foods, and (d) the introduction of ratio scaling, e.g. magnitude estimation, in conjunction with psychophysical laws to relate physical stimuli to sensory perception.

In previous papers (Moskowitz and Kapsalis 1974, 1976; Kapsalis and Moskowitz 1977) we have presented data and concepts which supported our view of the present usefulness and future potential of psychophysical approaches to food texture. The present paper further extends our views by (a) critical evaluation of published work and (b) presentation of an optimization process in product engineering based on *ad hoc* relations between physical levels of mechanical variables and texture perceptions, the purpose of which is to produce a desired sensory texture profile and maximize texture/product acceptability.

INSTRUMENTAL MEASURES AND CORRELATION WITH SENSORY DATA

Advances in the Definition of Optimum Instrumental Testing Conditions

Liquid foods are particularly helpful in defining optimum testing conditions since they are more or less homogeneous, their consistency can be controlled by varying the concentration of the dispersed phase (as e.g. in soups and emulsions), and their viscosity measurements can be conveniently made under a wide range of shear rates. Since soups and food emulsions are, in general, non-Newtonian liquids, their shear stress depends on the applied shear rate (Fig. 1, upper half). The

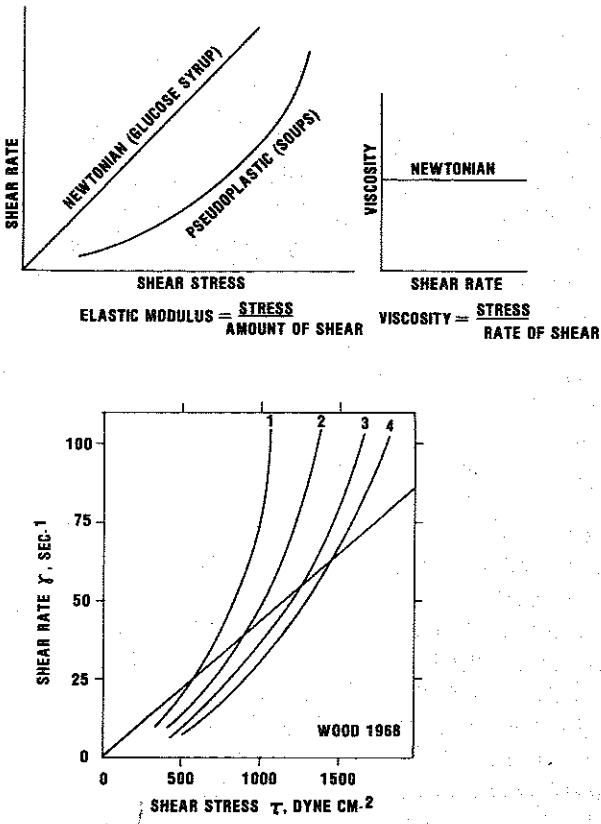

FIG. 1. MECHANICAL BEHAVIOR OF FOODS

question is what shear rate one should use for relating instrumental measurements with sensory estimates of viscosity, especially in the case where the shear stress-shear rate curves for two liquids intersect; in such cases one liquid may be less (or more) viscous than the other liquid below a certain shear rate, and the reverse may be true above this rate.

The procedure for defining the optimum testing conditions originated with the pioneering work of Wood (1968) who compared a series of different concentration sauces (non-Newtonian) with a Newtonian liquid (glucose syrup). The sensory panel was asked to define the sauce which was closest to the consistency of the Newtonian fluid. Subsequently, the shear stress-shear rate curves of the Newtonian syrup and of the sauces were established. The point where the sauces intersected the Newtonian liquid was taken as the optimum shear rate to be used for the instrumental measurement. In Fig. 1 (lower half) this optimum range was between sauces 2 and 3; the conclusion was that, in the mouth, the foodstuff was subjected to a shear rate of about 50 s^{-1} and that the corresponding stress was the perceived stimulus. This work was subsequently extended by the comprehensive experiments of Sherman and his co-workers (Sherman 1975; Shama and Sherman 1973b,c; Shama, *et al.* 1973) who found that Wood's sauces represented a limited range of liquid foods, occupying a short segment of a "universal curve" encompassing a much wider range of viscosity. They found that the rate of shear in the mouth is variable, fluid foods being assessed at a much higher rate of shear than viscous foods. A change in the stimulus associated with the sensory evaluation of viscosity of fluid and viscous foods occurs at about 70 cps. For fluid foods, the stimulus involves the shear rate developed at an approximately constant shear stress of 100 dyne cm^{-2}, but for viscous foods it involves the shear stress developed at a constant shear rate of approximately 10 s^{-1}.

