SPECTRAL COMPOSITION OF EATING SOUNDS GENERATED BY CRISPY, CRUNCHY AND CRACKLY FOODS

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ABSTRACT

Separate air and bone conducted food sounds generated by six subjects biting into eight foods were recorded and analysed by a fast Fourier transform (FFT) signal analyser. A panel of 60 subjects classified the 8 foods according to their texture: crispy, crunchy and crackly and these textural characteristics were described by spectral characteristics of biting sounds. Crispy foods (such as extruded flat breads) were found to generate high pitched sounds that show a high level of frequencies higher than 5 kHz, especially for air conduction. Crunchy foods (such as raw carrot) generate low pitched sounds with a characteristic peak on frequency range 1.25 to 2 kHz for air conduction. And crackly foods (such as dry biscuits) generate low pitched sounds with a high level of bone conduction. We hypothesize that discrimination between crunchy and crackly foods could be due to vibrations propagated by bone conduction that also generated vibrotactile sensations.

INTRODUCTION

Auditory sensations are important to perceive texture of many foods. The French descriptors: *croustillant, craquant* and *croquant* refer, in large part, to noise generated during its eating process. French words *croustillant* and *croquant* can be translated into English as crispness and crunchiness, respectively (Drake 1989) and *craquant* by crackliness. But meanings of corresponding French and English terms are not exactly equivalent. Szczesniak (1988) found that lettuce was the example the most often mentioned as crispy food by American people. French

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people would more likely describe lettuce as *craquante* (crackly) or *croquante* (crunchy) but not *croustillante* (crispy). However, most results obtained with English descriptors can be transposed to French descriptors. In order to make reading easier, we chose to use English terms in this paper, although the subjects worked with French words.

Since the work of Drake (1963), several attempts have been made to relate textural characteristics (especially crispness) to a spectral composition of food sounds that gives indications about sound quality. Sound quality is a complex function of several acoustical parameters (Marks 1974). Pitch is the main sound quality and is defined by the frequency of pure tones or by the frequency range with the highest energy level for complex tones. Density and tonal volume are two other sound qualities of pure tones. Complex tones present other dimensions, such as total consonance, vocality (for speech voice) or musical timbre. Musical timbre, for instance, is related to transients, i.e., the nonstationary part of a musical sound at its start. Spectral characteristics give information about perceived sound quality and especially pitch but do not completely describe it.

Andersson *et al.* (1973), Drake and Halldin (1974) and Seymour and Hamann (1988) studied sounds generated by foods fractured by a mechanical apparatus. Their methods allowed them to control fracture parameters such as deformation speed, applied force or geometry of the deformation probe, but the generated sounds are different from eating sounds and perhaps do not contain the relevant information for texture judgment. Other studies integrated individual variability of sounds generated during the eating process, but only a part of vibrations that generate auditory sensations were analysed: airborne sounds (Vickers and Bourne 1976; Lee *et al.* 1988) or bone conducted vibrations (Drake 1965; Kapur 1971).

Texture is usually judged on a quantitative basis, i.e., subjects are asked to judge crispness intensity of foods (from not crispy to very crispy); then, one looks for physical characteristics of foods that vary according to their crispness intensity. Typically, tested foods are of one type: Swedish bread (Andersson *et al.* 1973), potato and tortilla chips (Lee *et al.* 1988) or one product at several a_w levels (Seymour and Hamann 1988). Our approach was different: texture was judged on a qualitative basis, i.e., subjects were asked whether tested foods matched their crispness (crunchiness or crackiness) concept. Then, we looked for spectral characteristics of biting sounds that subjects used to decide whether one food was crispy, crunchy or crackly. Subjects judged texture both when they actually ate foods and when they only listened to reconstructed sounds so we could estimate how much information was lost when sensations other than auditory sensations were removed. Then, both air and bone conducted sounds were analysed by a fast Fourier transform (FFT) signal analyser that calculated the spectral power density of biting sounds.

MATERIALS AND METHODS

Food Products

For this study, 8 food products were selected according to three criteria: they had (1) to generate a sound when eating, (2) to be easily cut into standard size and shape, (3) to present an uniform texture (without filling, for instance). The characteristics of the selected foods are given in Table 1.

Sound Recording and Reconstruction

Six subjects (6 females) made five bites for each eight foods in a soundproof room. Air and bone conducted sounds were recorded simultaneously on the two tracks of a stereophonic tape with a digital recorder Sony DTC-55ES. An AKG microphone type C414EB (frequency band 20–20,000 Hz) held at about 5 cm in front of the ear canal opening recorded air-conducted sounds and an AKG contact microphone type C401B (frequency band 10–10,000 Hz) pressed firmly against the mastoid bone, behind the ear pavilion, recorded bone conducted sounds (Fig. 1).

