CONTRIBUTION OF AIR-AND BONE-CONDUCTION TO THE CREATION OF SOUNDS PERCEIVED DURING SENSORY EVALUATION OF FOODS

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ABSTRACT

The noises perceived during sensory evaluation of foods are transmitted to the inner-ear by both air and bone conduction. The contribution of the two conductions was studied for six foods "croquant" (crunchy), "craquant" (crackle) and "croustillant" (crispy), by six panelists. It was studied by reconstituting the attenuation of the air and bone conduction records needed to imitate sound actually heard during sensory evaluation of foods. The eating technique (bite or chew) modified the contribution of air- and bone-conduction to auditory sensation. Differences were shown between foods, but they could not clearly distinguish between the kinds of food. Modifying the attenuation of the air- and bone-conduction records was not enough. The bone-conduction records had to be attenuated over a frequency range around 160 Hz, which is the resonance frequency of the mandible. The air-conduction records had to be attenuated at a frequency range around 160 Hz and amplified at a frequency range around 3,500 Hz in order to match the action of the middle-ear muscles which behave differently when sounds were generated inside or outside the mouth.

INTRODUCTION

Auditory sensations are an important part of the sensory evaluation of food products. Vickers (1980) showed that they contain useful information to identify foods. In French, three textural terms refer to auditory sensations: "croustillant," "craquant" and "croquant" (Mac Leod and Sauvageot 1986). The words "croustillant" and "croquant" can be translated into English as crispness and crunchiness respectively (Drake 1989) and "craquant" as crackliness. This convention will be used in this paper, but it needs some restrictions. In the

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United States, Szczesniak (1988) asked 200 people to give examples of crisp foods. Thirty percent of the answers were Wet-crisp products, and lettuce was the most often cited example. In France, a similar survey (whose results are presented in this paper) showed that neither fruits nor vegetables are considered to be crispy.

Vickers and Bourne (1976) were the first to postulate a psychoacoustical theory of crispness. Vickers showed that auditory sensations are sufficient to evaluate crispness (Vickers 1981; Edmister and Vickers 1985; Vickers 1987), crunchiness (Vickers 1981) and crackliness (Vickers 1983).

Acoustic analysis seems to be a promising way to develop an objective measure of crispness. Two methods can be used to generate the noise for analysis: (1) the food sample is fractured by a mechanical, compressive or snapping test (Drake and Halldin 1974; Mohamed *et al.* 1982; Seymour and Hamann 1988); (2) the food sample is masticated by a person (Edmister and Vickers 1985; Vickers 1987; Lee *et al.* 1988; 1990).

A compression instrument such as the Instron fractures the food under controlled conditions. However, it is preferable to use sensory evaluation when working with masticatory sounds, because this includes changes that occur in the food during mastication, particularly its hydration by saliva. Pangborn and Lundgren (1977) showed that the amount of saliva secreted is related to textural properties of foods. The loudness of the generated sound decreases during mastication (Drake 1963; Lee *et al.* 1988; 1990). Furthermore, the nasal and buccal cavities modify emitted sound quality.

The noise generated in the mouth is transmitted to the inner ear by two routes: (1) through the air, outside the body (air-conduction); and (2) through the skull bones (bone-conduction). These two kinds of conduction both contribute to the auditory sensation. Acoustic analysis of masticatory sounds has been carried out by recording air-conduction (Edmister and Vickers 1985; Vickers 1987; Lee *et al.* 1988) or bone-conduction alone (Kapur 1971). The objective of this study is to determine the relative importance of bone and air-conduction in the perception of eating sounds and the effect of the kind of food, the eating technique and the panelist.

MATERIALS AND METHODS

Food Samples

Food products used for this work had to fit to three requirements:

(1) to have an homogeneous texture, i.e., not to present zones where texture is not the same;

(2) to have regular or easily adjustable dimensions. Vickers (1988) showed that

sample size (thickness and cross sectional area) affected sensory crispness perception;

(3) to have interesting textural characteristics.

