Chapter 11

Texture Evaluation

Abstract In this chapter the sensory evaluation of texture is discussed. The concept of texture is defined and then the visual, auditory, and tactile textures related to food (and to some extent textiles) are described in detail. Sensory texture measurements, specifically the Texture Profile Method, are described followed by a relatively brief discussion of correlations between instrumental and sensory texture measurements.

Whenever I
Eat ravioli
I fork it quick
But chew it sloli.

—(Italian Noodles, 1992)

Contents

11.1 Texture Defined **259**
11.2 Visual, Auditory, and Tactile Texture **262**
11.2.1 Visual Texture **262**
11.2.2 Auditory Texture **262**
11.2.3 Tactile Texture **264**
11.2.4 Tactile Hand Feel **268**
11.3 Sensory Texture Measurements **270**
11.3.1 Texture Profile Method **270**
11.3.2 Other Sensory Texture Evaluation Techniques **272**
11.3.3 Instrumental Texture Measurements and Sensory Correlations **274**
11.4 Conclusions **276**
References **276**

11.1 Texture Defined

Alina Szczesniak (2002) states that a generally accepted definition of texture is the following "texture is the sensory and functional manifestation of the structural, mechanical and surface properties of foods detected through the senses of vision, hearing, touch and kinesthetics." She then goes on to emphasize

a. "texture is a sensory property" which can only be perceived and described by humans (and animals) and any instrumental measurements must be related to sensory responses.
b. "texture is a multi-parameter attribute."
c. "texture derives from the structure of the food."
d. "texture is detected by several senses."

A number of texture review articles and textbooks have been published (Bourne, 2002; Chen, 2007, 2009; Christensen, 1984; Guinard and Mazzuccheli, 1996; Kilcast, 2004; McKenna, 2003; Moskowitz, 1987; Rosenthal, 1999; Szczesniak, 2002; Wilkinson et al., 2000; van Vliet et al., 2009).

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The texture of an object is perceived by the senses of sight (visual texture), touch (tactile texture), and sound (auditory texture), in some products only one of these senses is used to perceive the product texture and in other cases the texture is perceived by a combination of these senses. For example, the skin of an orange has a visual and tactile roughness that is absent in the skin of an apple. The crispness of a potato chip in the mouth is both a tactile and an auditory textural perception (Vickers, 1987b). The thickness (viscosity) of a malted milkshake can be assessed visually, in the glass, and then by proprioceptive sensations when stirring the milkshake with a straw as well as by tactile sensations in the mouth.

Ball and coworkers (1957) were among the first to distinguish between "sight" (visual) and "feel" (tactile) definitions of texture. Visual texture is often used by consumers as an indication of product freshness, for example, wilted spinach and shriveled grapes are deemed to be unacceptable in quality (Szczesniak and Kahn, 1971). Additionally, visual texture clues create expectations as to the mouth feel characteristics of the product. When the visual and tactile texture characteristics of a product are at variance the discrepancy causes a decrease in product acceptance.

Food texture can be extremely important to the consumer. Yet, unlike color and flavor, texture is frequently used by the consumer not as an indicator of food safety, but as an indicator of food quality. Szczesniak and Kahn (1971) found that socioeconomic class affected consumers' awareness of texture. Those individuals in higher socioeconomic classes were more aware of texture as a food attribute than those in lower socioeconomic classes. Also, consumers employed by a major food company placed relatively more emphasis on texture than the general population (Szczesniak and Kleyn, 1963). Szczesniak (2002) states that one of the main drivers of consumers' responses to food texture is that "people like to be in full control of the food placed in their mouth. Stringy, gummy or slimy foods or those with unexpected lumps or hard particles are rejected for fear of gagging or choking." Table 11.1 indicates the relative importance of consumers placed on texture versus flavor in a wide variety of foods.

Table 11.1 Relative importance of texture to flavor for a wide variety of food products (texture/flavor index[a])

Item	American consumers[b]	Consumers employed by general foods[c]
Total group	0.89	1.20
Sex		
Male	0.76	1.10
Female	1.02	1.30
Socioeconomic class		
Upper lower	0.60	
Lower middle	0.95	
Upper middle	1.20	
Geographic location		
Chicago, IL	0.96	
Denver, CO	0.95	
Charlotte, NC	0.63	

Adapted from Szczesniak and Kahn (1971)

[a]Index values less than unity mean consumers placed relatively more emphasis on flavor, values larger than unity mean more emphasis was placed on texture

[b]One hundred and forty-nine consumers (three geographic areas) did a word-association test using the names of 29 foods (Szczesniak, 1971)

[c]One hundred consumers did a word-association test using the names of 74 foods (Szczesniak and Kleyn, 1963)

In some foods, the perceived texture is the most important sensory attribute of the product. For these products a defect in the perceived texture would have an extremely negative impact on consumers' hedonic responses to the product. Examples are soggy (not crisp) potato chips, tough (not tender) steak, and wilted (not crunchy) celery sticks. In other foods, the texture of the product is important but it is not the principal sensory characteristic of the product. Examples are candy, breads, and many vegetables. Lassoued et al. (2008) stated that about 20% of bread acceptability was related to crumb texture. In still other foods, the perceived texture has a minor role in the acceptance of the product and examples are liquids with relatively low viscosities such as wine and sodas.

The texture contrast within a food, on the plate, or across food products in a meal is important. A meal consisting of mashed potato, pureed winter squash, and ground beef sounds much less appetizing than one consisting of Salisbury steak, French fries, and chunks of winter squash, yet the difference between the two meals are all related to texture. Szczesniak and Kahn (1984) formulated general principles that should be kept in mind when creating textural contrasts in individual foods or across foods within a meal. Hyde and Witherly (1993) formulated the principle that dynamic contrast (the moment-to-moment change in sensory textural contrast in the mouth during chewing) is responsible for the high palatability of potato and corn chips and of ice cream. Additional examples of foods with dynamic contrast would be ice cream with candy inclusions and chocolate covered peanut M&M candies.

The importance of texture in the identification of foods was shown by Schiffman (1977) who blended and pureed 29 food products to eliminate their textural characteristics. She then asked her panelists to eat the food and to identify the food products. Overall about 40% of food products were identified correctly by normal weight college students. Only 4% of the panelists could correctly identify blended cabbage; 7% correctly identified pureed cucumber; 41% correctly identified blended beef; 63% correctly identified pureed carrots; and 81% correctly identified pureed apple. These data indicate that American consumers use texture information when they identify and classify food products.

In a word-association test Szczesniak and Kleyn (1963) found that foods elicited texture responses differentially. The percentage of texture-related responses was relatively high (over 20%) for peanut butter, celery, angel-food cake, and pie crust. Their panelists used a total of 79 texture words, with 21 words used 25 or more times by the 100 panelists to describe the 74 foods. The most frequently used words described hardness (soft, hard, chewy, and tender), crispness or crunchiness, and moisture content (dry, wet, moist, juicy). Yoshikawa et al. (1970) used the Szczesniak and Kleyn (1963) study as a basis to study the texture descriptions of female Japanese panelists. They found that the Japanese used many more words to describe texture (406) than the American panelists (79). This was probably not due to genetic differences between the two groups but more likely due to cultural differences since Japanese foods tend to have more textural variety than American foods. Additionally, the Japanese language is also very rich in subtle nuances and older respondents would likely have used even more terms since they "would have a greater knowledge of Japanese than younger people." Later, Szczesniak (1979a, b) commented on the onomatopoetic nature of Japanese texture terms. That is, the word tends to sound like the type of texture that is experienced.