Subjects reconstructed biting sounds by mixing their own tape recordings of air and bone conduction in order to reproduce as closely as possible sounds they actually heard when they ate foods. Experimental conditions are described elsewhere (Dacremont *et al.* 1991).

TABLE 1.
FOOD CHARACTERISTICS

Food products (trade name)	sample size width (w) and thickness (t) or diameter (Ø)	characteristics
almond	Ø 7 to 9 mm	roasted
Bricelet (Kambly)	w=24∓1 mm ; t=4∓0.5 mm	dry biscuit
carrot	cylinder Ø16∓0.5 mm	raw
Cracotte (Diépal)	w=30∓2 mm ; t=7.5∓0.5 mm	extruded bread
Feuilleté (Belin)	w=21∓0.5 mm ; t=11∓0.5 mm	flaky pastry
Katimini (L'Alsacienne)	w=27∓1 mm ; t=6∓1 mm	flaky pastry
Langue de chat (L'Alsacienne)	w=29∓0.5 mm ; t=6∓0.2 mm	dry biscuit
Spéculoos (Verkade)	w=18∓1 mm ; t=6.4∓0.1 mm	dry biscuit

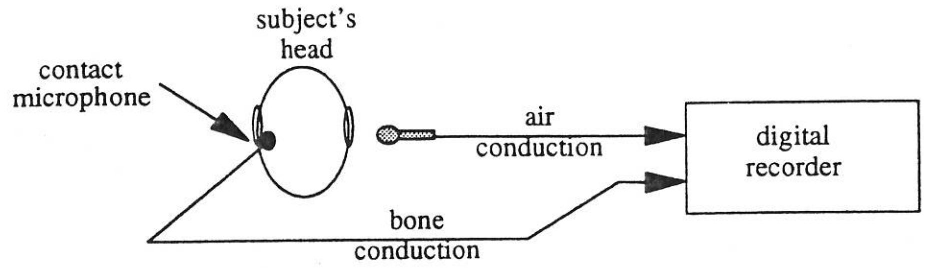


FIG. 1. BITING SOUND RECORDING

Texture Judgment

There were 60 subjects (40 females and 20 males), all students at the University, taking part in this test. None of them wore a denture or had audition disorder. Texture judgments were made by eating food samples or listening to tape recordings of reconstructed biting sounds. Half the subjects tested the food samples first and the others judged the tape recordings first.

To test actual foods, the subjects were blindfolded and were given food samples with a sugar tong, in order to eliminate visual and tactile clues. They tested 23 foods in a random order but only results from the 8 foods of Table 1 are reported here. Half the subjects bit the foods only with incisors and the others bit and chewed. For reconstructed sounds, subjects were also blindfolded. They were informed that sounds they heard were generated by someone biting into food samples. Subjects tested 96 reconstructed sounds (2 bites $\times$ 8 food products $\times$ 6 subjects). For both experiments, subjects had to say whether the food was crispy, crunchy or crackly. They had to pick only one of the three descriptors, but they could also reply that none of the three descriptors was appropriate. No indication was given about the meaning of the three descriptors.

For each food product, citation fractions for the four possible responses were calculated as follow:

$$F_{crisp} = \frac{N_{crisp}}{N_t - N_{none}} \quad F_{crunch} = \frac{N_{crunch}}{N_t - N_{none}} \quad F_{crackle} = \frac{N_{crackle}}{N_t - N_{none}} \quad F_{none} = \frac{N_{none}}{N_t}$$

with N_{crisp}: number of responses "crispy", N_{crunch}: number of responses "crunchy", $N_{crackle}$: number of responses "crackly", N_{none}: number of responses "none of the three descriptors is appropriate", N_t: total number of responses (60 for foods evaluation and 720 for tape recordings evaluation).