Figure 2 represents a case of solid foods where the selection of the proper instrumental testing conditions is of paramount importance if high, predictive correlations with sensory judgements are to be obtained (Shama and Sherman 1973a). The sensory texture panel always rated Gouda as being harder than White Stilton. The three dimensional diagram indicates that the curve for the White Stilton is always higher than that for Gouda if a crosshead speed of 5 cm min^{-1} is used. At a crosshead speed of 20 cm min^{-1} the 2 curves intersect at 2 points, so that within the range of 38-62% compression the curve for Gouda is always higher than that for White Stilton. The shaded area between the two curves defines the range of force-compression-crosshead speed conditions to be used with these products when good correlations with sensory assessment are desired.

Even if the plots of forces versus the crosshead speed do not intersect, it cannot be assumed that the test conditions will not affect the relationship between instrumental and sensory measures, and that the crosshead speed can be selected in an arbitrary manner. This point has been discussed recently by Voisey (1975) and illustrated with a specific example involving cooked spaghetti of three tenderness levels. The spaghetti was sheared at 8 speeds covering the range of 0.5-100 cm min^{-1} and evaluated by a trained panel for firmness and chewiness. Although high values of the correlation coefficient were obtained between instrumental and sensory assessments, the two measurements resulted in different levels of discrimination among specific samples. An examination of the force versus the shearing blade velocity curves revealed that, although there were no cross-overs, the

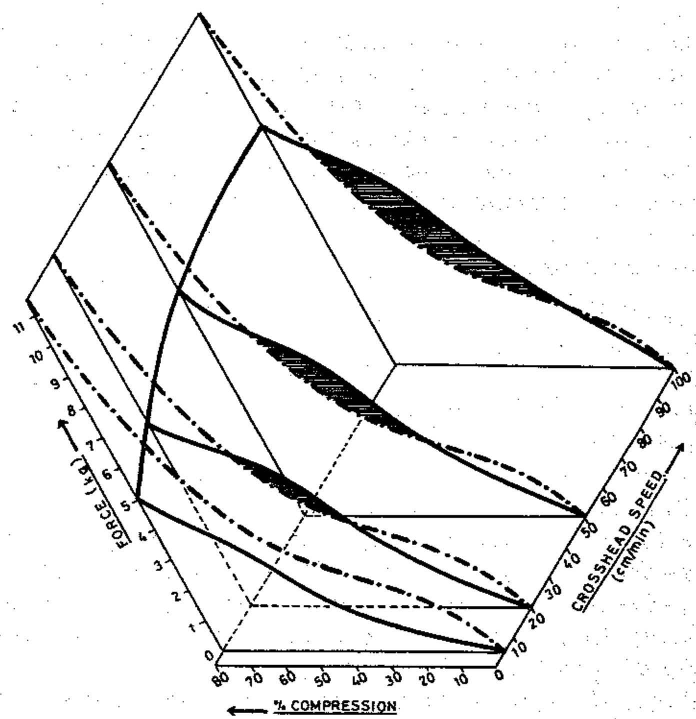

FIG. 2. THREE-DIMENSIONAL PLOT OF FORCE-COMPRESSION-RATE OF LOADING DATA FOR WHITE STILTON AND GOUDA CHEESES

—•—•—•— White Stilton; ———————— Gouda (Sherman and Shama 1973).

slopes of the lines were different. As a result, extrapolation to the crosshead speed of 150 cm min^{-1} (believed to be similar to the deformation rates occurring during sensory mastication) showed that some curves were converging and others were diverging. Force values calculated at the extrapolated speed of 150 cm min^{-1} gave the same level of discrimination among samples as the sensory evaluation.

A "Variance" to the Rule

Although a certain simulation of sensory testing conditions in instrumental testing can be useful, it is not always necessary in order to obtain good correlations between sensory judgements and mechanical parameters. This is due to the fact (to be discussed further in this paper) that such correlations may be the result of incidental unknown factors which affect the sensory and instrumental measurement in the same or opposite direction. It may not be possible or practical to always simulate the human masticatory process for successful measurement of texture. A great number of empirical, as well as well-defined, instrumental measurements provide satisfactory correlations and predictions without operating on the basis of the same testing conditions.

The Lexicon of Food Texture

The development of a basic lexicon or irreducible language of sensory evaluation of food texture is a prerequisite for any successful method of profiling, of scaling and quantifying, and of correlating with rheological data (Kapsalis *et al.* 1973; LeMagnen 1962; Szczesniak and Kahn 1971).