Rohm (1990) also used the Szczesniak and Kleyn (1963) study as a basis to study Austrian texture descriptors. They found that Viennese students (100 males and 108 females) used 105 texture terms in a word association with 50 foods. Eighteen of these terms were used more than 25 times each while 47 terms were used less than 5 times each. When Rohm (1990) compared his data with Szczesniak and Kleyn (1963), Szczesniak (1971) and Yoshikawa et al. (1970), he found that five of the ten most frequently used terms were similar across studies (Table 11.2). Based on these studies we can thus state that certain textural terms and sensations are universal across cultures. However, there are some major exceptions. As pointed out by Roudaut et al. (2002) in France vegetables and fruits are not considered "croustillant" (crisp) yet in the United States these products, when fresh, are frequently described as crisp. The sensory specialist in any country, culture, or region should therefore pay attention not only to the perceived flavor, taste, and color dimensions of food products but also to the perceived textural characteristics. Drake (1989) published a list of textural terms in 23 languages. This list is invaluable when training panelists who are non-native English speakers or panels in different countries.

Table 11.2 The ten most frequently used texture terms in Austria[a], Japan[b], and the United States[c,d]

		United States	
Austria[a]	Japan[b]	1963[c]	1971[d]
Crisp	Hard	**Crisp**	**Crisp**
Hard	**Soft**	Dry	**Crunchy**
Soft	**Juicy**	**Juicy**	**Juicy**
Crunchy	Chewy	**Soft**	Smooth
Juicy	Greasy	**Creamy**	**Creamy**
Sticky	Viscous	Crunchy	Soft
Creamy	Slippery	Chewy	Sticky
Fatty	**Creamy**	Smooth	Stringy
Watery	**Crisp**	Stringy	Fluffy
Tough	**Crunchy**	Hard	Tender

Words in **bold** occurred in the top ten in all four studies
[a]Two hundred and eight Viennese students did a word-association test using the names of 50 foods (Rohm, 1990)
[b]One hundred and forty Japanese students did a word-association test using the names of 97 foods (Yoshikawa et al., 1970).
[c]One hundred and forty-nine consumers (three geographic areas) did a word-association test using the names of 29 foods (Szczesniak, 1971)
[d]One hundred consumers did a word-association test using the names of 74 foods (Szczesniak and Kleyn, 1963)

11.2 Visual, Auditory, and Tactile Texture

In this section we will discuss visual, auditory, and tactile perceptions of texture in more detail and then we will discuss how the sensory specialist can measure these perceived textures in food products. The usual sequence of texture perception when consuming a food product is visual evaluation of texture followed by direct (with the fingers) and/or indirect (with eating utensils such as knife, fork, or spoon) tactile evaluations followed by oral–tactile (with the lips, tongue, palate, saliva) evaluations. Concurrent with the oral–tactile evaluation (and sometimes also when cutting/stabbing the food with a utensil) are also the aural (sound) evaluations of crunchy, crispy, crackly, etc. (Kilcast, 1999).

11.2.1 Visual Texture

Many surface characteristics of a food product do not only affect the perceived appearance of the product but also affect the perception of the texture. Consumers know from prior experience that the lumps seen in tapioca pudding are also perceived as lumps in the mouth. Visual texture assessment has some overlap with appearance characteristics such as shine, gloss, and reflectance (discussed in Chapter 12). In this section we will discuss visual texture not related to these appearance terms. These visual texture terms would include roughness, uniformity, surface powderiness or bloom, oiliness, greasiness, flakiness, stringiness, smoothness, wilting, and surface wetness (Chen, 2007).

The surface roughness of an oatmeal or the cookie can be assessed both visually and through oral and hand tactile evaluations. The blister level of tortilla chips was assessed by Bruwer et al. (2007) who found that the blister level was negatively related to orally perceived denseness of the tortilla chip. In a bread crumb appearance study trained panelists have evaluated fineness ("... visual estimation of the amount of gas cells"), degree of homogeneity ("...refers to the degree of uniformity of the pore sizes"), and orientation ("...degree of orientation of the crumb grain") (Gonzalez-Barron and Butler, 2008b). Lassoued et al. (2008) used flash profiling (see Chapter 10) to evaluate the visual crumb texture of wheat breads.

Using custards and a two level cup where the visible custards could be manipulated independently of the invisible ingested custards, de Wijk et al. (2004) found that the visual texture of the visible custards changed the oral texture ratings of the ingested custards. Carson et al. (2002) trained a descriptive panel to assess strawberry yogurts using visual texture terms including spoon impression ("the degree to which the product is jellified evaluated by looking at the impression left at the surface after lifting a spoonful from the unstirred product") and spoon covering ("the degree to which the product covers the back of the spoon evaluated by lifting a spoonful from the sample cup"). They found that both spoon impression and spoon covering were highly correlated with perceived oral thickness. The viscosity of a fluid can be assessed visually by pouring the fluid from a container, by tilting a container, or by evaluating the spreading of the fluid on a horizontal surface (Elejalde and Kokini, 1992; Kiasseoglou and Sherman, 1983; Sherman, 1977). Janhøj et al. (2006) trained a descriptive panel to evaluate low-fat yogurts using visual texture attributes such as grainy on lid and continuous flow from spoon. Lee and Sato (2001) used a paired comparison scaling technique to visually evaluate the perceived texture of real textile samples as well as photographic images of the samples. They found that the principal component spaces derived by the two methods were quite similar.

11.2.2 Auditory Texture

In some cases, consumers may find that the sounds (auditory texture) associated with eating a food product negatively impact the hedonic responses associated with the product. An example is the gritty sound of sand against the teeth when eating creamed spinach made with inadequately rinsed spinach leaves. On the other hand, auditory texture can add positively to consumers eating enjoyment as well, examples are the crisp sounds associated with many breakfast cereals or the crunchy sounds associated with eating a juicy apple. Consumers often use sound as an indication of food quality. Many of us have all thumped a watermelon to determine its ripeness (a hollow sound is indicative of a ripe watermelon) or broken a carrot to determine its crunchiness.

Auditory texture is to a large extent synonymous with crispness, crunchiness, and crackliness in foods. The early work in this area was done by Vickers and Bourne (1976). Lately there has been a resurgence of interest in the area with a review by Duizer (2001), and work by Luyten and van Vliet (2006), Salvador et al. (2009), and Varela et al. (2009). Sounds are produced by mechanical disturbances which generate sound waves which are propagated through the air or other media, such as bone conduction from the jaw bone to the bones of the middle ear (Dacremont, 1995).

Crisp and/or crunchy foods fall in two categories, namely wet foods and dry foods. Sound generation differs in these two types of foods (Vickers, 1979). Wet crisp foods, like fresh fruits and vegetables, are composed of living cells that are turgid if enough water is available. In other words, the cell contents exert an outward pressure against the cell walls. The tissue structure is thus similar to a collection of tiny water-filled balloons cemented together. When the structure is destroyed, by breaking or chewing, the cells pop and this produces a noise. In an air-filled balloon the popping sound is due to the explosive expansion of the air compressed inside the balloon. With turgid cells the noise is due to the sudden release of the turgor pressure. The amount of noise produced is less when the surface tension of the liquid is high. Exposing plant cells to sufficient moisture increases the turgor pressure of the cells and increases the perceived crispness of the product.

On the other hand, exposing dry crisp foods, like cookies, crackers, chips, and toast to moisture (humid air) decreases the perceived crispness of the food. These products have air cells or cavities surrounded by brittle cell or cavity walls. When these walls are broken any remaining walls and fragments snap back to their original shape. When the walls snap back vibrations are caused that generate sound waves (similar to a tuning fork). When the moisture content of dry crisp foods increases, the walls are less likely to snap back and the amount of sound generated is less.

Vickers (1981) and Christensen and Vickers (1981) showed that crispness and crunchiness of specified foods can be rated on the basis of sound alone, on the basis of oral–tactile clues alone, or on the basis of a combination of auditory and oral–tactile information. Crispness seemed to be acoustically related to the vibrations produced by the food as it is deformed (Christensen and Vickers, 1981). However, later work by Edmister and Vickers (1985) indicated that auditory crispness is not redundant with oral–tactile crispness evaluations and Vickers (1987a) also indicated that the oral–tactile sensations are very important to evaluating crispness.

