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Review

Crispness: a critical review on sensory and material science approaches

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Many texture studies have been published on crispness because of the great interest of consumers towards crispy foods. This work reviews the existing literature on the topic, and especially the different approaches, instrumental and sensory, applied to study crispness. These studies result in a wide range of data but, because crispness is not a clearly defined sensory attribute, the conclusions that can be drawn from these studies should be carefully examined. The physical basis for crispness are discussed and the role of structure, hydration and ingredients on crispness and its stability are presented.

Introduction

Living in a society of large choice of quality food, the consumers' appreciation has become one of the main criteria in their food choice, as well as nutrition and safety. The contribution of texture to the consumers' appreciation of a food product has been studied for nearly 40 years. In the early studies on the awareness of food texture, the importance of crispness was highlighted. For instance, word association tests, in which consumers were asked to generate attributes related to a list of specific foods, showed that the term "crisp" was mentioned more often than any other attribute (Rohm, 1990; Szczesniak, 1971; Szczesniak & Kleyn, 1963).

In 1972, Iles and Elson (1972) showed that products were ranked in the same order for crispness and consumers' preference. This result was later replicated by Katz and Labuza (1981) emphasizing the importance of crispness in food acceptability. Thus, the food industry has considered the necessity to control this characteristic both during production and storage. To achieve such an objective requires the knowledge of intrinsic parameters (physical, chemical, product-related) responsible for crispness. But crispness, like any other textural attribute, depends not only on *ad hoc* rheological/mechanical characteristics exhibited by a product, but also on the consumers who identify the sensations perceived upon eating, as relevant to crispness. Thus, to understand both the mechanisms underlying crispness perception and the meaning, consumers give to the term 'crispy', is relevant to this issue. This paper will then be structured as follows. In the first section, the sensory works on crispness and especially the strategies implemented to evaluate crispness are reviewed. In the second section, the instrumental approaches developed to study crispness are presented. In the final section, the key parameters for crispness control are reviewed.

Crispness: sensory approaches

Although texture researches cannot ignore sensory approach, there are only few studies dealing with methodological aspect of crispness assessment. Different approaches have been reported in the literature on crispness evaluation. In the 1970's and early 1980's, the magnitude estimation method was commonly used (Brennan, Jowitt, & Williams, 1974; Christensen & Vickers, 1981; Edmister & Vickers, 1985; Katz & Labuza, 1981; Mohamed, Jowitt, & Brennan, 1982; Vickers, 1981; Vickers & Wasserman, 1979). In this technique, one product is chosen as a reference and is given an arbitrary score. The assessors are asked to score the samples proportionally to this reference.

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Usually, these evaluations are carried out with a large number (20–50) of untrained assessors. In the 1980's, the descriptive analysis became popular and was acknowledged as a reliable technique to measure sensory properties. It became the reference technique for crispness measurement and profoundly changed the experimental protocols: ratio scales were abandoned in favour of interval scales (structured or unstructured linear scales) and assessments were performed with small group of trained panellists (about 10 people).

On the training stage of descriptive analysis, the objective is to reach a consensus among panellists on the meaning of every attribute. To achieve this, it is recommended in handbooks to provide assessors with a definition. Thus, in some studies, a verbal definition was given to the attribute 'crispy' (Barrett, Cardello, Lesher, & Taub, 1994; Dacremont, 1992; Duizer, Campanella, & Barnes, 1998; Onwulata & Heymann, 1994; Seymour & Hamann, 1988). The examination of these definitions (Table 1, including two earlier studies) shows a large diversity of meaning. The definitions provide varying explanations on which sensations assessors should focus to evaluate crispness. Five aspects have been quoted: structure of the intact product, sounds emitted at fracture, force needed to crush the sample, how the product collapses at fracture and how do the pieces appear after fracture. As shown in Table 2, there is at best only a moderate amount of agreement among definitions. Depending on the definition, some characteristics are stressed with more or less details, or omitted. Usually, definitions include a description of exploratory procedures, i.e. the way the sample should be manipulated. These procedures may also vary. In some studies, assessors are instructed to crush the samples either with their molars or their incisors. In other studies, the panel evaluates crispness by crushing or snapping the sample with the fingers (Omwulata & Heymann, 1994; Waichungo, Heymann, & Heldman, 2000).