As a basis for discussion toward a standardized methodology, Jowitt (1974) presented a systematic glossary of food texture terms within the following main groupings: (a) terms relating to the behavior of the material under stress or strain; (b) terms relating to the structure of the material (those relating to particle size, shape or character, and those relating to shape and arrangement of structural elements), and (c) terms relating to "mouthfeel" characteristics.

A plethora of words in English and other languages exist for the expression of food texture sensory perceptions. Many of these words are redundant and overlapping, and careful experimentation using the methods of Psychology, Statistics, and Food Science is necessary for the elucidation of the "unit elements" or basic descriptors.

The work of several investigators (Szczesniak 1971; Szczesniak and Skinner 1973; Henry *et al.* 1971; Kokini *et al.* 1977) showed that a reduced vocabulary is feasible for a large number of sensory texture perceptions. Yoshikawa *et al.* (1970) investigated Japanese words denoting texture in response to 97 food stimulus words, and compared results with those obtained by Szczesniak in the U.S.A. The most important words in descending order of frequency were: hard, soft, juicy, chewy, greasy, viscous, slippery, creamy, crispy, crunchy, and brittle. Using 40 texture-describing words as rating scales, texture profiles were constructed for 79 foods. The following words were important: soft, hard, juicy, chewy, not chewy, warm, cold, elastic, greasy, moist, and smooth. Finally, on the basis of a correlation matrix and multivariate analysis, they reported eight orthogonal factors with the most important dimensions being hard ⟷ soft, cold ⟷ warm, oily ⟷ juicy, elastic ⟷ flaky, heavy, viscous, smooth.

Recently, Cussler and his co-workers at the Carnegie-Mellon University combined the study of texture vocabulary with psychophysical measurements analyzed by simulation of mechanical processes involved in the sensory perception of liquids. In one paper (Cussler *et al.* 1977) they showed that the texture of liquids perceived with the fingers can be predicted on the basis of the assessment of just three attributes: smoothness, thinness, and warmth. Smoothness was related to the force of contact lubrication and could be predicted from measurements of coefficients of friction, whereas thinness was related to viscous forces (warmth was not studied). They presented equations that related smoothness and thinness with experimentally measured parameters. In a subsequent paper (Kokini *et al.* 1977) they examined liquid texture perceived in the mouth. In this case they found that the attributes of "thickness", "smoothness", and "slipperiness" were the best predictors of other consistency-describing words of liquid foods. These attributes closely related to a specific force in the mouth. "Thickness" was proportional to the viscous force between the tongue and the roof of the mouth. "Smoothness" was inversely proportional to the frictional force caused by the contact between the tongue and the mouth, and "slipperiness" was inversely proportional to a known average of viscous and frictional forces.

It is our opinion that more research along the above lines, in conjunction with the application of psychophysical approaches, will yield practical insights useful in objective texture methodology.

Very little work on the non-flavor sensory attributes of beverages has been reported in the literature. Recently Szczesniak (1977) has presented a classification of mouthfeel characteristics of beverages, using a large number of mouthfeel terms under 11 categories. Some of these terms may also be important in connection with solid foods.

Whereas the terminology of Rheology is universally understood in terms of physics and mathematics, the terminology of the sensory evaluation of foods depends on the semantic structure of the different languages. Perhaps in the future some terms may be internationally accepted for the purpose of communication. This will eliminate the difficulty which exists in some cases when comparing results of laboratories in different countries, and it will give an internationally recognizable meaning to individual terms for correlation work between sensory and instrumental measurements.

Even after a "pure" non-overlapping term has been identified, it may not be clear what structural components of food texture underly it. For example, the tenderness of meat (Laurie 1968) seems to reside simultaneously in the connective tissue, the myofibrils, and to some degree, in the sarcoplasmic proteins. Tenderness is based on an integrated impression and is not attributable to any single component. The same may be true with "crispiness" and other sensory dimensions of foods. This makes the problem of "what to measure" and of "how to interpret it" in texture research more difficult.

Instrumental Analogs of Sensory Texture Dimensions

A fruitful future area of texture research may be based on a study of the relationships between the individual segments of the force-deformation curves obtained instrumentally and sensory texture descriptors, as well as the study of the contribution of the different parts of the curve to the integrated sensory judgment. What human sensory dimensions correspond to the modulus of elasticity, yield, ultimate strength, area under the curve, etc. of the force-deformation curve, and what contributions do these individual mechanical parameters make to the sensory dimensions of "hardness", "chewiness" and "crushability"? To pursue this type of work, micro strain gauges may be fitted to the teeth and connected to an amplifier and recorder. As the force-deformation curve is being obtained during chewing, the panelist describes and quantifies the individual and total integrated sensory perceptions. It would be of interest to know the point at which the panelist has all the important elements of information to make a reliable texture judgment of hardness, crispness, etc.