Vickers and Wasserman (1979) studied the sensory characteristics associated with food sounds. They had panelists evaluate the similarity between pairs of sounds produced by crushing the food with pliers (Table 11.3). The results of their study indicated that there may be two sensory characteristics separating food sounds, the evenness of the sound and the loudness of the sound. As the loudness of the sounds increased the panelists' perceptions of the intensities of crunchiness, crispness, crackliness, sharpness, brittleness, hardness, and snappiness also increased. When the sound is continuous (even) the panelists perceived

Table 11.3 Foods crushed with rubber-coated pliers to produce recorded sounds

Food	Description
Hard candy	1 whole Reeds Rootbeer candy
Fresh celery	1 cm piece cut perpendicular to stalk
Blanched celery	1 cm piece cut perpendicular to stalk and immersed in rapidly boiling water for 30 s
Cracker	1 whole Sunshine saltine cracker
Unripe pear	1 cm wedge
Peanut	1 whole Fisher's Virginia style peanut
Ginger snap	1 whole Nabisco Brands ginger snap
Fresh carrot	Crosswise section, 1 cm long and 1.5 cm wide
Blanched carrot	Crosswise section, 1 cm long and 1.5 cm wide, immersed in rapidly boiling water for 1 min
Potato chip	1 whole Pringles potato chip
Ruffled potato chip	1 whole Pringles ruffled potato chip
Unripe golden delicious apple	1 cm wedge
Ripe golden delicious apple	1 cm wedge
Graham cracker	1 whole (manufacturer unknown)
Milk chocolate	1 square of Hershey's milk chocolate, cold
Water chestnut	1 whole Geisha canned water chestnut
Shortbread cookie	1 whole Lorna Doone (Nabisco Brands) cookie
Shredded wheat	1 whole shredded wheat cake (Nabisco Brands)

Adapted from Vickers and Wasserman (1979) the texture as popping or snappy and when the sound is not continuous the perception is of tearing or grinding. Zampini and Spence (2004) showed that potato chips were perceived as being crisper by panelists when the authors increased the overall sound level associated with biting the chip between the front teeth or when they increased was increased, or when they selectively amplified the high-frequency sounds (in the range of 2–20 kHz).

Dacremont (1995) found that crispy foods were characterized by high levels of air-conducted high-frequency sounds (5 kHz), crunchy foods were characterized by low pitched sounds with a peak in air-conduction at 1.25–2 kHz, and crackly foods were characterized by low-pitched sounds with a high level of bone conduction. Crunchiness is acoustically most related to a larger proportion of low-pitched sounds with frequencies less than 1.9 kHz, while a relatively larger proportion of high-pitched sounds, frequencies higher than 1.9 kHz, is related to crispness (Seymour and Hamann, 1988; Vickers, 1984a,b, 1985). It is more difficult to determine the crunchiness of a food through listening to someone else since many of the lower pitched sounds one hears while eating a crunchy food is conducted through the bones of the skull and jaw to the ear (Dacremont, 1995). The human jawbone and skull resonate at about 160 HZ and sounds in this frequency range are amplified by the bones, thus the panelists' own crunch sounds are perceived to be lower and louder than those of a person next to the panelist (Kapur, 1971). When training panelists to evaluate the perceived intensity of crunchiness one should train them to chew the food with the molars while the mouth is kept closed. Most of the high frequency sounds will be damped by the soft tissue and the crunchy sounds will be transmitted through the skull and jaw bones to the ear. Similarly, when training panelists to evaluate the perceived intensity of crispness one should train them to chew the food with the molars while the mouth is kept open (Lee et al., 1990). This method of chewing is seen as a violation of courtesy in some cultures but during training most panelists will succeed in chewing in this fashion. Most of the higher frequency sounds will travel undistorted through air to the ears (Dacremont et al., 1991).

Another view of crisp and crunchy foods looks at the time-sequence of breakage, the deformation and rupture of the food upon application of force (Szczesniak, 1991). Crisp foods break in a single stage whereas crunchy foods break in several successive stages. Thus, a crisp food will always be perceived as crisp regardless of the way the breaking force is applied, but a crunchy food may be perceived as crunchy or crisp depending on the applied force. A celery stick when chewed by the molars will be perceptibly crunchy since it will break in successive steps, but a celery stick snapped between the hands will be perceptibly crisp since the stalk will break in a single step.

Vickers (1981) found that it was possible to evaluate the perceived hardness of crisp foods based on sound alone. Castro-Prada et al. (2007) indicates that the best method of acquiring acoustical profiles of crispy foods to correlate with human sensory methods may be different from the best profiles to be used for fracture mechanical analyses. This may be because hardness is a component of crispness in these foods. Vickers (1984a, b) also evaluated the auditory component of the crackliness of foods. She found that like crispness and crunchiness, crackliness could be assessed by either sound or tactile evaluation. The number and amplitude of sharp repeated noises correlated with the perception of crackliness. However, oral–tactile sensations were more useful than auditory sensations for the assessment of hardness for most foods. As pointed out by Chen (2009) the vibrotactile perception of the teeth allows those hard of hearing to still enjoy crisp and crunchy foods.

11.2.3 Tactile Texture

Tactile texture can be divided into oral–tactile texture, mouth feel characteristics, phase changes in the oral cavity, and the tactile texture perceived when manipulating an object by hand (often used for fabric or paper and called "hand") or with utensils.

11.2.3.1 Oral–Tactile Texture

Oral–tactile texture encompasses all the textural sensations elicited in the mouth. The lips, teeth, oral mucosa, saliva, tongue, and the throat are involved in the perception of oral texture. Chen (2009), Lenfant et al. (2009), Xu et al. (2008), van der Bilt et al. (2006), Bourne (2004), and Lucas et al. (2002) provide reviews of food oral processing, mastication, and the effects of oral physiology on the perception of food texture. According to van Vliet et al. (2009) and others the sequence of oral texture perception involves ingestion by the lips, biting by the front (incisor) teeth, chewing of hard foods by the molars, wetting with saliva and enzymatic breakdown, deformation of semi-solid foods between the tongue and hard palate, manipulation of the food into a bolus by the tongue and swallowing.

During ingestion the lips may signal that the food is sticky, slimy, hard, grainy, etc. For example, Engelen et al. (2007) had their panelists rate perceived roughness and slipperiness of custards and mayonnaises by rubbing the tongue against the inside of the lip.

The first bite allows the perceptions of hard, springy, cohesive, crumbly, etc., to occur. The force applied during the first bite is related to the food itself. Mioche and Peyron (1995) using pellet-shaped models found that for elastic food models (silicone elastomers) the bite force was symmetric, the food did not fracture and the perceived hardness was related to the perceived deformation under constant bite force. A food example of such a food probably does not exist but some foods such as gelatin gels come close. For food models that were more plastic (dental waxes) the biting force increases until a yield point is reached where the food begins to flow and then fracture. They found that the maximal bite force was highly correlated to perceived hardness (r=0.96). A real food example of a plastic food is butter. For brittle food models (pharmaceutical tablets) they found that the first bite biting cycle was the shortest with abrupt increases and decreases in force and again perceived hardness was highly correlated to maximal bite force (r=0.99). Cookies are a real world food example of a brittle product. Perceived hardness based on first bite increases with food thickness (Agrawal and Lucas, 2003). De Wijk et al. (2008) found that the bite size through a straw for a chocolate-flavored dairy semi-solid was significantly smaller (5.8±0.3 g) than for a chocolate-flavored liquid dairy drink (8.7±0.45 g). However, when these authors removed the bite effort (by using a pump) they found that these differences disappeared.