Frequency Analysis

Signal Analyzer. A Hewlett Packard type 35660A fast Fourier transform (FFT) real-time analyzer was used. Frequencies from 64 to 12 864 Hz were analysed. Frequencies are audible up to 20 kHz but, for airborne sounds (1) frequencies higher than 14 kHz could not discriminate sounds generated by foods with dif-

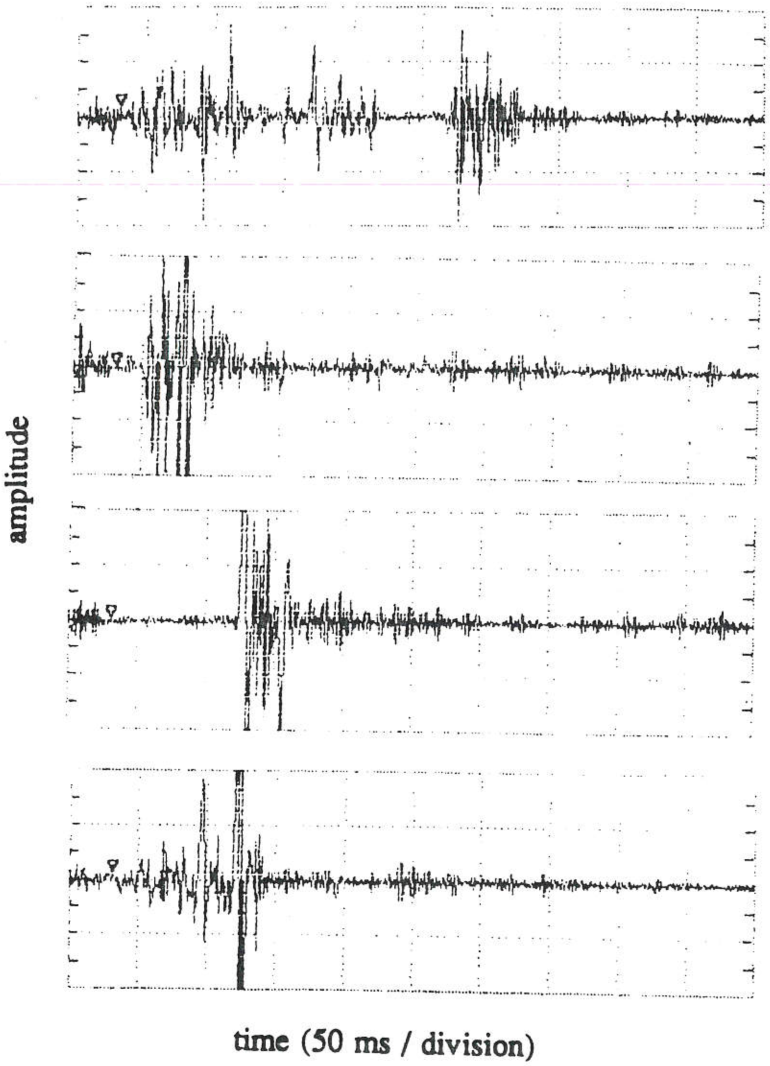


FIG. 2. WAVEFORMS OF BITING SOUNDS GENERATED BY ONE SUBJECT FOR (1) *CRACOTTE*, (2) *LANGUE DE CHAT*, (3) ALMOND AND (4) CARROT

ferent crispness levels (Lee *et al.* 1988); (2) level of those frequencies (14–20 kHz) was at least 30 dB lower than level of the 1 kHz frequency and (3) those frequencies have a low contribution to the auditory sensation because the perception threshold increases dramatically in this frequency range. Therefore, we could reasonably assume that frequency range 13–20 kHz brought negligible information.

Power Spectral Density. The signal analyzer computed FFT over 1024 samples, which were sampled over a 31.2 ms signal duration because of the chosen sample rate. Waveforms of biting sounds (some examples are given Fig. 2) showed that sound duration was longer than 31.2 ms. So, signals were cut into 31.2 ms signal segments, and the power spectral density of each segment was computed separately and then they were averaged together.

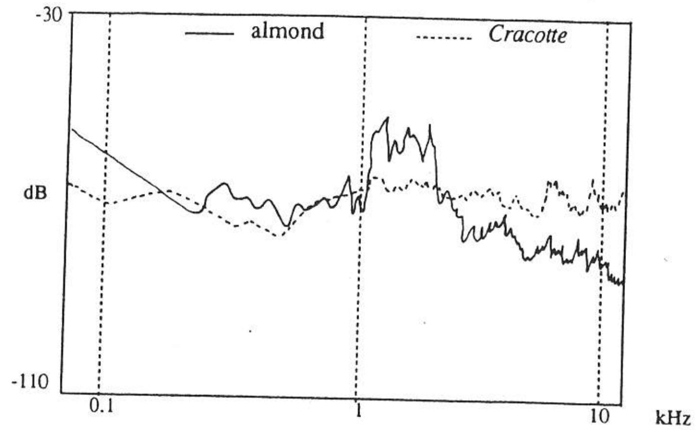
Eating sounds are complex tones, closer to white noise (broad-range spectrum with all frequencies at the same amplitude) than to musical tone (discontinuous spectrum with few well identified frequencies). The pitch of such sounds is governed by frequency ranges that have the highest spectral density level. So, we found it more appropriate to divide spectra into several bands rather than look for very specific frequencies. Spectra were divided into third octave intervals because octave partition is a logarithmic scale that imitates human ear response in regard to pitch; for frequencies higher than 500 Hz, pitch varies with frequency logarithm and third octave intervals approximately match critical ranges (Zwicker and Feldtkeller 1981). It means that, in a complex tone, two frequencies belonging to the same third octave interval are not perceived as different in pitch.