These definitions probably do not reflect an unique sensory concept, as indicated by the outcome of the experiments in which they were used:

- the definition of Seymour and Hamman (1988) only referred to high-pitched crushing sounds and a good correlation between crispness and energy in the high frequencies of eating sounds was found;
- the definitions of Jeon, Breene, and Munson (1975) and Barrett, Cardello *et al.* (1994) emphasised the importance of the force required to bite through the sample and, in both cases, a close relationship between crispness and hardness was found;

Table 1. Definitions of crispness

Reference	Attribute used	Location of the panel	Definition
Barrett *et al.*, 1994	Crispy	USA	*The perceived horizontal force with which the product separates into two or more distinct pieces during a single bite with the incisors. An abrupt and complete failure of the product is required.*
Brennan *et al.*, 1973	Crispy	UK	*Place a small piece between the molars and bite down slowly and evenly until a sudden and continuous breakdown of the biscuit structure occurs. Assess the rate at which this breakdown into small fragments occurs using as near as possible the same biting rate.*
Dacremont, 1992	Croustillant	France	*Noisy at biting, aerated, light and that crumble. The fracture is progressive during biting* (translation from French).
Duizer *et al.*, 1998	Crispy	New Zealand	*A combination of the noise produced and the breakdown of the product as it is bitten entirely through with the back molars.*
Jeon *et al.*, 1975	Crispy	USA	*Relative force required to bite through* [the sample].
Onwulata and Heymann, 1994	Crispy	USA	*The perceived relative force used by crunching* [the product] *in the mouth.*
Seymour and Hamman, 1988	Crispy	USA	*First bite: Place sample between incisors, bite through and evaluate the lever of higher pitched noise.*

Table 2. Stimuli cited for the definition of the attribute crispy

References	Noise	Force	Fracture	Particle	Structure
Barrett *et al.*, 1994		Horizontal force	Abrupt and complete	Two or more pieces	
Brennan *et al.*, 1973			Sudden and continuous	Small fragments	
Dacremont, 1992	Noisy		Progressive	Crumble	Aerated and light
Duizer *et al.*, 1998	Noise		Breakdown		
Jeon *et al.*, 1975		Relative force			
Onwulata and Heymann, 1994		Relative force			
Seymour and Hamman, 1988	High pitched				

- the definition of Dacremont (1992) referred to the structure of the product and a correlation was found between crispness, aeration and crumbliness.

One wonders whether these results are the cause or the consequence of the definitions. If the verbal definition of crispness is relevant, there is no need for further investigation on the meaning of crispness. If the definition is not relevant, then, at best, the definition is ineffective and, at worst, it leads assessors to evaluate some other sensory concepts. Aware of this shortcoming, some panel leaders did not provide panellists with a verbal definition but allowed them to reach a consensus at the training step, by discussing together when tasting products (Brown, Langley, & Braxton, 1998; Lee, Schweitzer, Morgan, & Shepherd, 1990; Liu & Tan, 2000; Piazza & Masi, 1997; Roudaut, Dacremont, & Le Meste, 1998; Sauvageot & Blond, 1991). However, the problem remains because there is no guarantee that two groups, independently trained, would reach a consensus on the same meaning. Thus, trained assessors provide reliable responses but, the validity of responses, i.e. the ability to provide reproducible results between independently trained groups, might be jeopardized by the training itself.

In many studies, untrained assessors were used (Christensen & Vickers, 1981; Edmister & Vickers, 1985; Katz & Labuza, 1981; Mohamed, Jowitt, & Brennan, 1982; Vickers, 1981; Vickers & Wasserman, 1979; Dacremont, 1995; Norton, Mitchell, & Blanshard, 1998; Sherman & Deghaidy, 1978; Suwonsichon & Peleg, 1998; Vickers, 1984, 1985, 1987, 1988; Vickers & Christensen, 1980), though this methodological choice has been rarely justified. Working with untrained assessors might have been a way to avoid the adulteration of the crispy concept due to training in laboratory conditions. Such a method requires to work with a larger number of assessors, to compensate the possibility that their concepts were not aligned initially. The question of whether or not untrained assessors are able to quantify their perceptions in a reliable way is still under debate (Dugle, 1997; Hough, 1998; Moskowitz, 1996, 1997, 1998). However, it is obvious that protocols developed for descriptive analysis cannot be directly transposed to untrained assessors. Some authors used specific protocols, such as ranking task (Norton *et al.*, 1998; Sherman & Deghaidy, 1978) or categorisation task (Dacremont, 1995), which are more adapted to untrained assessors than the rating task.

Vallés Pàmies, Roudaut, Dacremont, Le Meste, and Mitchell (2000) proposed an alternative approach to overcome the difficulty. First, the consensual 'crispy' concept is measured in the population of interest. This can be achieved, for instance, by asking consumers to categorise a large range of products as 'crispy', 'not crispy' or 'borderline'. Then, prototypical products are identified and used as a perceptive (as opposed to verbal) definition to train a conventional descriptive panel. At the end of training, the efficiency of the learning stage is tested, to check that panellists' concepts are aligned. Afterwards, the familiar procedure of descriptive analysis is carried out. In this way, the ecological validity of the measure and its reliability are both achieved.