Chewing fragments solid and semi-solid foods into small enough particles to swallow and to mix these particles with saliva to form a lubricated bolus for swallowing. There is large variation in chewing cycles and the length of chewing across individuals and across foods (Brown et al., 1994, 1995; Wintergerst et al., 2004, 2005, 2007). Engelen et al. (2005a) found that for 87 subjects with normal dentition the chewing cycles to ready 9.1 cm^3 peanuts for swallowing ranged from 17 to 110. In general, individuals producing more saliva tended to need fewer chewing cycles to ready a piece of dry toast for swallowing (Engelen et al., 2005a). These authors also found that buttering toast decreased the number of chew cycles prior to swallowing. Food hardness is also positively correlated to chewing length, chewing cycle, and muscle activity associated with chewing (Foster et al., 2006, Hutchings et al., 2009; Wintergerst et al., 2007). Blissett et al. (2007) showed that increased sample size (in their case 1, 2, or 4 orange-flavored Tooty-Frooties from Nestle, York, the United Kingdom) led to multiple changes in chewing behavior and that some of these changes were idiosyncratic.

A number of studies have shown wide ranges in salivary flow rates among individuals. Engelen et al. (2005a) found a mean flow rate of 0.45 ± 0.25 ml/min for unstimulated flow and a mean of 1.25 ± 0.67 ml/min for stimulated flows. Saliva has many functions but from an oral texture perspective it acts as a lubricant. The mucins (glycoproteins) are responsible for the lubrication effects of saliva. As shown by Prinz et al. (2007) salivary lubrication is increasingly efficient with high surface speeds and increased surface load. A few studies have shown that tougher meat samples lead to higher incorporation of saliva into the bolus prior to swallowing (Claude et al., 2005; Mioche et al., 2003). The salivary pH and α-amylase content also affects perceived texture. Engelen et al. (2007) found that α-amylase activity was negatively correlated to perceived thick mouth feel of custards and to perceived prickly mouth feel for mayonnaise.

11.2.3.2 Size and Shape

Tyle (1993) evaluated the effect of size, shape, and hardness of suspended particles on the oral perception of grittiness of syrups. He found that soft, rounded, or relatively hard, flat particles were not perceptually gritty up to about 80 μm. However, hard angular particles contributed to grittiness perception when they were above a size range of 11–22 μm. Richardson and Booth (1993) found that some of their panelists could distinguish between average fat-globule size and distance distributions of less than 1 μm (range: 0.5–3 μm, depending on the individual). Engelen et al. (2005b) found that polystyrene spheres between 2 and 80 μm decreased the perceived smoothness and slipperiness and increased perceived roughness of custards. Above 80 μm the perception of roughness decreased. In other studies the minimum individual particle size detectable in the mouth was less than 3 μm (Monsanto, 1994). Richardson and Booth (1993) working with milks and creams found that their panelists were sensitive to viscosity changes of about 1 mPa. Runnebaum (2007) working with wine found that his panelists could distinguish viscosity changes of about 0.057 mPa.

By definition (Peleg, 1983) a property is a characteristic of a material which is practically independent of the method of assessment. A property can only be called objective if its magnitude is independent of the particular instrument used and of the specimen mass and size. For example, the percentage of fat in an ice cream is the same regardless of the amount of the ice cream analyzed. However; sensory textural properties are affected by sample size. Large and small sample sizes may or may not be perceptually the same in the mouth. A debated question is whether humans compensate automatically for the difference in sample size or whether humans are only sensitive to very large changes in sample size. It is not known which of these happen, if either. One of the few studies to explicitly study the effect of sample size on texture perception was done by Cardello and Segars in 1989. They evaluated the effect of sample size on the perceived hardness of cream cheese, American cheese, and raw carrots and on the perceived chewiness of center cut rye bread, skinless all beef franks, and Tootsie roll candies. The sample sizes (volumes) evaluated were 0.125, 1.00, and 8.00 cm^3 and their experimental conditions were sequential versus simultaneous presentation of samples, sample presentation in random order or by ascending size; evaluation of samples by blindfolded and not blindfolded panelists; panelists allowed to handle the sample or not. These authors found both hardness and chewiness increased as a function of sample size independent of subject awareness of sample size. Therefore, texture perception does not appear to be independent of sample size. Additionally, as shown by Dan et al. (2008) the sensory perception of hardness varies with the specific definition associated with the bite procedure. Initially panelists were instructed to evaluate the hardness of a cheese sample by biting the cheese normally with the molars on their habitual chewing side (Control condition). Subsequently, they were asked to evaluate hardness by either biting into the sample with the molar teeth (H1 condition) or to bite completely through the sample with the molar teeth (H2 condition). They found that the H2 condition led to high inter-panelist differences while the panelists were relatively homogeneous across the H1 condition. However, both conditions led to the same rank ordering of the cheese samples. For the sensory specialist the important "take-home" message is that all conditions such as sample dimensions, samples size, or volume must be specified since these could materially affect the results.

11.2.3.3 Mouth Feel

Mouth feel characteristics are tactile but often tend to change less dynamically than most other oral–tactile texture characteristics. For example, the mouth feel property astringency associated with a wine usually does not change perceptibly while the wine is manipulated in the mouth but the chewiness of a piece of steak or the consistency of ice cream will change during in-mouth manipulation. Often cited mouth feel characteristics are astringency, puckering (sensations associated with astringent compounds), tingling, tickling (associated with carbonation in beverages), hot, stinging, burning (associated with compounds that produce pain in the mouth such as capsaicin), cooling, numbing (associated with compounds that produce cooling sensations in the mouth such as menthol), and mouth coating by the food product. From this list it is clear that mouth feel characteristics are not necessarily related to the force of breakdown or to the rheological properties of the product. However, some mouth feel attributes are related to the rheology of the product and/or the force of breakdown, examples are viscosity, pulpy, sticky. Other mouth feel attributes are chemically induced tactile sensations such as astringency and cooling and these were discussed in Chapter 2.

As will be seen later (Brandt et al., 1963), the original Texture Profile method had only a single mouth feel-related attribute "viscosity." Szczesniak (1966) classified mouth feel attributes into nine groups: Viscosity-related (thin, thick); feel of soft tissue surfaces related (smooth, pulpy); carbonation related (tingly, foamy, bubbly); body related (watery, heavy, light); chemical related (astringent, numbing, cooling); coating of the oral cavity related (clinging, fatty, oily); related to resistance to tongue movement (slimy, sticky, pasty, syrupy); mouth after feel related (clean, lingering); physiological after feel related (filling, refreshing, thirst quenching); temperature related (hot, cold); and wetness related (wet, dry). Jowitt (1974) defined many of these mouth feel terms. Bertino and Lawless (1993) used multidimensional sorting and scaling to determine the underlying dimensions associated with mouth feel attributes in oral health-care products. They found that these clustered in three groups: astringency, numbing, and pain.

11.2.3.4 Phase Change (Melting) in the Oral Cavity

The melting behaviors of foods in the mouth and the associated textural changes have not been studied extensively. Many foods undergo a phase change in the mouth due to the increased temperature in the oral cavity. Examples are chocolates and ice cream. As mentioned earlier Hyde and Witherly (1993) proposed an "ice cream effect." They stated that dynamic contrast (the moment-to-moment change in sensory texture contrasts in the mouth) is responsible for the high palatability of ice cream and other products. The work by Hutchings and Lillford (1988) on emphasizing the dynamic breakdown of the sample in the mouth during mastication was a breakthrough that should (but has not yet) lead to the testing of a general physical and psychophysical hypothesis of perceived texture.

For some time the trend in food marketing and product development has been to eliminate as much fat as possible from food products. However, the fat is primarily responsible for the melting of ice cream, chocolates, yogurt, etc., in the oral cavity (Lucca and Tepper, 1994). Thus the characteristics associated with phase change should receive additional scrutiny as product developers attempt to replace the mouth feel characteristics of fats with fat replacer compounds.