Texture Versus Rheology

Much discussion and intellectual ferment continues to exist on the issue of whether Rheology can accurately reflect the sensory perception of texture. The question is at the center of the fundamental difference between texture, which according to Kramer (1973) is evaluated through a sensation of touch or feel by the human hand and mouth, and mechanical properties studied by Rheology, which is a branch of Physics dealing with the deformation and flow of matter under applied forces. Can mechanical properties reflect sensory reactions to texture?

In a previous paper (Kapsalis *et al.* 1973) we have discussed some of the events which take place during chewing which tend to make texture difficult to simulate by mechanical means and to measure instrumentally. The paper states: "In the mouth, the variables of heat, saliva, and enzymes subject the food to continuous change. The latter may be related to hydration, displacement of air pockets by liquid, changes in the degree of dispersion and flocculation, changes in pH, chemical degradation, etc. The mouth operates not only as a "testing laboratory", but also as a "processing factory." Mechanical measurements show us that the above changes may significantly affect mechanical properties. For example, in dessert gel systems and whipped toppings, an increase of temperature alone may produce a drastic decrease in shear strength, rigidity, and other mechanical properties (Szczesniak 1975). The human subject measures and integrates sensory chewing perceptions on a material which undergoes continuous transformation. It is as if testing is done on a long series of different samples which are produced not only by the mechanical destruction of the original structure, but also by the biochemical conditions in the mouth. From the beginning of chewing to the time of swallowing, a multitude of tests have been performed, recorded and evaluated. In contrast, mechanical testing applies usually to the biochemically unaltered state. Suppose, then, that at different times during the chewing of a food sample, aliquot portions were withdrawn and subjected to mechanical testing by an instrument. What would be the characteristics of the plot of the modulus of elasticity, ultimate strength, etc. versus time or number of chewing cycles? How will this compare with a plot of the same properties when derived from the mechanical testing of an original ("unchewed") sample through successive loading-unloading cycles?"

The subject has been discussed extensively by Bourne (1975, 1977a,b) who suggested that food texture measurements fall partially within and partially outside the field of conventional Rheology. He pointed to the multitude of non-rheological factors which contribute to the sensory texture judgment; these include factors associated with size, shape, and roughness of food particles. Other factors to be considered are phase transformations as a result of temperature changes, such as those occurring during the melting of ice cream and chocolate.

For all the above reasons, we believe that correlations between sensory and instrumental texture measurements are usually of an associative, indirect (at times even coincidental) nature, reflecting underlying effects which may be operating in the same or different directions on the two sides of the correlation. For this and other (statistical) reasons, correlation and prediction do not imply equality — more important, they do not imply understanding of the mechanisms behind the association. The psychophysical law applied by Stevens (1960) does not suppose that the same principles are operating in the physical measurement and in the sensory assessment. Its success is due to the fact that the underlying principles on both sides of the equation (although they may be unknown) tend to make the exponential function useful in practice.

Small Strain Versus Failure-Type Instrumental Tests

This problem is a special case of the problem discussed above with regard to "Texture Versus Rheology." The sensory masticatory process usually involves rupture and gradual disintegration of the food through successive cycles. In contrast, many rheological measurements involve small strains. The question is whether such measurements are suitable for correlation studies with sensory ratings.

Recently, Mohsenin and his co-workers (Mohsenin 1977; Mohsenin and Mittal 1977) emphasized the importance of failure-type phenomena, especially in fruits and vegetables, and the value of solid mechanics and rupture theory as a foundation to the understanding of sensory texture. In many foods, sensory evaluation involves strain levels beyond the ultimate strength of the food at which yielding and fracturing (defined as failure) occur. The authors point out the fact that many failure type tests by instruments such as the Shear Press, the Texturometer, the Warner Bratzler shear apparatus and the Magness-Taylor pressure tester give good correlations with sensory evaluation in contrast to non-destructive, small strain tests that may not be highly correlated.

Although fracture may be of critical importance in many foods, we believe that non-destructive small strain tests may also be very valuable; they should not be excluded without direct experimentation on their applicability. For example, small strain tests are useful in the instrumental measurement of the "rubberiness" of meat and of the "springiness" of cakes.