The level of third octave intervals was visually evaluated with reference to the graphic spectra. One of each food eaten by each subject was characterized by levels of 45 third octave intervals, 23 from the air conduction spectrum and 22 from the bone conduction spectrum (the third octave interval 10 to 12.5 kHz was not measured because the contact microphone did not record frequencies higher than 10 kHz). Spectra examples are given Fig. 3.

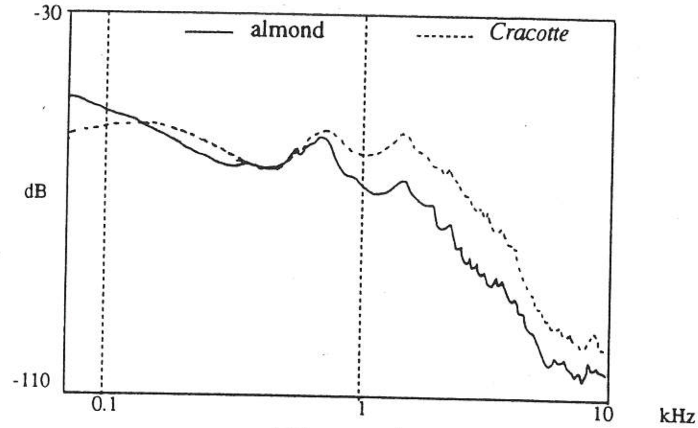
RESULTS

Texture Judgments

Texture judgments (i.e., citation fractions) for actually eaten foods and for reconstructed sounds from tape recordings are shown in Fig. 4. Each triangle vertex stands for one descriptor: crispy, crackly and crunchy. Foods are plotted according to citation fractions of the three descriptors. The more often the descriptor was quoted, the closer to the vertex the food was plotted. When texture judgments were made by eating foods, citation fraction of "none of the descrip-



a) air conduction



b) bone conduction

FIG. 3. SPECTRA EXAMPLES: AIR AND BONE CONDUCTED SOUNDS GENERATED BY ALMOND AND *CRACOTTE*

tors is appropriate'' was below 5% for each food. But when texture is judged from reconstructed sounds, citation fraction of ''none of the descriptors is appropriate'' increased, especially for almond (from 5 to 22%), carrot (2 to 11%) and *Bricelet* (3 to 10%). These foods were judged crunchy or both crackly and crunchy when actual foods were tested. They also had the shortest biting sound duration (less than 100 ms). When texture judgments were made from tape recordings, discrimination between crackliness and crunchiness seemed to disappear. Carrot was judged crunchy and *Langue de chat* and *Spéculoos* crackly when foods were eaten, but they were judged both crackly and crunchy when reconstructed sounds were tested. More crispy when eaten was also found for crispy foods but to a lesser extent.