The measurement of crispness by sensory mean is not a straightforward process. The difference between a sensory concept (i.e., the collection of perceptions identified as relevant to the same class) and its label (i.e., the word used by a community to refer to it) should be acknowledged. Thus, the use of the same label in different studies, especially with trained panellists, is not a guarantee that the same sensory concept is measured. On the opposite, different labels might have been used to refer to the same concept. For instance, 'crunchy' is used to characterize some products described as 'crispy' by other panels (Brown *et al.*, 1998; Guraya & Toledo, 1996; Segnini, Dejmek, & Oste, 1999). The question whether crispy and crunchy refer to the same sensory concept is quite difficult to answer. The strong positive correlation observed in studies where crispness and crunchiness were estimated by the same panel, on the same products (Barrett, Cardello *et al.*, 1994; Seymour & Hamann, 1988, Suwonsichon & Peleg, 1998; Vickers, 1981, 1985) favours the hypothesis of two labels for an unique concept. However, other works (Dacremont, 1995, 1996) suggest that crispy and crunchy refer to different concepts. The question is still open.

Moreover, studies on crispness were conducted in several countries, which adds difficulties to compare results due to the inherent distortion of meaning in translation (see Zannoni (1997) for a review on translation in descriptive analysis). For instance, Table 3, extracted from the polyglot list of textural terms published by Drake (1989), outlines that crispness can have more than one equivalent term in other languages. But, even if one equivalent word exists in two languages, they may not have exactly the same meaning. For example in France, neither fruits nor vegetables are considered 'croustillant' (translation of crisp) (Dacremont, 1992), as opposed to the United States (Szczesniak, 1988). The consensual meaning of a word is culture-dependent, i.e. it

Table 3. Translations of the terms crispy and crunchy from Drake (1989)

English	Crispy		Crunchy
French	Croustillant		Croquant
Italian		< Croccante >	
Iceland		< – >	
Japanese	Baribari		Karikarisuru
	Boriori		Pariparisuru
	Karikari		

depends on the language but also on other cultural facts such as food habits, for instance.

Outcomes of sensory studies are often difficult to compare because of the confusion between concept and label, the lack of homogeneity in the procedures implemented for sensory assessments and the difficulties inherent to multi-cultural studies in the perception field. Therefore, this might explain some contradictory results reported in the crispness literature, especially in studies dealing with relationships between instrumental and sensory data.

Crispness: instrumental approaches

Although sensory analysis gives a more complete description of the texture of tested products, there has been a great interest in developing instrumental techniques to assess crispness. Instrumental techniques present some advantages, especially in industrial environments where quick and easy-to-use methods are in great demand and economically more profitable. Crispness being described as a concept with kinesthesic and auditory components, it is not surprising that the instrumental methods developed to evaluate it, have focused on the measurements of these properties singularly or in combination. Although a recent analysis of crispy bread has been performed by a complex instrumental set up considering at the same time flavours, mechanical and acoustic properties (Winquist, Wide, Eklov, Hjort, & Lundstrom, 1999), the measurements are generally performed separately.

Mechanical measurements

Crispness 'measurements' are performed on instruments originally, developed for material science, providing physical parameters with fundamental significance in terms of rheological properties. These parameters cannot give straightforward crispness measurement, if any, but can be used as indicators, provided they are validated by sensory data.

Considering the perception of crispness upon eating, large deformation and fracture tests seem to be the most suitable instrumental tests. However, small deformation data, such as those acquired in dynamic rheology (George & Smith, 1996; Kalichevsky, Blanshard, & Mash, 1993; Le Meste, Roudaut, & Davidou, 1996; Nikolaidis & Labuza, 1996; Roudaut *et al.*, 1998) or prior to fracture at larger deformation (such as for apparent Young's modulus measurement) (Fontanet, Davidou, Dacremont, & Le Meste, 1997; Hutchinson, Mantle, & Smith, 1989; Nicholls, Appelqvist, Davies, Ingman, & Lillford, 1995), may provide information not directly related to crispness, but to the molecular basis of this attribute.

Examples of measurements of rheological behaviour are numerous in the literature. Independently of the probe type or of the method used, they are all based on recording the force when a deformation is applied to the product. Although constant loading rate tests have been suggested to provide more information (Jowitt & Mohamed, 1980), in most cases, tests are performed at constant deformation rate. Some authors also suggested the use of a high impact test (Hayter & Smith, 1988; Hayter, Smith, & Richmond, 1986; Hutchinson *et al.*, 1989) to overcome the limitations of the testing deformation speeds used (i.e. <16.6 mm s^{-1} for an Instron Universal Testing Machine) compared to the high speed of mastication (between 20 and 50 mm s^{-1}); nevertheless, this type of test is not used.