In an early study Kokini and Cussler (1983, 1987) found that the perceived thickness of melting ice cream in the oral cavity was related to the following equation:

$$\text{Thickness } \propto \mu^{\frac{3}{4}} f^{\frac{1}{4}} V \left[\frac{2(1-\phi)\Delta H_i \rho}{3\, K \Delta T \pi R^4} \right]^{1/4}$$

where

μ = liquid phase viscosity
T = temperature difference between the solid phase (frozen ice cream) and the tongue
ϕ = volume fraction of air in the product (overrun)
H_i = heat of fusion of ice
ρ = density of ice
V = velocity of tongue movements
F = force applied by tongue
R = tongue radius (assuming a circle) in contact with the food
K = thermal conductivity of melted ice cream

As pointed out by Lawless et al. (1996) "while this equation may be useful to point out the various factors influencing melting systems, it is doubtful that all the parameters could be known in practice or standardized among sensory panelists." Thus, at this time, the study of melting is still being done empirically using panelists and descriptive sensory evaluation or time–intensity methodology. There has been a plethora of low-fat ice cream-related perceived texture and melt rate studies using generic descriptive analysis (Hyvönen et al., 2003; Liou and Grün, 2007; Roland et al., 1999). Lawless et al. (1996) studied the melting of a simple cocoa butter model food system and found that this system could be used to study the textural and melt properties of fat replacers. Changes in melting behavior, as assessed by descriptive analysis and by time–intensity measurements, were related to the degree of fat substitution by carbohydrate polymers. Mela et al. (1994) had found that panelists could not use the degree of melting in the oral cavity to accurately predict the fat content in oil-in-water emulsions (products similar to butter) with a melting range of 17–41°C.

11.2.3.5 Oral Crispness, Crunchiness, and Crackliness

As discussed in the section on auditory texture crispness, crunchiness, and crackliness clearly have an auditory component but these sensations also have an oral textural component. See the review by Roudaut et al. (2002) for a critical appraisal of the evaluation of crispness.

Vincent (1998) stated that these sensations are related to the sudden drop in force experienced by the teeth and the jaw muscles when a food item breaks between the teeth. Initially he thought that crumbliness, crispness, crunchiness, and hardness are descriptors falling on a continuous load-drop-size continuum. Subsequently (Vincent, 2004), he suggested that crack initiation and propagation in hard and crunchy foods are related to the force needed to fracture the sample and that crispness is a distinct and separate sensation related to fracturability of glassy cellular materials. Crispness decreases as product water activity (a_w) increases and at a water activity of 0.40–0.55 (depending on the product) the perceived crispness of the product decreases dramatically (Heidenreich et al., 2004). Primo-Martin et al. (2008) found that toasted rusk rolls lost 50% of their perceived crispness at critical water activities between 0.57 and 0.59.

11.2.4 Tactile Hand Feel

Tactile hand feel of foods are usually evaluated through the use of utensils (the amount of effort to cut a piece of steak, the ease of butter spreadability with a knife, the ease with which a fork penetrates a boiled potato, etc.) or by manipulation by hand (the ease of snapping a celery stalk, the difficulty in compressing a piece of cheese between the thumb and forefinger, etc.). Table 11.4 summarizes a few tactile hand feel attributes. Pereira et al. (2002) used a trained descriptive panel to evaluate cheese analogs and all of their texture attributes were through tactile hand feel. Ares et al. (2006) used non-oral texture evaluation to characterize dulce de leche. Dooley et al. (2009) used some tactile hand attributes in their evaluation of lip products. Darden and Schwartz (2009) found that their trained descriptive analysis panel could reproducibly score fabric abrasiveness, sensible texture, slipperiness, and fuzziness using their finger tips. Lassoued et al. (2008) used flash profiling to evaluate the tactile crumb texture of wheat breads.

The texture evaluation of fabric or paper frequently includes touching or manipulating the material with the fingers. Much of the work in this area comes from the textile literature; however, we feel that this area of sensory evaluation has potential application in the food arena as well. We will thus describe some of the vocabulary associated with fabric or paper hand with the intention of stimulating food sensory specialists to allow their panelists "to play with their food" on occasion when it could lead to appropriate results. Most of the information in this section was drawn from Civille and Dus (1990), Meilgaard et al. (2006), and Civille (1996).

Civille and Dus (1990) describe the tactile properties associated with fabric and paper as mechanical characteristics (force to compress, resilience, and stiffness), geometrical characteristics (fuzzy, gritty), moisture (oily, wet) and thermal characteristics (warmth), and non-tactile properties (sound).

Table 11.4 Examples of sensory hand tactile attributes

Texture attribute	Manipulation by hand
Fracturability	Extent to which a cheese slice (1 cm thick, 9 cm long) can be bent between the thumb and the index and middle fingers, until the ends touch, without breaking
Firmness (compression)	Amount of resistance to compression offered by a 1 cm thick slice of cheese, when pushed between the thumb and the index finger, until fingers touch each other (force required to deform the cheese structure)
Firmness (cutting)	Force required to cut through a 1 cm thick slice of cheese with a knife (pushed down on an angular, guillotine-like movement, from tip to full length of the knife)
Curdiness	Extent to which the original sample produces curdy lumps after being kneaded seven times between thumb and index and middle finger
Hardness	Force required scooping up a teaspoonful of the sample
Ropiness	The amount of threads or drops that fall down when introducing the spoon vertically into the sample and raising it vertically from the sample once
Spreadability	The ease with which the product can be manipulated on the surface of the forearm (Vaseline=5, Classic Chapstick=9; Johnson & Johnson 24-h Moisturizer = 13)
Tackiness	The degree to which fingers adhere to the product; amount of adhesiveness (Johnson & Johnson Baby Oil=0, Post-it note=7.5)

Adapted from Pereira et al. (2002), Ares et al. (2006), and Dooley et al. (2009)

The fabric/paper methodology developed by Civille is based on the General Foods Texture Profile (described in the next section) and includes a series of standard scales with reference anchors and precise definitions for each attribute evaluated. Some of these are listed in Table 11.5.

In a series of studies Japanese textile scientists (Kawabata and Niwa, 1989; Kawabata et al., 1992a, b; Matsudaira and Kawabata, 1988) quantified and correlated sensory evaluation results of textiles with instrumental measurements. Their techniques have been extensively used, studied, and adapted within the textile industry (Bertaux et al., 2007; Cardello et al., 2003; Chen et al., 1992; Kim et al., 2005; Koehl et al., 2006; Sztandera, 2009; Weedall et al., 1995).

Other sensory textile measurements have also been developed. Paired comparison discrimination tests have been used to assess the stiffness, smoothness, and softness of cotton fabrics (Ukponmwan, 1988). Burns et al. (1995) found that subjects who viewed and felt fabrics described the sensory properties of fabrics differently than did subjects who only felt the fabrics for their hand. They cautioned that laboratory techniques that only concentrated on hand may not correlate with consumer perceptions of fabric textures. Bertaux et al. (2007) used a paired comparison method to evaluate roughness and prickle of woven and knitted fabrics. Hu et al. (1993) used Steven's law as a psychophysical description of fabric hand evaluations. In another study, the tactile qualities of fabrics were evaluated using bipolar descriptive scales (Jacobsen et al., 1992). The authors found good correlations between the values obtained by the panel and with instrumental bending and compression evaluations. Philippe et al. (2004) and Cardello et al. (2003) described the use of generic descriptive analysis in the evaluation of the textile hand of cotton fabric treated with different industrial finishes and in military clothing fabrics, respectively.