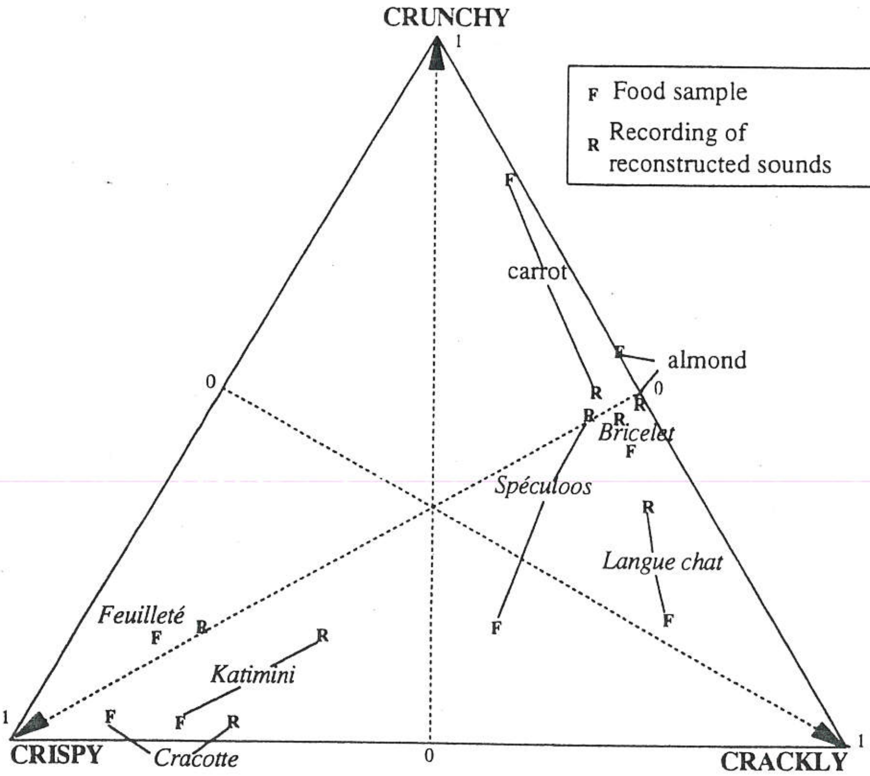


FIG. 4. TEXTURE JUDGMENTS PERFORMED WITH FOODS SAMPLES AND RECORDINGS OF RECONSTRUCTED BITING SOUNDS
Foods are plotted according to citation fractions of the three descriptors: crispy, crackly and crunchy.

Frequency Analysis

This analysis was conducted in three steps. First, we studied individual differences. Differences between sounds generated by different subjects eating the same food product were expected because spectral characteristics may be affected by resonance of the oral cavity (related to its shape) and by the force-deformation pattern applied by the incisors. Both vary from one subject to another. So, we had to make sure that differences between foods were larger than differences between subjects.

Principal component analysis was performed on a matrix 48 rows (8 foods × 6 subjects) and 45 columns (levels of third octave intervals from air and bone conduction) and was run from the covariance matrix. The first three principal components accounted for 77.8% (50.4%, 15.8% and 11.6%, respectively) of the variability in the data and the fourth principal component less than 5%. The first principal component was positively correlated with the global spectral density (that corresponds to amount of sound) of bone conduction and the frequency range 250 to 1250 Hz of air conduction. Samples are separated along the second principal component according to their levels of very low and high frequencies (especially for air conduction) and along the third principal component according to their levels of air and bone conduction.

A cluster analysis was performed with food coordinates in the derived sample space and food sounds were divided into six clusters (Table 2). For four foods out of nine, sounds generated by five subjects were grouped together, and for three other foods, sounds generated by four subjects were grouped together. Differences between foods seemed larger than individual differences and so, sound characteristics due to food products could be found independently from subjects that generated sounds. Cluster analysis also showed that *Katimini* spectrum from one subject (identified as subject AN), was probably an outlier. Comparison of spectra from this subject and the others shown that spectral density level for this subject was about 10 dB higher than for the others. No similar event was found for the other foods. The extreme value for *Katimini* eating by subject AN seems to be due to an error during signal analysis and these data were discarded for subsequent analyses.

In a second step, individual differences were eliminated by averaging spectral density over subjects and a further principal component analysis was performed. The analyzed matrix still had 45 columns (levels of third octave intervals for spectra from both conductions) but only 8 rows (the 8 tested foods). The first three prin-

TABLE 2.
CLUSTER ANALYSIS PERFORMED WITH COORDINATES OF FOODS ON THE SAMPLE SPACE GENERATED BY PRINCIPAL COMPONENT ANALYSIS: COMPOSITION OF THE 6 RESULTING CLUSTERS

cluster #	1	2	3	4	5	6
almond	5			1		
Bricelet		3		3		
carrot	4			2		
Cracotte	1				5	
Feuilleté				5	1	
Katimini				4	1	1
Langue chat			4	2		
Spéculoos		1		5		

The composition of clusters is given by the number, for each food, of biting sounds generated by different subjects that were grouped together (for example, cluster 1 grouped 5 people's almond sounds, 4 people's carrot sounds and 1 *Cracotte* sound).

cipal components accounted for 95.3% (50.3%, 26.1% and 18.9%, respectively) of the variability and the fourth principal component less than 2%. Attribute loading plots (Fig. 5) are very similar to those of the previous principal component analysis. The first principal component corresponds to the overall level of bone conduction and frequency range 125–1,250 Hz of air conduction. The second principal component is still explained by an opposition between high frequencies (2.5–12.5 kHz for air conduction and 1–10 kHz for bone conduction) and very low frequencies (60–125 Hz for air conduction and 60–80 Hz for bone conduction). The third principal component is positively correlated to medium and high frequencies from air conduction, 1.25–2 kHz (also negatively correlated to the second principal component) and 2–10 kHz (also positively correlated to the second principal component).