The most commonly used tests can be categorized into three groups: flexure (Andersson *et al.*, 1973; Attenburrow, Davies, Goodband, & Ingman, 1992; Van Hecke, Allaf, & Bouvier, 1995; Vickers & Christensen, 1980), shear (Bhattacharya & Hanna, 1987; Faubion & Hoseney, 1982) and compression tests. The latter are probably the most commonly employed because of their similarities with the mastication process. In these tests, the specimen is compressed either between two parallel plates (Moskowitz, Segars, Kapsalis, & Kluter, 1974) or by a plunger compressing the sample held in a cylinder (Andersson *et al.*, 1973). Samples can be tested individually or as bulk when contained in a cell (Nixon & Peleg, 1995). Puncture tests have been extensively used as well (Georget, Parker, & Smith, 1995; Hayter & Smith, 1988; Hutchinson, Sdiolak, & Smith, 1987; Li, Kloeppel, & Hsieh, 1998; Van Hecke, Allaf, & Bouvier, 1998) for they simulate the incisors impact at biting. In this case, a cylindrical or conical probe of small diameter plunges in the specimen at constant and rather low speed. This test has specially been employed for the characterization of foamed products, and the probe is expected to fracture separately the different cell walls constituting the product. The force–deformation pattern is characterised by series of sharp force peaks corresponding to the rupture of individual cell walls (Fig. 1). Rheological studies differ in the way the force–deformation plots have been analysed, either by extracting some parameters, or by considering the signal as a whole.

First, the data analysis of compression tests was considered based on a fundamental approach in terms of rheological parameters, providing Young's modulus and fracture stress values (Brennan *et al.*, 1974; Fontanet *et al.*, 1997; Hutchinson *et al.*, 1987; Katz & Labuza, 1981; Nicholls *et al.*, 1995; Roudaut *et al.*, 1998; Sauvageot & Blond, 1991; Seymour & Hamann, 1988). These analyses concentrate only on the linear region of the force–deformation plot, and reflect the mechanical properties with a material science approach. Such parameters, when corrected for the sample dimensions, are suitable for comparisons between specimens.

Another approach is to collect information from the jagged part of the force–deformation curves. For some authors (Barrett, Normand, Peleg, & Ross, 1992; Rohde, Normand, & Peleg, 1993), the overall force–deformation plot would be better analyzed by the description of its irregularities than by the extraction of some parameters. Three main analyses have been developed: extracting parameters from each force peak, calculating the power spectrum and determining the fractal dimension of the signal.

Barrett, Rosenberg, and Ross (1994) and Vincent (1998) described quantitatively the distribution of fracture forces occurring during compression, or bending of brittle foods. Using puncture tests, Van Hecke *et al.* (1998) and Vallés Pàmies *et al.* (2000) calculated the average of the so-called puncturing force (integral of force–time), the Number of Spatial Ruptures (NSR, ratio of the total number of peaks to the distance of puncturing), the average specific force of structural ruptures (ratio of the sum of force drops per peak to the number of peaks) and the ‘crispness’ work (ratio of the average puncturing force to the NSR). NSR and puncturing force were found to correlate with crispness and hardness (sensory data) respectively (Vallés Pàmies *et al.*, 2000). This is in agreement with Guraya and Toledo (1996) who claims that compressive force alone is insufficient to describe accurately the texture of crispy products.

In the last 10 years, with faster computers and thus the possibility of acquiring digital data from mechanical tests, novel methods for measuring crispness throughout the jagged plateau of the force–deformation pattern have been developed. Many authors (Barrett *et al.*, 1992; Barrett, Cardello *et al.*, 1994; Barrett, Rosenberg *et al.*, 1994; Harris & Peleg, 1996; Peleg, 1997; Rohde *et al.*, 1993) and references therein, suggest the determination of the power spectrum using Fast Fourier Transform (FFT) analysis. Indeed, relations between average power of the spectrum, and sensory attributes such as fracturability and crispness have been shown (Barrett, Cardello *et al.*, 1994; Barrett, Rosenberg *et al.*, 1994).

Finally, fractal techniques have become popular for analyzing multi-peak pattern from force-deformation curves (Nixon & Peleg, 1995; Norton *et al.*, 1998; Nuebel & Peleg, 1993; Peleg, 1997; Suwonsichon & Peleg, 1998; Vallés Pàmies *et al.*, 2000). The approach consists in considering the force–deformation plot in its whole complexity and jaggedness. However, this idea is debated: Vincent (1998) has indicated that the study of jaggedness is not appropriate because it does not account for forces and energies. The fractal analysis is based on the determination of the fractal dimension. Among the available algorithms, the Kolmogorov algorithm is one of the most used. It is based on a box-counting method. The signal is surrounded by a grid, and the number of boxes occupied by the signal is counted. Of course, decreasing the grid size increases the number of boxes occupied. The log (number of occupied boxes) is plotted versus log (relative box size) and the apparent fractal dimension of the signal is the slope of the obtained line. Barrett *et al.* (1992) suggest a relation between fractal dimension and crispness when observing a sigmoidal effect of water for both of them. However, this suggestion does not appear relevant for Suwonsichon and Peleg [33] for they found that the critical water content for the sensory crispness and fractal dimension of puffed cereals did not coincide.