Mahar et al. (1990) found that there were cultural differences in the handle preferences for men's winter suit fabrics. The panelists from Australia, India, New Zealand, the United States, and Hongkong/Taiwan had consistent preferences based on their evaluation of the fabric hand using the descriptors sleekness, fullness firmness, and drape. The panelists from Japan and the People's Republic of China had internally consistent and somewhat opposite preferences to that of the first

Table 11.5 Selected fabric hand profile attribute definitions and reference anchors

Attribute	Definition	Scale value	Fabric type
Force to compress	Amount of force required to compress gathered sample in palm (low force to high force)	1.5	Polyester/cotton 50/50 knit tubular
		3.4	Cotton cloth greige
		9.3	Cotton terry cloth
		14.5	#10 Cotton duck greige
Resilience	Force with which sample presses against cupped hands (creased to folded original shape)	1.0	Polyester/cotton 50/50 knit tubular
		7.0	Filament nylon 6.6 semi-dull taffeta
		14.0	Dacron
Stiffness	Degree to which sample feels pointed, ridged, and cracked, not round, pliable, curved (pliable to stiff)	1.3	Polyester/cotton 50/50 knit tubular
		4.7	Mercerized cotton print cloth
		8.5	Mercerized combed cotton poplin
		14.0	Cotton organdy
Geometrical properties			
Fuzziness	Amount of pile, fiber, fuzz on surface of sample (bald to fuzzy or nappy)	0.7	Dacron
		3.6	Cotton crinkle gauze
		7.0	Cotton T-shirt, tubular
		15.0	Cotton fleece
Grittiness	Amount of small picky particles in surface of sample (smooth to gritty)	1.5	Filament arnel tricot
		6.0	Cotton cloth greige
		10.0	Cotton print cloth
		11.5	Cotton organdy

Adapted from Civille (1996)

group. Raheel and Liu (1991) used a mathematical technique called fuzzy sets logic to integrate sensory fabric hand data with instrumental assessments. This is one of the earliest uses of the fuzzy logic technique with sensory data; however, it is still in use (Koehl et al., 2006).

11.3 Sensory Texture Measurements

Many texture attributes can be measured using standard sensory techniques such as discrimination testing, ranking, and descriptive techniques. Textural differences between two samples can be determined using the two-alternative forced choice test. The panelists should be trained to discriminate between the samples based on the specified textural attribute. For example, panelists can be trained to evaluate viscosity as "the amount of force required to draw a liquid from a spoon over the tongue" (Szczesniak et al., 1963) and could then be asked to determine if the perceived viscosity of two maple syrup samples differed.

It is also possible to quantify texture attributes using ordinal or interval scales. Examples would be "rank the . . .." or "score the . . .." Visual texture, especially, lends itself well to simple intensity or ordinal scales, such as apparent roughness of the surface, size or number of surface indentations, and density or amount of sediment in a container of a liquid product. Most of these simple and concrete attributes require little training and can be easily worked into a descriptive profile of the product. Of course, as in any other descriptive or scaling technique, the scale becomes more calibrated and there is better agreement among panelists if the low and high ranges are shown to provide the frame of reference that anchors the scale.

Szczesniak et al. (1975) used consumers to evaluate foods using terminology developed for the General Foods Texture Profile method (see below) and they found that consumers could use the scales and were sufficiently aware of the texture of food products to do a rudimentary and "fuzzy" texture profile.

11.3.1 Texture Profile Method

The Texture Profile method was developed at General Foods Corporation in the early 1960s. The scientists at General Foods based their texture evaluation approach on the Flavor Profile developed by A.D. Little. They were interested in developing a method that would allow the evaluation of texture and which would be built on a well-defined and rational foundation.

Szczesniak (1963) developed a texture classification system to bridge the gap between consumer texture terminology and the rheological properties of the product (Table 11.6). She categorized the perceived textural characteristics of products as three groups: mechanical characteristics, geometrical characteristics, and other characteristics (alluding mostly to the fat and moisture content of foods). This classification formed the basis of the Texture Profile method (Brandt et al., 1963). These authors defined their method as a technique that would allow the description of the mechanical, geometric, and other textural sensations associated with a product from the first bite through complete mastication. The technique therefore borrows the "order of appearance" principle from the Flavor Profile and is thus a time-dependent method. The time sequence is the "first bite" or initial phase, the "chewing" or masticatory second phase followed by the residual or third phase. The textural sensations were evaluated by extensively trained panelists using standard rating scales. The original standard rating scales were developed by Szczesniak et al. (1963) to cover the range of intensity sensations found in foods. They used

Table 11.6 Texture classification and the bridge to some consumer texture descriptions

Primary terms	Secondary terms	Consumer terms
Adhesiveness		Sticky, tacky, gooey
Cohesiveness	Brittleness	Crumbly, crunchy, brittle
	Chewiness	Tender, chewy, tough
	Gumminess	Short, mealy, pasty, gummy
Elasticity		Plastic, elastic
Hardness		Soft, firm, hard
Viscosity		Thin, thick
Particle shape and orientation		Cellular, crystalline, fibrous, etc.
Particle size and shape		Coarse, grainy, gritty, etc.
Fat content	Greasiness	Greasy
	Oiliness	Oily
Moisture content		Dry, moist, wet, watery

Adapted from Szczesniak (1963)

specified food products to anchor each scale point. The earliest standardized texture scales were developed for adhesiveness, brittleness, chewiness, gumminess, hardness, and viscosity. These authors validated their scales by correlating the results obtained by the sensory panelists to the results obtained instrumentally by viscometer and texturometer. A later section will discuss sensory and instrumental texture correlations.

The Texture Profile method was used extensively at General Foods and the number of standardized rating scales was expanded over time, for example, Brandt et al. (1963) added elasticity which was later changed to springiness (Szczesniak, 1975), Szczesniak and Bourne (1969) added firmness and later brittleness was renamed fracturability (Civille and Szczesniak, 1973). The original Texture Profile had scales of varying length, for example, the scale for chewiness had seven points, gumminess had five points, and hardness had nine points (Bourne, 1982). The article by Civille and Szczesniak (1973) uses a 14-point intensity scale and the paper by Muñoz (1986) describes a 15 cm line scale with the intensity anchors positioned on the scale.

Civille and Szczesniak (1973) succinctly described how a Texture Profile panel should be selected and trained. They suggested training about ten panelists with the goal of having at least six available at all times. The panelists should undergo a physiological screening to eliminate potential panelists with dentures and those without the ability to discriminate among textural differences. Panelists are also interviewed to assess interest, availability, attitude, and communication skills. During panel training, the panelists are exposed to the basic concepts associated with flavor and texture perception and the underlying principles of the Texture Profile. They are also trained to use the standard rating scales in a uniform and consistent fashion. The panel will practice using the rating scales on a series of food products. This practice may be quite extensive, lasting several months. Any inconsistencies among panelists are discussed and resolved.

Once the panel has been trained, which in some cases could mean a time commitment of 2–3 h daily sessions for 2 weeks followed by 6 months of 1 h session four to five times a week; the panel can begin evaluating test products. On the other end of the time scale one of us was trained as a fish texture panelist where the training lasted only about 2 weeks. A well-trained panel should be maintained by testing their reproducibility with blind samples and by reviewing their results regularly. During these review sessions any inconsistencies among panelists should be ironed out. Additionally, the panel leader should continually strive to keep the panel motivated.

The Texture Profile has been modified and refined since its original creation. Civille and Liska (1975) described the modifications to that date. These included modifying some of the food products used to anchor the standard intensity scales, adding the evaluation of the products surface properties to the initial stage of the evaluation, and adding standard scales to evaluate liquids and semi-solids. Additionally, the cohesiveness of mass standard scale was developed as was a scale for bounce or elasticity.

Muñoz (1986) published a paper describing the selection of new products to anchor the intensity points on the standard scales. Between 1963 and 1986 many products had changed in formulation and were no longer representative of a specific intensity on a specified Texture Profile scale and others were not available anymore. She also modified and fleshed out a number of the scale definitions. Tables 11.7 and 11.8 are principally based on the improvements to the Texture Profile made by Muñoz (1986).