The foods used in this study were selected from the results of a survey held at the International Gastronomic Fair of Dijon. About 100 persons were asked to name *croustillant* (crispy), *craquant* (crackly) or *croquant* (crunchy) foods. A factorial correspondence analysis (software Statitcf 8, av. du Pr. Wilson 75116 Paris, France) placed food products and the three textural terms together (Fig. 1).

Although some products, like rusk, are mentioned equally for the three textural terms, there are some clear trends among them. *Croustillant* (crispness) is associated with foods which have a hard crust (French bread, food coated with breadcrumbs or grated cheese) or flaky pastry. Biscuits made from flaky pasty

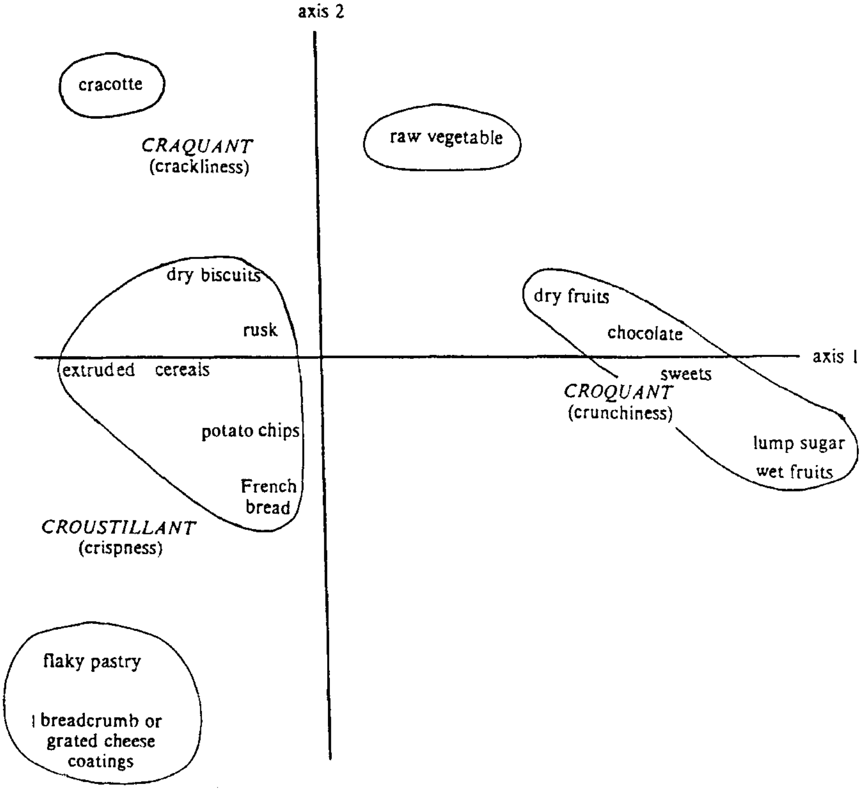

FIG. 1. FACTORIAL CORRESPONDENCE ANALYSIS
Foods and descriptors are plotted with the two principal axes. Groups are constituted with an ascending hierarchical clustering.

(*feuilletè Belin*) and wafers with several fine layers (*èventail d' or St. Michel*) were selected to represent this class. *Croquant* (crunchy) foods are rather hard and/or wet products (fresh or dry fruits, vegetables, sweets). Apple and carrot were used for this class. *Craquant* (crackliness) is more difficult to define because cited foods are also described as crunchy (raw vegetables and sweets) or crispy (dry and extruded biscuits). Hard and compact biscuits (*caprice Lu* and *langue de chat L'alsacienne*) were finally selected to represent this class. The sizes and shapes of the food samples are given in Table 1.

Subjects

Six students (three men and three women) participated in this study. All of them play music or sing which helped them to estimate pitch and loudness of sounds. An auditory test showed that none of them had a loss of hearing acuity between 500 and 10,000 Hz. They were paid for their participation.