Mitchell and collaborators (Norton *et al.*, 1998; Vallés Pàmies *et al.*, 2000) applied the fractal analysis following a slightly different approach, based on the measurement of the curve dimension as a function of the sampling frequency. This plot has a sigmoidal shape, and the inflexion point provides information on the mean width of the force–deformation plot, whereas the slope at this point describes the distribution of the peaks: The smaller the slope, the greater the dispersion of the peaks. Comparisons with sensory data showed the crispier the products, the lower the average width of the peaks. As an example, for the crispier product of their study, the average peak width is around 200 μm, that is about five fractures per mm. Van Hecke *et al.* (1998) obtained a similar value for similar products, when counting the peaks of the force–deformation curves. Crispy products break through numerous and neighbouring fractures; when crispness decreases (after rehydration for example), the number of fractures decreases which increases the width of the peaks on the force–deformation plot.

Acoustic measurements

As described in Table 1, crispness has an auditory component. It is therefore not surprising that some methods, developed to study crispness, have focused on the sounds generated at fracture, the sound being recorded during instrumental crushing or during mastication. The instrumental approach (using a texture analyser, for instance) is favoured because all aspects of fracture are then controlled. However, the sounds recorded during mastication are more representative of the auditory stimuli related to crispness, especially when bone- and air-conducted vibrations are recorded and analysed together. As a matter of fact, bone conduction was reported as very important to identify crispness from other auditory-related texture attributes, such as crunchiness and crackle (Dacremont, 1995; Dacremont, Colas, & Sauvageot, 1991). A very interesting and comprehensive review on the acoustic research applied to the study of crispy, crunchy and crackly textures has recently been published by Duizer (2001).

Two main approaches have been used to study fracture sounds, analysing either the amplitude-time plot of the acoustic signal (Dacremont, 1992; Duizer *et al.*, 1998; Lee *et al.*, 1990; Nussinovitch, Corradini, Normand, & Peleg, 2000; Vickers, 1987) or the amplitude-frequency plot, the latter being derived from the former via a FFT (Fast Fourier Transform) (Dacremont, 1995; Duizer *et al.*, 1998; Lee, Deibel, Glemblin, & Munday, 1988; Roudaut *et al.*, 1998; Seymour & Hamann, 1988; Winquist *et al.*, 1999).

Combining these approaches, sonograms are a 3-D (amplitude–time–frequency) graphical representation of acoustic signals. As emphasized by Brochetti, Penfield, and Burchfield (1992), it is a very powerful tool for sound analysis. It is widely used in the field of speech analysis but, despite some early attempts (Drake, 1963; Vickers & Boume, 1976), it has been rarely used for eating-sounds analysis. The main reason is that a sonogram represents a huge amount of data, from which pertinent information are difficult to extract. Liu and Tan (2000) overcame this difficulty recently, using artificial neural networks and thus succeeded in predicting sensory scores for crispness of 10 food products from their sonograms. This might be one of the most promising approaches for analysing eating sounds.

Bio-rheology

Another promising field is the in-mouth measurement of texture which permits to follow the textural changes of products during the whole mastication process. This temporal aspect is especially important for dry crisp products due to their hydration by saliva.

Kohyama and Nishi (1997) used a multiple-point pressure sensor method to display the distribution of forces on the biting surface. Textural differences of products and their changes during biting were thus discriminated.

Electromyography has also been used to understand texture through structural breakdown during eating (Brown & Braxton, 2000; Brown *et al.*, 1998). The activity of the jaw muscles is recorded non invasively during mastication, reflecting the eating activity in usual consumption conditions. Brown and Braxton (2000) identified different groups of consumers exhibiting specific mastication patterns, clearly related to the perceived texture of crisp biscuits.

Parameters controlling crispness of dry crisp products

Process and structure

Process parameters and macrostructure are difficult to separate, since the latter often results from the former.