Others have modified the standard scales to better suit their needs, see, for example, Chauvin et al. (2008) who created new scales for the wet and dry food attributes: crispness, crunchiness, and crackliness. In this case the authors used acoustical parameters and sensory panelists to determine the appropriate products to use on the standard scales. In a few cases the modifications of the Texture Profile standard scales were made because the American food products used as anchors were not available in other countries, for example, Bourne et al. (1975), or Otegbayo et al. (2005); for non-food products, see Schwartz (1975). The Schwartz paper is a useful starting place for skin care products and related personal care or cosmetic items that have important skin feel properties. The review by Skinner (1988) is a very complete treatise on the state of the texture profile to that date. The sensory texture profile is still in use, see, for example, Lee and Resurreccion (2001) who used the technique for peanut butter and Breuil and Meullenet (2001) who used it for cheeses. Chauvin et al. (2008) developed new standard scales for crispness,

Table 11.7 Texture profile attribute definitions

Texture attribute	Definition
Non-oral	
Manual adhesiveness	Force required to separate individual pieces adhering to each other using the back of a spoon, after placing entire contents of the standard cup on a plate
Viscosity	Degree of resistance when stirred by a spoon
	Rate at which sample flows down the side of a tilted container
Oral	
Initial lip contact	
Adhesiveness to lips	Degree to which the product stick/adheres to the lips. The sample is placed between the lips and compressed once slightly and released to assess lip adhesiveness
Wetness	Amount of moisture perceived on the surface of the product, when in contact with the upper lip
Initial insertion in mouth	
Roughness	Degree of abrasiveness of the product's surface, as perceived by the tongue
Self-adhesiveness	Force required to separate individual pieces with the tongue, when the sample is placed in the mouth
Springiness	Force with which the sample returns to its original size/shape, after partial compression (without failure) between the tongue and the palate
Initial bite	
Cohesiveness	Amount of deformation undergone by the material before rupture when biting completely through sample with molars
Adhesiveness to palate	Force required to remove product completely from palate, using tongue, after compression of the sample between tongue and palate
Denseness	Compactness of the cross section of the sample after biting completely through with molars
Fracturability	Force with which the sample ruptures when placed between molars and bitten completely down at a fast rate
Hardness	Force required to bite completely through sample placed between molars
After chewing	
Adhesiveness to teeth	Amount of product adhering on/in the teeth after mastication of the product
Cohesiveness of mass	Degree to which the mass holds together after mastication of product
Moisture absorption	Amount of saliva absorbed by the sample after mastication of product

Adapted from Muñoz (1986) and Sherman (1977)

crackliness, and crunchiness in dry and wet foods (Table 11.9).

Cardello et al. (1982) used free-modulus magnitude estimation to rescale the standard texture profile scales of adhesiveness, chewiness, fracturability, hardness, gumminess, and viscosity. They found that the category scales of the traditional Texture profile were concave downward when plotted against the magnitude estimation scales. This indicates that for these attributes the panelists exhibit a greater discrimination at the lower levels of intensity. This is a pattern consistent with Weber's law (see Chapter 2). Weber's law predicts smaller difference thresholds at low levels of intensity. The data also suggest that the results from category scales and magnitude estimation scales are different but similar.

11.3.2 Other Sensory Texture Evaluation Techniques

The sensory scientist does not have to train a panel use the sensory texture profile analysis technique. It is entirely possible to use generic sensory descriptive analysis to describe differences in the textures of products. For example, Weenen et al. (2003) used consensus training to train a panel to evaluate mayonnaises, salad dressings, custards, and warm sauces. They found that the panel grouped the sensory texture of these semi-solid foods into six clusters (visco-elastic-related attributes; surface feel-related attributes; bulk homogeneity-related attributes; adhesion/cohesion-related attributes; wetness/dryness-related attributes;

Table 11.8 Examples of texture attribute intensity anchors

Texture attribute	Scale	Product
Adhesiveness	Low	Hydrogenated vegetable oil
	Medium	Marshmallow topping
	High	Peanut butter
Adhesiveness to lips	Low	Tomato
	Medium	Bread stick
	High	Rice cereal
Adhesiveness to teeth	Low	Clam
	Medium	Graham cracker
	High	Jujubes
Cohesiveness	Low	Corn muffin
	Medium	Dried fruit
	High	Chewing gum
Cohesiveness of mass	Low	Licorice
	Medium	Frankfurter
	High	Dough
Denseness	Low	Whipped topping
	Medium	Malted milk balls
	High	Fruit jellies
Fracturability	Low	Corn muffin
	Medium	ginger snap (inside part)
	High	Hard candy
Hardness	Low	Cream cheese
	Medium	Frankfurter
	High	Hard candy
Manual adhesiveness	Low	Marshmallow
	Medium	Dough
	High	Nougat
Moisture absorption	Low	Licorice
	Medium	Potato chip
	High	Cracker
Roughness	Low	Gelatin dessert
	Medium	Potato chip
	High	Thin bread wafer
Self-adhesiveness	Low	Gumi-bear
	Medium	American cheese
	High	Caramel
Springiness	Low	Cream cheese
	Medium	Marshmallow
	High	Gelatin dessert
Wetness	Low	Cracker
	Medium	Ham
	High	Wafer

Adapted from Muñoz (1986) and Meilgaard et al. (2006)

and fat-related attributes). These authors subsequently used generic descriptive analysis panels to evaluate a wide range of semi-solid foods under different conditions (Engelen et al., 2003; Weenen et al., 2005). Others have also used generic descriptive analysis to describe the texture of cooked potatoes (Thybo et al., 2000), ketchup (Varela et al., 2003), oat breads (Salmenkallio-Marttila et al., 2004), creamy foods (Tournier et al., 2007), crisp and crunchy dry foods (Dijksterhuis et al., 2007), mango puree with added barium sulfate (Ekberg et al., 2009), and mayonnaises (Terpstra et al., 2009).

Table 11.9 Crispness, crackliness, and crunchiness standard scales for dry foods

Attribute	Reference	Manufacturer	Sample size and scale value
Crispness (dry food)			
2	Rice Krispies treats	Kellogg's, Battle Creek, MI	1/6 bar
5	Fiber rye bread	Wasa, Bannockburn, IL	1/3 slice
8	Multigrain mini rice cakes	Honey Graham, Quaker, Chicago, IL	1 cake
10	Bite size Tostitos tortilla chips	Frito Lay, Dallas, TX	1 chip
15	Kettle Chips	Frito Lay, Dallas, TX	1 chip
Crackliness (dry food)			
2	Club cracker	Keebler, Battle Creek, MI	½ cracker
7	Multigrain mini rice cakes	Honey Graham, Quaker, Chicago, IL	½ cake
9	Le Petit Beurre tea cookie	Lu, Barcelona Spain	1/8 square
12	Triscuit	Nabisco/Kraft Foods, Chicago, IL	¼ broken with grain
15	Ginger snap	Archway, Battle Creek, MI	½ cookie

Adapted from Chauvin et al. (2008)

11.3.3 Instrumental Texture Measurements and Sensory Correlations

"Texture is a sensory property" (Szczesniak (2002) and thus the goal of instrumental "texture" measurements is to produce a mechanical test that can replace sensory panels as texture evaluation tools. The need to replace the sensory panel is usually due to cost or efficiency. Basic questions that should be asked are what are meant by objective mechanical "texture" properties and does a sensory textural property have universal meaning across food products? For example, is the sensory hardness of cheese the same as the hardness of a cookie, or is the perceived juiciness associated with a grape the same as that perceived in cooked steak?