Even in foods where rupture is important, high correlations between small strain instrumental measurements and sensory testing may be obtained for the following reasons:

(1) All events during chewing, from the moment when the teeth make contact with the food to the moment of rupture and finally — after successive cycles, to the moment of swallowing, contribute to the sensory texture judgment. The latter is an integrated composite judgment consisting of many transitory, partial sensations which are weighted by the brain through different psychometric coefficients. In the chewing of meat, for example, a considerable amount of information is probably obtained much before the rupture point of the myofibrils and of the connective tissue is reached. Even in the case of hard candy, where stress-dependent type of mastication predominates (Bourne 1977b), several conclusions may have been reached by the brain before the point of failure. We need to know more about the procedures through which these components of individual perceptions contribute to the final, integrated texture judgment.

High correlations between small strain instrumental tests and sensory evaluation are possible through common underlying causes. An example of this situation was obtained recently in our laboratory by Segars *et al.* (1977) who showed high correlations between Poisson's ratio and the sensory attributes of "chewiness," "difficulty of cutting," and "residue" in beef (r=0.899, −0.876 and −0.916, respectively). Poisson's ratio was linear in the 2—20% compression range. The modulus of elasticity, also a small strain parameter, did not show good correlations (r=0.432—0.502). In explaining the data, Segars *et al.* postulated that Poisson's ratio, being the ratio of transverse to axial strain, reflects primarily the amount and elastic properties of connective tissue. They further argued that, since the three sensory attributes assessed involve the properties of the connective tissue, a good correlation with Poisson's ratio is not surprising. The argument that the evaluated sensory parameters reflect a single characteristic (viz. the connective tissue) was supported by the high correlation between them (r=0.992—0.996).

PSYCHOPHYSICS OF TEXTURE AND PRODUCT ENGINEERING

In the foregoing section of the paper we have discussed some basic and applied aspects of the instrumental-sensory texture relation. We have examined certain recent approaches of defining the instrumental testing conditions on the basis of mechanical modeling of conditions operating in sensory testing. In this part of the paper we shall deal with a method of applying sensory and instrumental measurements to goal-oriented product development. The method makes use of non-linear multiple regression analysis to engineer and then optimize a product profile with maximum purchase interest.

Psychophysicists have developed powerful measuring methods to quantify perceptions, including those texture perceptions correlated with antecedent mechanical properties. The last decade has seen the development of ratio scales of texture, in which panelists assign numbers to perceived hardness or viscosity, with the property that if product A seems to be perceptually twice as hard as product B then A is assigned a number twice that assigned to B (viz., 35 vs. 70). The specifics of such ratio scales for texture appear in numerous journal articles and books (see Stevens 1975; Marks 1974). Of importance here are two aspects of psychophysics:

- Functional relations
- Applications of these functional relations.

Functional Relations in Texture

Psychophysical studies with ratio scaling of perceptions reveal that a simple empirical function, $S = KI^n$, relates the perceived sensory intensity (S) to mechanical or physical variables (I). The exponent usually lies between 0.2 and 2.0 and is unique and reproducible for different sensory modalities (e.g., the sweetness of sugar in water versus concentration; the hardness of rubber or of cracker sized portions of compressed foods versus modulus of elasticity; the viscosity of liquids and semi-solid suspensions versus the apparent physical viscosity.)

Power functions are discovered when the researcher has the luxury of systematically varying one (or possibly two) mechanical variables over a sufficient range to detect differences in perception. Although the graduations of a single physical variable do not have to be dramatic, they should span a sufficient range so that the panelists notice (and can thus scale) the perceived changes in hardness, viscosity, etc. When the experiment is done properly (as discussed at length by Stevens 1975) the results of the scaling study reveal a very tractable psychophysical equation which relates the single physical/mechanical variable to the sensory texture response.

Multiple Functional Relations

In actuality, each single texture perception is traceable to the confluence of many physical/mechanical properties of matter acting simultaneously. As a consequence, the understanding of texture perception is hindered if the researcher must methodically plod along, generating psychophysical functions of one variable.

Pragmatically, the understanding of texture perception can be enhanced by the use of statistical procedures for multivariate analysis (Levitt 1974). If, in fact, one can generate a reasonable mathematical description of interrelations between a texture perception and a variety of physical variables, then one can discern:

- The relative contribution of each physical/mechanical variable to a specific textural attribute.
- The interactions (in a statistical sense) among mechanical variables to generate the specific textural attribute.

The method of multiple regression analysis is very useful in this regard. Multiple regression analysis assumes a specific functional relation between a series of independent variables (viz., the mechanical variables measured by the rheologist) and a single dependent variable (viz., the sensory perception of hardness, elasticity, viscosity, etc.).