Most cereal-based crispy products are brittle material characterized by a cellular, lamellar or puffed structure (Barrett, Cardello *et al.*, 1994). More precisely, their structure has been defined (Taranto, 1983) as on the one hand, a discontinuous phase (gaseous) made of air bubbles formed upon fermentation and vaporization of water upon baking and on the other hand, a continuous solid phase supporting the sample weight. This structure is often described as a solid foam or sponge and commonly characterized by microscopy (Faubion & Hoseney, 1982; Guraya & Toledo, 1996). The parameters controlling the mechanical properties of cellular material (Gibson & Ashby, 1988; Smith, 1989) such as density, cell wall thickness, cell size and cell number are expected to predict the product crispness (Desrumaux, Bouvier, & Burr, 1999; Gurayad & Toledo, 1996; Hutchinson *et al.*, 1989). Barrett, Cardello *et al.* (1994) suggest a relationship describing crispness (through fractal dimension) with a combination of cell area (A) and bulk density (ρ) expressed as follow:

$$\text{Fractal Dimension}: \ 1.37 - 0.0112\text{A} + 1.93\ \rho$$

The relations between process and crispness have been studied considering different processing conditions. But most of the studies are based on extrusion cooking works, investigating the role of water content, screw speed, torque, pressure and temperature. These parameters interact to a large extent and therefore, depending on the combination chosen, their action on texture may be variable. For example, the amount of water required in extrusion-cooking for an optimal crispness lays between the low values, inhibiting expansion, and higher ones leading to a dough viscosity too low for cells formation. Furthermore, decreasing water content during extrusion increases the Specific Mechanical Energy (SME), favouring starch conversion and overall macromolecular degradation, thus giving rise to a more fragile structure and a greater fracturability. Temperature is also among the most effective parameters for crispness control. Simultaneous high shear and high temperature give rise to lower crispness (Omwulata & Heymann, 1994).

The key role of the process was confirmed by the experiment of Guraya and Toledo (1996) comparing half products (pellets) prepared by drum-drying and cold extrusion. The half product preparation was proven to be more determining for the texture than the subsequent puffing methods.

The crispness development during the process has been investigated for frying, baking and toasting. Upon frying, crispness of chips increases as porosity increases and moisture decreases (Kawas & Moreira, 2001). When considered upon baking, crispness is shown to develop with the setting of the sponge structure at the latest stages of the baking (Piazza & Masi, 1997). Drake (1963) showed that crispness increased with toasting time.

Ingredients and hydration

Most low moisture baked or extruded products such as breakfast cereals, wafers, biscuits and snacks have a crispy texture. If the moisture content of these products increases, due to water sorption from the atmosphere or by mass transport from neighbouring components or

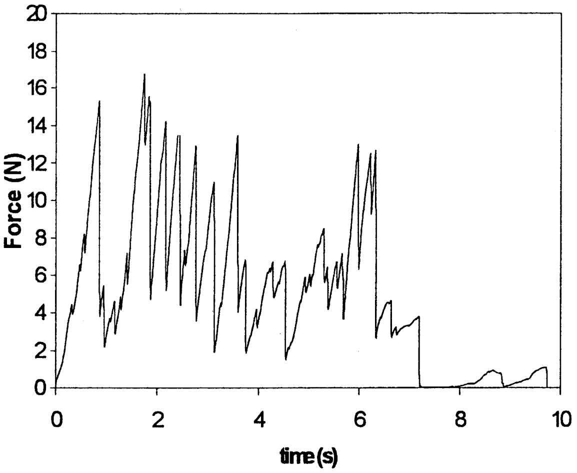

Fig. 1. Characteristic jagged force–deformation plot of a crispy product.

phases, a loss of crispness is observed (Nicholls *et al.*, 1995). A great number of studies has been published on this topic (Harris & Peleg, 1996; Peleg, 1993, 1994, 1998, 1999; Wollny & Peleg, 1994) with a view to characterizing and predicting the effects of water on crispness or to suggest the physical basis for such effects. The effect of hydration on crispness is illustrated in Fig. 2 (from Peleg, 1994); it can be described by a Fermi equation expressed as :

$$Y = Y_0/\{1 + \exp[(a_w - a_{wc})/b]\}$$

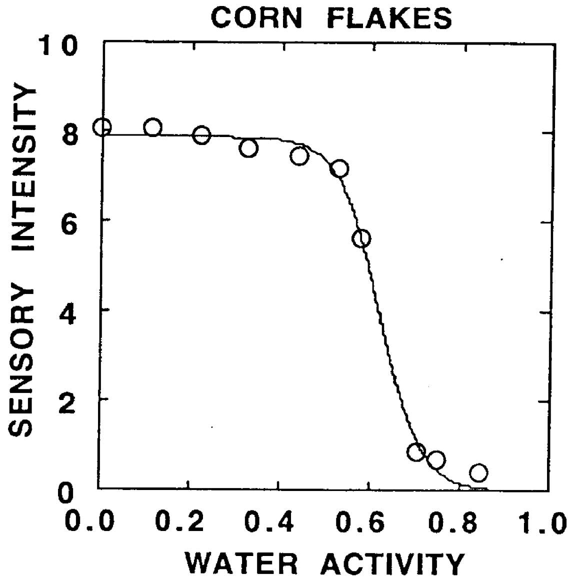

Fig. 2. Sensory crispness of corn flakes as a function of water activity. Open circles are experimental data published by Sauvageot and Blond (1991), and solid line the Fermi fit (Peleg, 1994).

where Y is crispness, Y_0 crispness in the dry state, a_{wc} the critical water activity corresponding to $Y = Y_0/2$ and b a constant that expresses the transition range.