In a third step, we tried to describe food texture judgment by spectral characteristics of eating sounds. Multilinear regressions were performed between citation fractions for the three descriptors and coordinates of foods in the space generated by principal component analysis, using a vectorial model:

$$F_{crispy} = a_1X_1 + a_2X_2 + a_3X_3$$

where F_{crispy} is the citation fraction for crispy and X_1, X_2 and X_3 the coordinates of food sounds on the first, second and third principal component, respectively. The same model was used with citation fractions for crackly and crunchy. Vectors show directions in which crispness, crackliness or crunchiness are increasing and their length is proportional to the regression coefficient. Their projections are represented by arrows on the food space (Fig. 6). Sounds generated by crispy foods are high pitched (especially the air conduction). They have a low level of bone conduction, which emphasizes perception of high pitch. Sounds generated by crunchy foods are low pitched and have an intermediate level of bone conduction. They show a characteristic spectral density peak at the frequency range 1.25–2 kHz for air conduction. Sounds generated by crackly foods are also low pitched but have an higher level of bone conduction and very low frequencies.

As an example, spectrum from *Cracotte* (Fig. 3), judged crispy, shows a high level of high frequencies for both air and bone conduction. Air conduction spectrum from almond shows a characteristic peak on frequency range 1–2 kHz and a high level of low frequencies.

DISCUSSION

Our results support the conclusions of Vickers (1984b, 1985): foods referred to as crispy in our work generate biting sounds higher in pitch than crunchy foods.

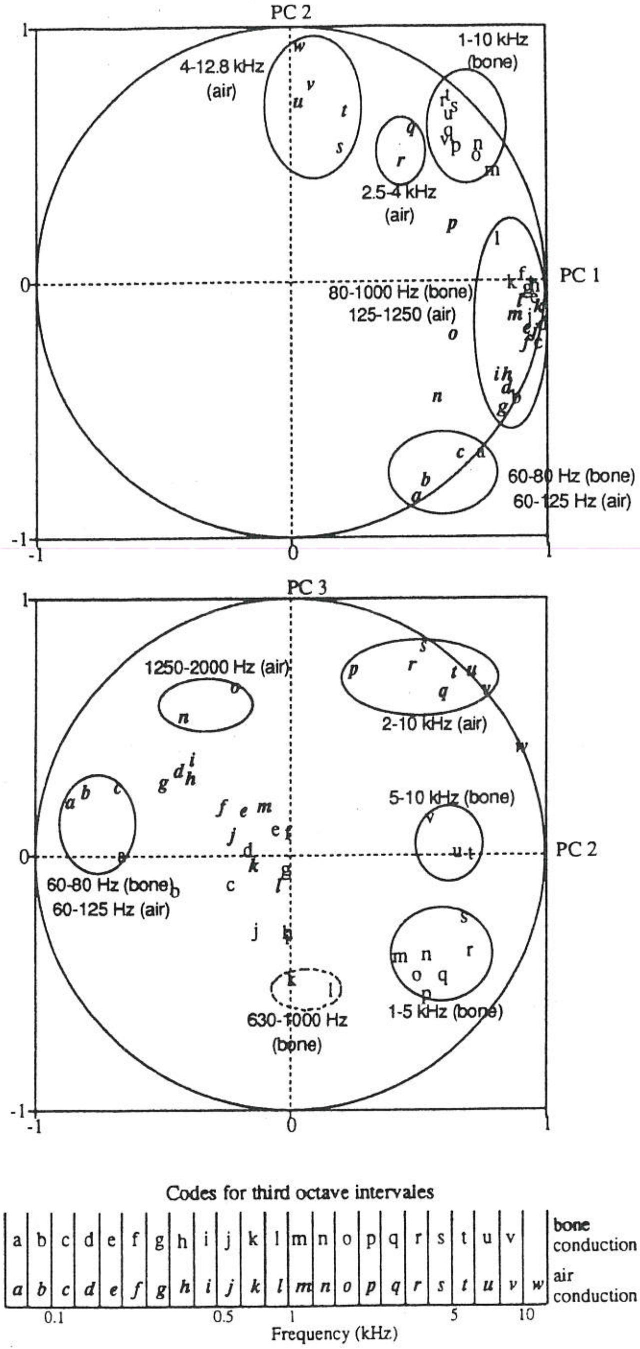
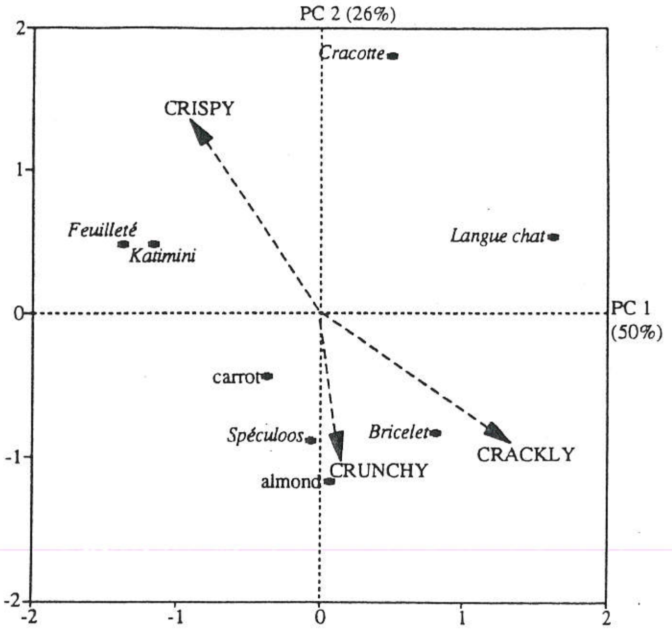