The function chosen for multiple regression analysis is usually linear and of the form:

$$\text{dependent variable} = k_1(M.V.X_1)+k_2(M.V.X_2)\ldots k_n(M.V.X_n)$$

$$(M.V_i = \text{mechanical variable i}) \quad (1)$$

That is, the regression equation assumes that there exists a linear relation between the independent variables (X_1,X_2, etc., which are mechanical or physical measurements) and the dependent variable (which is often a sensory percept).

Although scientists find that working with linear equations is easy, nature often does not agree. Consequently, the scientist must resort to non-linear equations to describe the relation between sensory and mechanical variables. The properties of these non-linear equations are such that they take into account:

- Interactions between physical variables,
- The observation that occasionally as a food scientist increases the physical level of a variable, the panelist may perceive a sensory attribute (or a hedonic attribute) to first increase, level off, and then diminish, even though that physical variable continues to increase.

A non-linear regression equation in three variables can be expressed by the equation:

$$\text{dependent variable} = k_1X_1^2 + k_2X_1 = k_3X_2^2 + k_4X_2 + k_5X_1X_2 + k_6 \quad (2)$$

Equation 2 represents one of the more simple non-linear expressions. There is an infinite number of ways that non-linear equations can be developed to describe the relationship between physical/mechanical properties and sensory perceptions. Andersson *et al.* (1973) evaluated the relationships between fracture force, hardness and brittleness in crisp bread. They quantified some 27 different instrumental variables. In order to keep the approach tractable, these researchers selected subsets of four mechanical variables. Furthermore, they developed more than a dozen different "composition" rules by which they could combine instrumental variables.

For example, the sensory system could:

- Weight each variable separately and add them together,
- Square each of the four variables separately, sum the squares, and then extract the square root.

The major finding of that study was that several alternative mathematical expressions accounted equally well for the data. Whereas for some empirical data one type of equation would be best as an empirical description, for another set of data that same equation might fail. In its stead, yet another equation might be adequate.

In developing these non-linear models, therefore, the researcher must make sure that:

- The equations are grounded in a model of how the system works, or
- There is a common model for various product sets to facilitate intercomparisons of products and parameters of a single equation.

Why Regression Analysis

Foods are complex stimuli with which to work. They comprise many different mechanical variables interacting in ways that may take years to truly understand. However, if the researcher can develop an *ad hoc* model or equation relating a single sensory perception of texture (e.g., perceived hardness of a food) to a set of physical parameters, then the researcher will at least have a good idea as to what perceptual changes will occur as the single mechanical variable (or combinations of the variables) changes in magnitude.

Regression analysis, therefore, provides a powerful (albeit statistical) means to predict what will happen to a sensory variable for known changes in the physical variables. Furthermore, when the regression equation contains terms, or is laid out in a form to follow a specific theoretical model, then the regression analysis will provide the empirical parameters for that model.

Using Functional Relations From Regression to Engineer a Profile

Since the regression equations permit the researcher to predict what the likely sensory/textural perception will be for known changes in mechanical variables, the researcher can predict what will occur when the physical characteristics of a product are modified.

Let us now turn the situation around. In order to insure a desired specific perception, let us estimate via our statistical equations what physical variables are needed, and at what levels. Recall that the regression analysis can indicate the expected sensory perceptions for physical changes in products. By turning the approach around 180°, we can use the profile of perceptions in order to ascertain the necessary physical levels of variables that would produce those perceptions. Furthermore, the only other constraint which exists is to ensure that each and every physical variable lies between physical achievable limits.

Consider the data shown in Table 1. The product was a snack food and its physical variables were obtained from:

- color measures (Hunter, L. a, b)
- texture measure (shear value)

Table 1. Illustrative use of optimization to engineer desired profile "data" on six snack food items

Physical Level					Sensory Level[1]					
	Hunter									
L	a	b	Shear	Baking Level	Total Purchase Interest	Softness	Whiteness	Fluffiness	Firmness	Crunchiness
73.35	−2.40	12.75	85.80	1.00	58.8	64,600	67.100	71.000	59.200	22.800
71.05	−2.75	16.70	112.20	1.00	54.6	66.200	52.100	66.600	57.500	24.900
71.20	−3.05	17.50	103.40	1.00	69.3	54.600	38.600	54.900	53.200	19.600
74.25	−3.45	11.55	129.80	2.00	59.8	53.900	73.400	58.600	68.700	29.600
72.15	−2.85	12.65	132.00	2.00	48.7	54.600	64.800	57.800	66.800	31.500
71.65	−2.55	14.30	103.40	2.00	39.0	52.600	60.600	46.900	49.800	22.900

[1] Via magnitude estimation scaling

- type of processing treatment (1 = baked at high temperature,
  2 = baked at lower temperature).