The pioneering work on the effect of water on crispness was presented by Brennan *et al.* in 1974, followed by Katz and Labuza (1981), in studies presenting sensory crispness and mechanical data of snacks equilibrated at different water activities.

The baking and extrusion-cooking processes of starch-based material lead to the major loss of the materials crystallinity (Le Meste *et al.*, 1996). Thus, crispness has been associated with the amorphous state, and the change from crispy (brittle, noisy) to deformable (ductile, silent) following rehydration was attributed to the occurrence of the glass transition of the product at room temperature (Ablett, Attenburrow, & Lillford, 1986; Slade & Levine, 1993). The critical effect of moisture was associated to a plasticization mechanism consisting in a free volume increase through the addition of low molecular weight molecules (water), resulting in a greater mobility and increased flexibility of the macromolecules in the dynamically constrained glass (Ferry, 1980; Sears & Darby, 1982). The plasticization causes a decrease of the glass transition temperature (Tg) below ambient temperature, and thus a decrease of the rigidity of the hydrated product (Ablett *et al.*, 1996; Hutchinson *et al.*, 1989).

However, several authors report that crispness of cereal-based products could be affected by hydration (Attenburrow *et al.*, 1992; Fontanet *et al.*, 1997; Hutchinson *et al.*, 1989; Kaletung & Breslauer, 1993; Le Meste *et al.*, 1996; Li *et al.*, 1998; Nicholls *et al.*, 1995; Roudaut *et al.*, 1998) at temperatures well below their T_g or the T_g measured for hydrated wheat starch (Zeleznak & Hoseney, 1987). Studying crackers, Nikolaidis and Labuza (1996) attributed hydration-induced texture changes to the glass transition of gluten. It could be argued that the studied products contain not only gluten but also other ingredients (starch, sugars) which might affect T_g of the complex product. Moreover, due to the complexity of the products, the existence of a unique glass transition and the role of the transition in the texture change are questioned. Several authors (Kalichevsky *et al.*, 1993; Slade & Levine, 1993) have stressed out that due to their complexity and heterogeneity, products may contain multiple phases with different T_g's. The textural changes could thus be caused by the glass transition of a minor phase, which may not be visible on DSC thermograms. However, such a point may not be valid, for single component sample. For Peleg (1999), the contribution of the glass transition to the texture changes might not be relevant, since all properties may not change in unison as predicted by the glass transition theory. Indeed, different crispness-associated properties can be observed to vary within a wide range of water contents and thus may not result from a single event (Peleg, 1993; Tesch, Norman, & Peleg, 1996).

While the contribution of the glass transition to texture changes is questioned, the importance of sub-T_g motions is given attention. Indeed, localized movements preceding the α relaxation (onset of large amplitude cooperative movements) could participate in texture changes of glassy polymers (Fontanet *et al.*, 1997; Le Meste *et al.*, 1996; Roudaut, Maglione, & Le Meste, 1999; Wu, 1992). Below 15% water content, starchy products are glassy at ambient temperature; however, between 0 and 10% of water, they exhibit a decrease of crispness concomitant to an increase of hardness (observed by instrumental and sensory measurements) upon rehydration (Harris & Peleg, 1996; Roudaut *et al.*, 1998; Suwonsichon & Peleg, 1998; Vallès Pàmies *et al.*, 2000; Waichungo *et al.*, 2000). An antiplasticizing mechanism was suggested to interpret such a phenomenon, the increasing hydration being possibly responsible for both a molecular densification of the product (decreasing free volume) (Benczedi, 1999; Seow, Cheah, & Chang, 1999; Vrentas, Duda & Ling, 1988), and additional interactions between water and the biopolymer matrix. This stiffening has also been attributed to a molecular rearrangement facilitated by an initial increased mobility due to the water uptake (Fontanet *et al.*, 1997). Above 9–10% of water, the plasticization phenomenon would become dominant, and the hardness would decrease (Roudaut *et al.*, 1998) (Figure 3).