TABLE 1.
FOOD SAMPLES CHARACTERISTICS

TEXTURE	NAME	SHAPE	DIMENSIONS (cm)
"croustillant" (crispy)	feuilletés BELIN *	parallelepiped rectangle	thickness 1.04 ± 0.02 width 1.85 ± 0.11 length(1) 2.7 ± 0.2
	wafer èvantail d'or ST MICHEL **	triangle	thickness 0.52 ± 0.06 width(1) 3 ± 0.3
"craquant" (crackly)	caprice LU ***	oval	thickness 0.83 ± 0.02 width 3.51 ± 0.10 length(1)1 2.7 ± 0.2
	langue de chat L'ALSACIENNE ***	oval	thickness 0.64 ± 0.06 width 3.11 ± 0.09 length(1) 3.2 ± 0.2
"croquant" (crunchy)	apple (golden delicious)	cylinder(2)	diameter 1.55 ± 0.02 length 4.68 ± 0.2
	carrot	cylinder(2)	diameter 1.63 ± 0.04 length 1.13 ± 0.1

(1): Food samples dimensions were modified by cutting biscuits with a knife.
(2): Cylinders were obtained with a borer. They were stamped out perpendicular to carrot length and parallel to apple core.
*Belin, BP93 91003 Evry Cedex, France.
**St. Michel, Grellier Sarl, 44730 St. Michel-Chef-Chef, France.
***Lu, L'Alsacienne, 6, rue E. Vaillant 91201 Athis-Mons Cedex, France.

Sound Production

Two eating techniques were used, either a bite (to shear sample with incisors, lips opened) or a chew (to compress sample between molars, lips closed). These two kinds of sounds were recorded separately. The bite sounds of each food were recorded in duplicate, in a random order. Subjects had to bite as normally as possible, across the full width of the biscuit or perpendicular to the cylinder axis of the apple and carrot samples. For the wafer, they had to bite a corner of biscuit. For chew, subjects were required to place a piece of food between their molars on one side of their mouth, to close their lips and to chew six times consecutively. Two sets of six chews were recorded for each food, using the same order as in the bite series.

Records

The experiments were conducted in a sound-proofed recording studio. Bone-conduction was recorded with a microphone Shadow 4001 (frequency band: 80–15000 Hz) pressed firmly against the cheek of the subject, near the maxillar angle, on the eating side. Air-conduction was recorded with a microphone AKG C414EB (frequency band: 20–20,000 Hz) held on the other side of the subject's head. The diaphragm of the microphone was in front of the ear canal opening at 8 cm. Each sound (air- and bone-conduction) was recorded on one of the two tracks of a stereo tape (Ampex Grandmaster 456 1/4″). The tape recorder was a Tascam 32 and tape speed was 32 cm/min.

Reconstitution of Eating Sounds

Each subject recorded his eating sounds and evaluated his own records, i.e., the records of the eating sounds he had produced himself. The panelist had to reconstitute sounds he truly heard during eating. The sounds from the two records (air- and bone-conduction) were mixed together with a mixing console Tascam M520 and reproduced with a headphone Beyer DT 100. The subject listened to his own records of two bites (or two chews) and then ate that food and estimated the differences between this eating sound and the records. From this information, the experimenter changed the mix of the two records until the subject found no difference between the record and the direct evaluation. The foods were available as often as the subject wished.

Two stages were usually needed in the sound mixing procedure:

(1) Modify the output intensity of each channel (air- and bone-conduction records) before they were mixed. The signals from the two records were

separately gained (i.e., modified) in the mixing console before feeding them into the headphone. The gain equation is:

$$\text{Gain} = 20 \log \frac{U_{output}}{U_{input}}$$

with U_{input} mixing console input tension

U_{output} mixing console output tension.