By the traditional regression model, shown in Table 2, the researcher can ascertain the correlations between the physical measures and the sensory perceptions (acceptability, firmness, etc.). These approaches have been published by numerous researchers and the use of regression equations in relating instrumental measurement to sensory perception is well established.

Table 2. Regression equations relating sensory attributes to physical measures (data in Table 1)

	Intercept	L	a	b	Shear	Type	Multiple R
Total Purchase Interest	−532.81	7.72	4.36	1.58	.31	−14.23	.80
Softness	−318.18	5.14	17.51	1.78	.45	−14.97	.94
Whiteness	− 87.41	2.88	10.88	−3.84	.28	− 6.20	.94
Fluffiness	−582.49	8.58	19.98	2.66	.59	−17.88	.94
Firmness	− 82.68	1.85	− .06	−1.85	.47	−12.86	.95
Crunchiness	148.01	−1.61	− 3.19	−2.00	.16	− 3.34	.89

Thus, this integrated information of product ingredients/physical variables and product perceptions can now be used in order to "engineer" the product by systematic modification.

Goal Oriented Product Development

Product optimization procedures have been developed which permit the product developer to reverse the regression equations and to specify what physical levels of ingredients produce products with a desired sensory profile (Moskowitz *et al.* 1977). There are two such methods:

(a) Goal programming — whose aim is to determine those ingredients or mechanical variables which, in concert, generate a product with the desired sensory profile.

(b) Non-linear optimization — whose aim is to determine that array of ingredients or mechanical variables which, in concert, produce a product that is most highly acceptable to consumers.

An Example of Imitating a Product Profile

Table 3 shows the use of the goal programming methods to generate

Table 3. Combination of physical parameters for achieving a pre-specified sensory profile

Physical Variable		Highest Allowed	Lowest Allowed	Optimum Combination
Color Hunter	L	74.25	69.90	74.16
	a	− 2.3	− 3.45	− 2.3
	b	11.4	17.5	11.4
Shear		129.8	85.8	129.4
Baking Level		2	1	1

Competitor's Sensory Profile to be Achieved		Product Should Generate
Softness	86.5	86.5
Whiteness	92.1	88.1
Fluffiness	87.4	96.1
Firmness	77.1	82.3
Crunchiness	30.6	30.6

a product profile for a snack product. The specific aim of the study was to generate a snack product which exhibited the same sensory characteristics as a competitive product currently on the market. Note that the only physical variables of the product were color and texture. The goal programming method was permitted to select a profile that would be as close as possible to the profile generated by the commercial item. By statistical analysis, the physical variables shown in Table 3 were able to match the desired profile fairly closely.

The importance of this approach to product development can be stated as follows:

- The method supplies direction to the product technologist by providing him with a target profile.
- The method integrates the rheologist, food scientist and product developer into a coordinated unified group, with each individual in the link providing actionable information.

An Example of Optimizing a Product Profile

Table 4 shows the use of non-linear optimization to generate a set of physical parameters of the product that maximizes consumers' purchase interest (the consumers' stated interest in buying the product, which is the standard marketing measure of product performance).

Table 4. Mathematical, *ad hoc*, non-linear model relating consumers stated purchase interest in the snack product to physical variables

$$\text{Purchase Interest} = -2169(L) - 6.8(a) - 1102.6(b) + 1.01\ (\text{Shear}) -15.4\ (\text{Type of Processing} + 13.72(L)^2 + 1.82(L)\ (a) +15.6(L)\ (b) + 84815$$

Multiple R = 0.97

● Ingredient Limits

Ingredient Variable	Upper Limit	Lower Limit	Optimal
L	74.25	68.9	69.9
a	− 2.3	− 3.45	− 2.3
b	17.5	11.4	11.4
Shear	129.8	85.8	129.8
Baking Level	2	1	1

Expected Purchase Interest = 100+

Note that in Table 4 the researcher must:

● Develop a mathematical model that accurately relates purchase interest to ingredients.

● Account for the fact that the purchase interest is not only related to physical ingredients/measures, but also depends upon interactions and non-linearities in these ingredients.

● Optimize the equation making sure that the physical measures lie within physically permissible levels.

As Table 4 demonstrates, there does exist an optimized product within the constraints. The optimization method returns the set of physical variables to the researcher, along with predictions of the likely sensory perceptions occasioned by the optimized product.