Since ingredients affect the structural organisation of products, they are likely to control their mechanical properties (Barrett *et al.*, 1994; Desrumaux *et al.*, 1999; Faubion & Hoseney, 1982; Mohamed, Abd Hamid, & Abdul Hamid, 1998; Moore, Sanei, Van Hecke, & Bouvier, 1990; Onwulata, Smith, Konstance, & Holsinger, 2001; Van Hecke *et al.*, 1998) and most expectedly their crispness. Literature does not offer a large number of studies on the influence of formulation on crispness. It is likely that industrial trials are actually run on the matter, however, faced with a competition issue, their results remain confidential. In most studies, the role of ingredients on crispness is extrapolated from their role on mechanical or structure properties, and rarely on their effects on the perceived crispness. However, a few studies report sensory data (Desrumaux *et al.*, 1999; Ferriola & Stone, 1998; Mohamed *et al.*, 1998; Roudaut, Dacremont, Vallès Pàmies, Mitchell, & Le Meste, 2001; Thakur & Saxena, 2000; Van Hecke *et al.*, 1995, 1998). Based on the assumption that texture of snack foods is controlled by ingredients providing enough viscosity and retaining texture and shape, Thakur and Saxena (2000) have studied the influence of different types of flour (corn, gram) and gums (xanthan, guar, arabic gum, carboxymethylcellulose). However, because the measured sensory attributes are not clearly defined, and because large interactions between the effects of the ingredients exist, it is quite difficult to draw a clear conclusion on the individual role of the tested ingredients. Mohammed *et al.* (1998) have investigated the effects of pregelatinized rice flour, tapioca starch, proteins (egg yolk, gluten, skimmed milk, whey and ovalbumin), emulsifiers and calcium chloride on the crispness of frying batters. Adding pregelatinized rice flour, increasing amylose content and adding calcium chloride up to an optimum level improved crispness. These results remain ambiguous for the crispness evaluation is unclear (hardness and crispness attributes are used undistinctively). The interactions between proteins, polysaccharides and water have been suggested to play a role in the crispness of some products (Mohamed *et al.*, 1998; Van Hecke *et al.*, 1995). Proteins and fibers have generally a deleterious effect on crispness (Moore *et al.*, 1990; Sotillo & Hettiarachy, 1994). Fatty acids and emulsifiers may control crispness through the formation of complexes with starch (Desrumaux *et al.*, 1999; Mohamed *et al.*, 1998; Van Hecke *et al.*, 1998); when used at low concentrations (0.5%), they provide maize grits with optimal crispness (Desrumaux *et al.*, 1999).

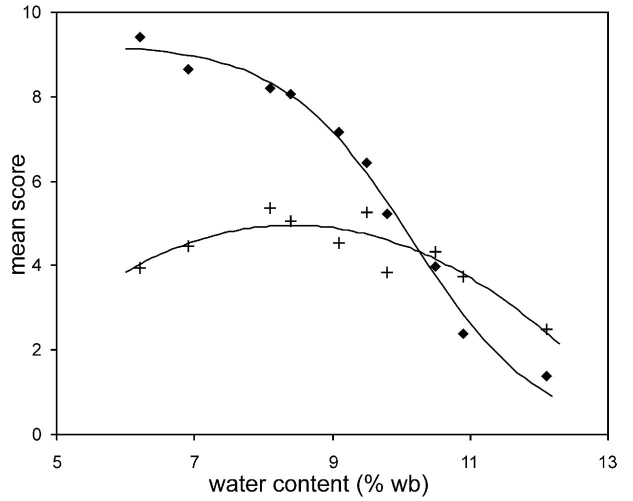

Fig. 3. Influence of water content on crispness (◆) and hardness (+) for extruded flat bread.

The effect of sucrose on crispness has been investigated in various ways. Nussinovitch *et al.* (2000) observed that, for freeze-dried agar prepared with or without infused sucrose, sucrose increased brittleness (and thus expectedly crispness), although the interpretation was ambiguous for sucrose affected the density of the material. Sucrose exhibits a crispness protecting action against hydration, shifting for sucrose-rich extruded starch the critical hydration towards values higher than for pure extruded starch (Roudaut *et al.*, 2001; Vallès Pàmies *et al.*, 2000).

Finally, the influence of secondary sweeteners (coating) on the 'bowl life' of crispness was considered by

Ferriola and Stone (1998), with a significant 'wet' crispness stabilization by honey.

Conclusions

Crispness is a complex attribute resulting on the one hand from multiple sensations and on the other hand from multiple physical parameters, combining molecular, structural and manufacturing processes, as well as storage conditions.

In general, research works should better merge sensory and instrumental approaches. Indeed instrumental related information such as sonograms or electromyographies data would enable a better understanding of the mental representation of texture through modelling cognitive activities from stimuli characteristics. In turns, sensory aspects should be considered in physical studies and take into account aspects such as, for example, the mastication dynamics induced by changes in both temperature and moisture content due to saliva.

Moreover, further studies should consider the role of ingredients to control and preserve crispness, as well as standardization of the sensory tests to ensure consistency in the outcomes of the studies, especially in an international research context.

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