A glance at the literature would indicate many examples where the authors use the same word (e.g., hardness) for their measurements of both sensory and instrumental texture parameters in the food product. The problem is that these measurements are often not highly correlated with one another. When this occurs the author of a protocol or paper should be extremely careful to distinguish between the sensory and the instrumental measurement. Figure 11.1 indicates a

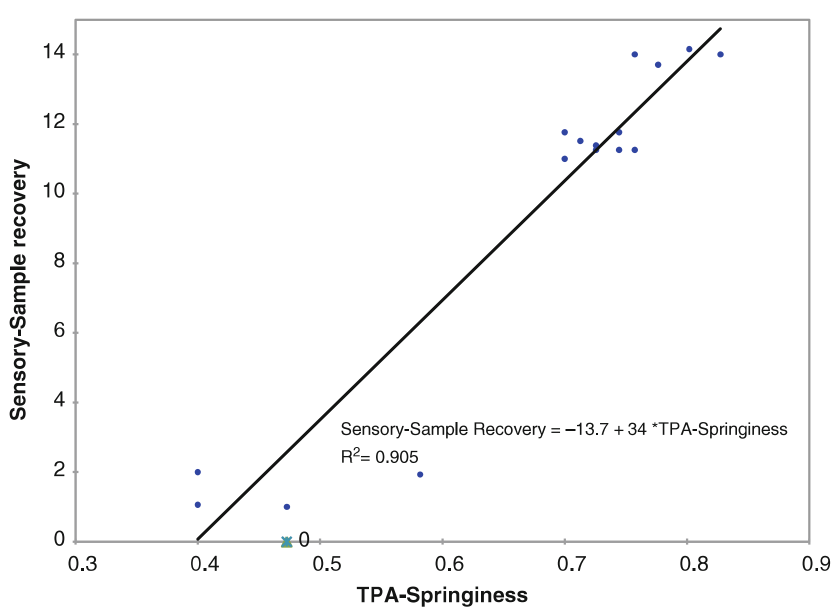

Fig. 11.1 Linear regression and correlation between the sensory texture attribute sample recovery and the instrumental texture parameter springiness (TPA= texture profile analysis). Redrawn in a different orientation from Kim et al. (2009).

linear regression and correlation between a modified Texture Profile Analysis (TPA) and the sensory texture attribute (sample recovery) for cereal snack bars (Kim et al., 2009).

In this case the authors were very careful to use different terms for their sensory and instrumental measurements. Originally, many instrumental texture measurements were attempts to find a single parameter (or an overall value) to correlate with sensory texture evaluations. But "...it is often extremely difficult to predict sensory attributes from a unique instrumental parameter ..." (Breuil and Meullenet, 2001) and thus recently, many scientists have been exploring methods that would be more multivariate in nature (Varela et al., 2006).

One of the earliest papers to correlate instrumental texture parameters with sensory texture attributes was Friedman et al. (1963). These authors were part of the group developing the General Foods Texture Profile. They designed a new piece of equipment to translate the texture measurements defined by Szczesniak (1963) in physical measurements. The General Foods Texturometer had plungers which penetrated the food in two cycles, the penetration force was recorded and attributes of the instrumental texture profile were selected to correlate well with the sensory texture parameters rated by the trained Texture Profile panelists. Due to this careful selection of the instrumental texture parameters the authors had high correlation between their sensory and instrumental measurements. They continued to refine the Texturometer and published a number of papers correlating instrumental and sensory texture attributes (Szczesniak et al., 1963). The measurement technique based on the Texturometer became known as the Texture Profile Analysis (TPA) which is different from the sensory Texture Profile method. Later, the TPA techniques, developed with the Texturometer, were used with the Instron Universal Testing Machine and other related equipments (Breene, 1975; Finney, 1969; Szczesniak, 1966, 1969; Varela et al., 2006).

Szczesniak (1968, 1987) cautioned sensory specialists and food engineers against blindly correlating sensory and instrumental attributes. She cited a series of studies correlating sensory tenderness and shear force values obtained by Warner-Bratzler shear, the correlation coefficients ranged from –0.94 to –0.16. She stated that if one assumes that both the sensory and instrumental measurements were performed using standard good practices (not always an appropriate assumption) then these inconsistent correlations are due to other contributing conditions such as

(a) The correlation coefficient is dependent on the range and number of samples used. Additionally, the Pearson's correlation coefficient is based on a linear relationship, thus if the relationship is curvilinear the values may need to be logarithmically transformed.
(b) The instrumental measurement should mimic as far as possible the conditions used to evaluate the sensory attribute. Thus if tenderness is evaluated by a single bite through the sample with the incisors then a shear force measurement is more likely to be highly correlated. On the other hand, if the tenderness of the sample is evaluated by chewing with the molars then a shear force measurement may not be correlated with the perceived tenderness. If the sample is evaluated at above ambient temperature then the instrumental measurement should be made at the same temperature. Despite the evident obviousness of this statement this is not always done. Hyldig and Nielsen (2001) pointed out that in salmon-related studies the instrumental texture measurement is frequently performed on the raw fish and the sensory texture is measured on the cooked fish. It should not be surprising that resultant correlations between the two measurements are low.
(c) Since the sample is often destroyed during either measurement the same sample cannot be evaluated by both methods. Therefore the sample itself may be part of the problem, especially, if there is considerable variation in the texture attributes of samples from the same source. This is frequently a problem with meat samples where the tenderness within a single muscle can vary longitudinally (Cavitt et al., 2005). Newer non-destructive methods such as near-infrared spectroscopy (Blazquez et al., 2006) allow the sensory scientist to use the same sample for both the instrumental and texture measurements but many of these methods are in their infancy.
(d) Natural variability among panelists in terms of chewing cycles, dentition, salivary flow rates, etc., is a factor that will affect the quality of instrumental texture relationships.

Brennan and Jowitt (1977) categorized the instrumental texture measurement techniques as fundamental, imitative, and empirical. The fundamental techniques measure well-defined physical properties and at that time the authors felt that no measurement technique actually did a fundamental measurement. Recently, Ross (2009) stated that steady shear and dynamic viscometer measurements on fluids as well as measurements of deformation on solids are probably fundamental measurements of texture. Kim et al. (2009) stated that the 3-point bending test used to measure the fracturability of sheet-shaped foods was also a fundamental measurement. This technique was used with success by Rojo and Vincent (2008) to study perceived crispness in potato chips. With imitative techniques the measurement mimics the actions of the teeth and the jaws during the sensory measurement as closely as possible. Hyldig and Nielsen (2001) stated that the instrumental firmness evaluation of salmon by compression was an imitative method related to the sensory firmness evaluation of pressing the salmon with the index finger. Examples of imitative techniques are the puncture test which measures the force required to punch a hole in the food (a combination of shear and compression forces), the use of sound measurements (gnathosonics, Duizer, 2001; Ross, 2009; Kim et al., 2009), and electromyography (EMG). The early work by Vickers and coworkers (see Vickers, 1987b) on using the sounds associated with biting/chewing dry and wet crisp/crunchy food to determine perceived crispness and crunchiness has been expanded through the use of fast Fourier transform algorithms (Al-Chakra et al., 1996) and fractal analyses (Barrett et al., 1994, Gonzalez-Barron and Butler, 2008a) to analyze sound frequencies (de Belie et al., 2002). See González et al. (2001) for reviews of EMG in food texture evaluations. Additional information on EMG can be found in Foster et al., 2006; González et al., 2004; Ioannides et al., 2007, 2009.

Most instrumental texture measurements are empirical and do not necessarily "translate" across food products. This is not necessarily a problem since Drake et al. (1999) stated that "While fundamental rheological test reveal important information on network structure and molecular arrangement [in cheese], . . . empirical texture evaluations work equally well or better at predicting sensory texture properties."

Image analyses and/or microscopy are also used in relationship to visual and, sometimes, oral and nonoral–tactile texture (Di Monaco et al., 2008; Gonzalez-Barron and Butler, 2008b; Lassoued et al., 2008; Martens and Thybo, 2000; Zheng et al., 2006). Chen (2007) reviews these instrumental techniques and their uses in the characterization of perceived surface texture.

11.4 Conclusions

The sensory evaluation of texture has advanced a great deal since the middle of this century, yet in 1991 Alina Szczesniak, surely the doyenne of food texture in the United States, could still state that "there are still many important gaps in the consumer/texture interface where progress has not kept up with that in the area of instrumental texture measurements." She continues "Quantitative measures of the relative importance of texture in specific food categories should be developed and related to the level of textural quality." This state of affairs is emphasized by Chen (2009) who stated that ". . . a thorough understanding of the principles and mechanisms involved in food oral processing will be essential. Without such knowledge, our studies of food texture probably would not go far." Given the importance of food texture in food quality and acceptance, there is still a great deal of work that must be done in this area.

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