For each record, the gain G is positive in case of an amplification ($U_{output} > U_{input}$) and negative in case of an attenuation ($U_{output} < U_{input}$). On the mixing console, attenuation was controlled by a fader (rectilinear potentiometer).

(2) Equalize the modulation, which consisted of a selective attenuation or amplification of certain frequency ranges of the modulation. We chose the middle of the frequency range, and we modified its gain. This operation was carried out when the first stage was not enough to exactly reconstitute the auditory perception.

Food sounds were evaluated in the same order as they were recorded. Three subjects began with bites and the other began with chews.

RESULTS AND DISCUSSION

The two previously described stages will be discussed successively.

Gains

The contributions of bone- and air-conduction to the perceived sound is obtained by reconstituting the gains of the bone and air records. The relationship between gain and signal is:

- bone-conduction: $G_{bone} = 20 \log \frac{U_{bone.Output}}{U_{bone.Input}}$
- air-conduction: $G_{air} = 20 \log \frac{U_{air.Output}}{U_{air.Input}}$

with:

G_{bone} and G_{air}: bone- and air-conduction record gains (dB)

$U_{bone.Output}$ and $U_{air.Output}$: mixing console output tensions (V)

$U_{bone.Input}$ and $U_{air.Input}$: mixing console input tensions (V)

The mix of the two sources furnished to the panelist is the algebraic sum of the bone signal plus the air signal. The global gain (G_t) is:

$$G_t = 20 \log \frac{(U_{bone.Output} + U_{air.Output})}{(U_{bone.Input} + U_{air.Input})}$$

An algebraic sum, or mean, of bone and air-conduction gains G_{bone} and G_{air} has no significance and cannot estimate the mix gain G_t. Therefore, the variance analyses of air-conduction and bone-conduction gains must be performed separately.

As the measured air and bone-conduction gains were negative, we will use the word attenuation instead of gain, with the convention: Attenuation = |Gain|. The greater the attenuation, the more the recorded sound is estimated loud in comparison with sound actually heard when eating. And, the more a source is attenuated in comparison with the other source, the less important is its contribution to global sensation. Therefore, an analysis with attenuation differences between the two kinds of conduction yields some useful insights.

Eating Technique (Fig. 2). The difference between bite and chew is highly significant ($P < 0.001$) for both routes of conduction. For bone-conduction, bite is less attenuated than chew, and for air-conduction bite is more attenuated than chew. Furthermore, the difference between bone- and air-conduction is significantly lower ($P < 0.0001$) for bite (2 dB) than for chew (15.8 dB). The small difference for bite shows that bone and air-conduction have a similar importance. For chew, bone-conduction being much more attenuated than air-conduction, air-conduction contributes significantly to global sensation.

Vickers (1984) showed that changing eating technique from bite to chew depressed crispness judgment. It may be partially explained by the difference in contribution of air- and bone-conduction to bite and chew sounds.

Food Products. Group scores analysis show no significant differences between foods. There are no interactions between the food factor and the two other parameters (eating technique and subject).

In order to sharpen the analysis, bite measurements were repeated three times by one subject. The results are shown in Table 2. The distinction between the three textural characteristics (*croquant, craquant* and *croustillant*) is not obvious. For the two crackly biscuits (*langue de chat* and *caprice*) the attenuation data are similar. For the other descriptors, the attenuation margins between two products with the same textural characteristic (apple and carrot: *croquant*; *wafer* and *feuilleté*: *croustillant*) are greater (11 and 8 dB, respectively, for bone-conduction) but still not significant. Air-conduction is always attenuated in the same proportion for all foods. The restitution of air-conduction records maintains the ratio of sound intensity between goods. The contribution of bone-