Conditions to be Satisfied Before Multiple Regression in Product Engineering Can Be Successfully Applied

A number of conditions have to be satisfied before the multiple regression analysis can be applied to engineering a profile. They concern not the multiple regression itself, but mainly the conditions of testing from both instrumental and sensory points of view. They can be summarized as follows:

(1) Ideally, the mechanical measures should be independent from each other. In contrast, the practice suggests that in many products mechanical properties, such as stiffness and maximum shear stress, are

interrelated. However, there are parameters which can be considered independent, as for e.g. the modulus of elasticity and Poisson's ratio in meat (Segars 1977).

(2) The conditions of instrumental testing should be defined experimentally. As stated earlier in this paper, instrumental measures of the majority of foods depend on the rate of force application and other test conditions. Therefore, test conditions should be established that will correlate with sensory ratings. Boyd and Sherman (1975) have demonstrated that the mechanical operations involved in sensory testing depend on the textural properties of the food. The panelists judge the hardness of soft foods by the forces, pressures and work necessary to compress the sample between the tongue and the hard palate, and the hardness of very hard foods by biting strokes. The critical percent compression for correlating the sensory data with Instron measurements appear to be lower for soft than for hard foods (when using crosshead speeds of up to 20 cm^{-1}) as is the associated force.

Once the above conditions are met, our *ad hoc* relations between the physical levels of mechanical variables and the texture perceptions can be used in conjunction with the optimization techniques to determine the combination of variables that (a) produce a desired profile, and (b) maximize texture/product acceptability.

An Overview

The foregoing approach represents an extension of the traditional methods of psychophysics which, in the past eight years, have found increasing acceptance by food scientists, texture researchers and consumer researchers. Psychophysical measurements of the type suggested here have the following properties:

(1) They use the powerful method of magnitude estimation in the same manner that laboratory-based research has used magnitude estimation to quantify texture, flavor and other product perceptions.

(2) They recognize the necessity of developing functional relations between ingredients and perceptions, but at the same time they also recognize that these functional relations must be descriptive and *ad hoc* in nature. In the study of actual food products for the purpose of product development, often there is little time to assess the precise parameters of power law relations, which could be measured were the researcher to possess unlimited time and funds and the technological capability of modifying products.

(3) They allow the researcher to utilize these functional relations in an engineering approach in order to suggest the optimum combinations of physical variables which produce the desired consumer perceptions.

FUTURE TRENDS

A number of trends which are presently emerging in texture research merit emphasis for their future potential in instrumental-sensory applications. The following topics reflect our preferences and ideas.

In certain foods and under specified conditions of geometry and testing, empirical instruments may give good correlations with sensory ratings. The rheological analysis of such instruments can be valuable in the designing of testing probes which use well-defined physical measurements, and which are applicable to a wider range of foods, geometries and testing conditions. Voisey and his co-workers have reported recently on the mechanical analysis of some empirical instruments used by the Food Industry. (Voisey 1976, 1977; Voisey and Crete 1973; Voisey and Larmond 1974; Voisey and Klock 1978; Voisey *et al.* 1975).

More work is necessary on the phenomena associated with fracture (point of origin, propagation through the mass, etc.) We need rheological fracture models to supplement the classical elements of elasticity, viscosity, and plasticity, together with an understanding of their psychophysical significance in foods (Drake 1971; Peleg 1976). Work along those lines has been initiated by Peleg at the University of Massachusetts (Peleg 1976, 1977) and Chen at Rutgers, the State University of New Jersey (Chen and Rosenberg 1977).

The international standardization of texture nomenclature is of both practical and theoretical importance. In addition to the efforts discussed earlier in this paper, the current initiative of Drake (1978) of the SIK-The Swedish Food Institute for a comparative semantic-linguistic study of fifty words of Food Rheology is worth mentioning. A main goal is to find general traits helpful in correlating sensory and instrumental properties.

The calibration of instruments in terms of consumer responses on the basis of the psychophysical law (Moskowitz and Kapsalis 1974) could be of substantial practical benefit to the Food Industry.

The development of mathematical-mechanical models that simulate both the structure of the food and its rheological behavior (Segars and Kapsalis 1976) could shorten the development time of successful tests by excluding non-promising approaches.

On the theoretical level, we need an internationally accepted theory of psychorheology (Moskowitz and Kapsalis 1974).

Finally the application of research findings to product engineering through multiple regression analysis and optimization, as shown in this paper, is an example of the present value of psychorheology and statistics in solving market-oriented problems.

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