FIG. 5. ATTRIBUTE SPACE DERIVED FROM PRINCIPAL COMPONENT ANALYSIS OF SPECTRAL DENSITY OF BITING SOUNDS

Third octave intervals are coded by light upright characters for bone conduction and bold italic characters for air conduction. Elipses include consecutive third octave intervals closed together in the space. Labels are the corresponding frequency range. (PC: principal component).



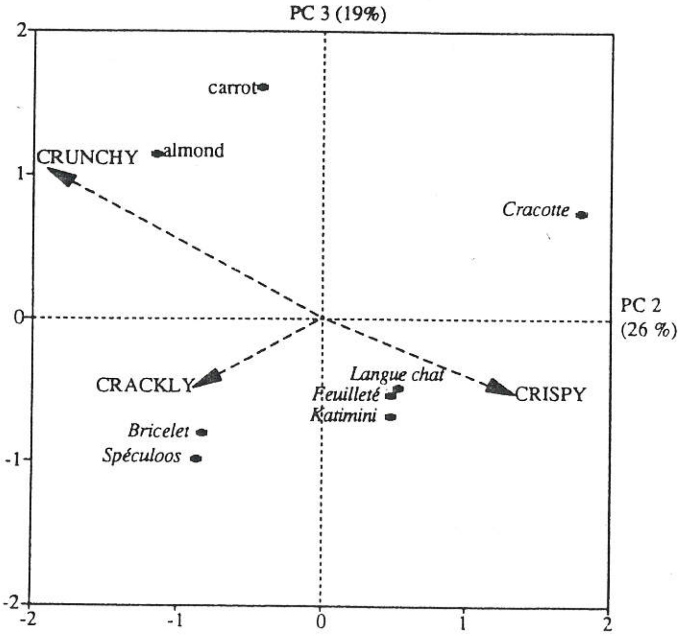


FIG. 6. SAMPLE SPACE DERIVED FROM PRINCIPAL COMPONENT ANALYSIS OF SPECTRAL DENSITY OF BITING SOUNDS

Arrows are vector projections showing correlation between texture judgments and spectral composition of biting sounds. Vector direction is the direction in which crispy, crunchy or crackly attribute increases and vector length is proportional to the correlation coefficient. (PC: principal component).

Table 3 recapitulates results from four studies (including this one) dealing with frequency analysis of sounds generated by crispy foods. Seymour and Hamann (1988) and Lee *et al.* (1988) compared food sounds and crispness intensity, while Gouilleux (1990) tested *Cracotte* and did not study correlation with texture judgments. Even if the methodologies are very different, some interesting coincidences are noticeable.

(1) We found that sounds generated by crispy foods have an high level of frequencies, 5–12.8 kHz; Lee *et al.* (1988) and Gouilleux (1990) also found characteristic frequencies around 6 kHz and 8.5–9 kHz respectively.

(2) The three mentioned studies showed characteristic frequencies around 3 kHz. We found that the frequency range 2–5 kHz (principal component 3) was not really specific for crispy foods but separated *Cracotte* from *Feuilleté* and *Katimini*. Spectral density of this frequency range might vary according to crispness intensity; this is supported by the results from another study, not reported here. In that study, nine subjects were trained to perform a quantitative descriptive analysis of food texture and crispness was one of the rated descriptors. *Feuilleté* and *Katimini* were judged very similar and *Cracotte* was significantly crispier.