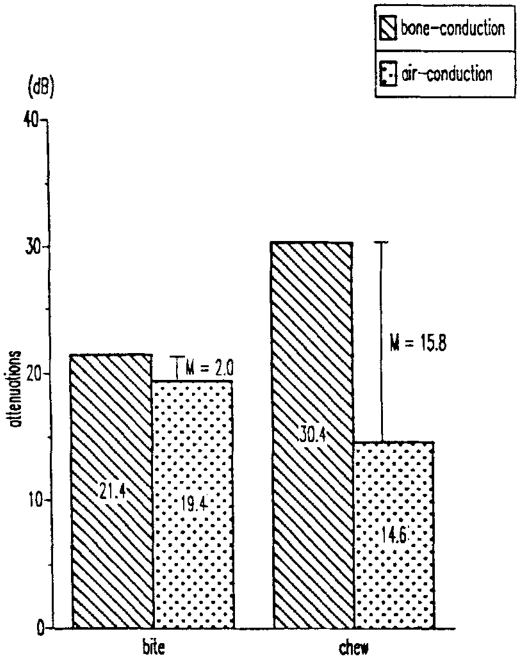

FIG. 2. ATTENUATION MEANS OF BONE AND AIR-CONDUCTION RECORDS
M = Attenuation margins between bone and air-conduction
(attenuation = |gain| when gain < 0)

conduction is more variable. For example, the attenuation of bone-conduction record is smaller for carrot than for wafer. So the contribution of bone-conduction to global food sound is more important for carrot than for wafer. Analysis of attenuation margins between bone and air conduction shows a very significant difference between carrot and three biscuits (*wafer, caprice* and *langue de chat*). This may be due to a difference between dry and wet food products, although there is no significant difference between *feuilleté* and apple. Bite sounds of wet foods may be constituted in large part of bone-conduction.

Sex Effect. Food products analysis showed no significant difference between foods for the six subjects. This permitted a new variance analysis, where the food factor was ignored, therefore, to find other sex-related variations. The results (Table 3) show that the differences between bone and air-conduction attenuations are lower for women than for men for bite and chew. For bone-conduction records are globally less attenuated with women (about 20 dB) than with men (about 32 dB).

TABLE 2.
ATTENUATION DATA MEANS FOR THREE REPETITIONS OF BITES FOR ONE SUBJECT

Foods		Bone conduction	Air conduction	Bone - Air conduction
wafer	*crispy*	36.0 ^{a} *(1.7)*	22.3 ^{a} *(3.8)*	13.6 ^{a} *(3.1)*
caprice	*crackly*	32.3 ^{ab} *(6.0)*	22.3 ^{a} *(2.1)*	10.0 ^{a} *(4.6)*
langue chat	*crackly*	32.0 ^{ab} *(7.0)*	23.0 ^{a} *(1.7)*	9.0 ^{a} *(7.8)*
feuilletes	*crispy*	28.3 ^{ab} *(5.1)*	25.0 ^{a} *(5.1)*	3.3 ^{ab} *(5.5)*
apple	*crunchy*	29.0 ^{ab} *(6.6)*	26.3 ^{a} *(3.5)*	2.7 ^{ab} *(10.1)*
carrot	*crunchy*	18.3 ^{b} *(6.6)*	26.3 ^{a} *(5.5)*	−8.0 ^{b} *(2.6)*

Attenuation = |gain| when gain < 0, *in brackets = standard deviation*
(for each type of conduction, means indexed with the same letter are not significantly different at P = 0.01).

The differences in bone-conduction records attenuation between men and women cannot be a real difference in the eating sounds, but it may be due to the recording technique. Bone-conduction is picked up by a microphone held on the subject's cheek level with the jawbone. This bone is generally less prominent in women than in men because of the thicker covering of skin and fatty tissue in women. The skin of women may cause greater attenuation of the sound waves before they reach the microphone than the skin of men. Women's records should be played back with less attenuation than men to compensate for this difference.