Seymour and Hamann (1988) studied correlations between crispness intensity and sound quality (and other physical parameters) for one product at several a_w levels and found that the frequency range 1.9–3.3 kHz was better correlated to crispness judgments than the frequency range 0.5–1.9 kHz. But they defined sensory crispness as the "degree of high pitched noise perceived when biting through sample." It is not really surprising that crispness was correlated with frequency range 1.9–3.3 kHz, the highest analysed frequencies.

Sounds generated by foods referred as crunchy were low pitched as found by Vickers (1984b, 1985). For commercial chocolate, Gouilleux (1990) found characteristic frequencies at the following values: 2.8–3 kHz, 5.3–5.5 kHz and 9.5–9.6 kHz. This did not coincide with the specific frequency range 1.25–2 kHz of air conduction that we found or with a low pitched sound. Brochetti *et al.* (1992) found that a "formant trends to occur within the frequency range of 1–2 kHz for all foods and all subjects." This is not contradictory with our results; the amplitude of that frequency range might be higher for almond and carrot than for the other foods.

Sound is only a part of the perceived sensations that allow subjects to make their texture judgment. Crunchiness and crackliness are not very well separated when judgments are made on the basis of sound only. We found that sounds generated by crackly foods are low pitched with a high level of bone conduction. Yet, vibrations and especially low frequencies, being propagated through bones and other tissues also generate vibrotactile sensations that are lost when texture is judged by sound only. Vickers (1984a) concluded that "either oral or auditory stimuli can be used to make crackliness judgments." We hypothetise that bone

TABLE 3.

CHARACTERISTIC SPECTRAL COMPOSITION OF EATING SOUNDS GENERATED BY CRISPY FOODS

references		Seymour and Hamann (1988)	Lee *et al.* (1988)	Gouilleux (1990)	this study	
methodology	analysed frequency range (kHz)	0.5 - 3.3	0 - 20	0.02 - 20	0.06 - 12.8	
	fracture method	instrumental	eating	instrumental	eating	
	tested food	one food at several A_w levels	potato chips	*Cracotte*	crispy foods	*Cracotte*
characteristic frequency ranges (kHz) for crispy foods		1.9 - 3.3	3 - 4 6	2.5 - 3 8.5 - 9 13.5 - 14	5 - 12.8	2.5 - 5 5 - 12.8

conduction that generated both auditory and vibrotactile sensations allow subjects to discriminate between crunchy and crackly foods, both generating low pitched biting sounds.

Texture judgment was designed to classify food products into three classes that the French call crispness, crunchiness and crackliness. Subjects tested foods once only because responses had to be spontaneous. Therefore, we obtained group results but no indications about individual differences. For those foods that were judged both crispy and crackly (or both crackly and crunchy), we do not know whether they actually exhibited both characteristics at the same time or were definitely judged crackly for some subjects and definitely crispy (or crunchy) for others.

Vickers (1988a) reviewed the literature dealing with correlations between instrumental parameters and sensory crispness and found that the best correlations with sensory crispness were obtained with one acoustical parameter and one mechanical parameter together. Stimuli other than auditory stimuli are involved in crispness judgment (Vickers 1987, 1988b) and crackliness judgment (Vickers 1984a). So, acoustic analysis might never be sufficient to predict perceived crispness (crackliness/crunchiness). However, acoustic analysis could be improved in order to obtain more accurate parameters from eating sounds. First, bone conduction has to be analysed along with air conduction and their respective contributions to the auditory sensations should be considered. Dacremont *et al.* (1991) showed that contribution of both conduction ways depends on eating technique and tested foods. Furthermore, FFT was designed to process stationary signals, i.e., signals where the spectral characteristics are time independent. Eating sounds are very likely to be nonstationary signals. This is supported by the work on time representation of eating sounds by Edmister and Vickers (1985) and Vickers (1984a, 1987, 1988a). The implementation of time-frequency processing methods, such as spectrographic analysis, wavelet representation or Wigner-Ville transform, should improve the accuracy of the reuslts. Those analytical methods are already applied to various fields of acoustics (speech analysis, bioacoustics, propagation) and spectrographic analysis was already used to process eating sounds (Drake 1965; Vickers and Bourne 1976; Brochetti *et al.* 1992). The main problem with time-frequency representations is that they are usually visually interpreted. An appropriate statistical tool needs to be found in order to obtain the information used for texture judgment among data variability.

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