Equalization

Each subject used equalization to a different extent, ranging from 1 to 11 equalized evaluations over 12 evaluations. Bone-conduction records were equalized over a frequency range around 160 Hz. This frequency was selected on the basis of two earlier reports. Franke *et al.* (1952) showed that low frequency threshold (about 200 Hz) was about 2 dB lower with the closed mouth than with the open mouth. This may be explained by jaw vibrations. Kapur (1971) showed that the mandible has an effective resonance frequency of about 160 Hz. During eating, the signal recorded at the level of the mastoid bone, which surrounds the ear and transmits vibrations to it, is much more attenuated at this frequency range than the signal recorded at the bottom of the mandible

TABLE 3.
ATTENUATION DATA MEANS BY SEX

eating technique	kind of conduction	Women	Men
Bite	bone	15.6 ^{a} *(7.2)*	27.2 ^{b} *(10.7)*
	air	23.6 ^{a} *(5.2)*	15.2 ^{b} *(5.1)*
	margin bone - air	−8.0 ^{a} *(6.9)*	12.0 ^{b} *(14.3)*
Chew	bone	24.4 ^{a} *(11.1)*	36.3 ^{b} *(5.7)*
	air	13.8 ^{a} *(5.4)*	15.4 ^{a} *(4.4)*
	margin bone - air	10.6 ^{a} *(12.1)*	20.3 ^{a} *(5.0)*
Bite plus Chew	bone	20.0 ^{a} *(10.2)*	31.7 ^{b} *(9.6)*
	air	18.7 ^{a} *(7.2)*	15.3 ^{a} *(4.7)*
	margin bone - air	1.2 ^{a} *(13.7)*	16.2 ^{b} *(11.6)*

Attenuation = $|\text{gain}|$ when gain < 0, for bite or chew $n = 18$, for bite plus chew $n = 36$, *in brackets: standard deviation* (for each eating technique and each kind of conduction, means indexed with the same letter are not significantly different at $P = 0.01$).

angle. Frequencies around 160 Hz are recorded in excess compared with vibrations actually reaching the ear. Therefore, the playback of these records have to be attenuated over this frequency range.

Air-conduction records were also equalized. The subjects required attenuation at low frequencies and amplification at medium to high frequencies. The two frequency ranges equalized are around 160 Hz and 3,500 Hz. This may be caused by the activity of the middle-ear muscles. Their contraction reduces tympanic membrane-ossicular chain mobility and hence the amplitude of the soundwaves transmitted to the inner-ear. This attenuates sound frequencies below 2,000 Hz. Reflex activity of intraaural muscles may be activated by different phenomena:

(1) exposure to intense sounds, upper than 80 dB SPL (Chiveralls and Fitzsimons 1973);
(2) self-stimulating activities, such as talking or eating, from the lowest sound level produced (Borg *et al.* 1984);
(3) facial muscular activity (grimacing, smiling, voluntary head movements) or perorbital muscular activity (blink upper eyelid) (Djupesland 1964).

Eating involves facial muscular activity and produces noise in the mouth, especially with food products used in this work. The middle-ear muscle reflex activity that occurs during mastication is perceived during sensory evaluation. However, during playback of the records, this reflex is not activated because the reproduced sound level does not reach 80 dB SPL. Hence, the record seems to be too low pitched. There is a need to attenuate a specific frequency range around 160 Hz. But this is not enough, because the middle-ear muscle activity causes an attenuation of frequencies below 2,000 Hz, and this frequency range is not completely equalized. To compensate for this, the gain is increased over higher frequencies in order to minimize the masking effect caused by low frequencies. Amplification was applied on a frequency range around 3,500 Hz.

The results are presented in two ways:

(1) Table 4 gives values of equalisation (i.e., added gains over some frequency range);
(2) Table 5 gives global gain over the frequency range: record gain plus added equalization. This does account for sensory modifications of the record. The equalization result depends on both gain of the record and gain of the equalisation.

Bone-Conduction. Added attentuations at 160 Hz to bites and chews records are not significantly different. The difference of global gain is only due to differences in source gain.

Air-Conduction. The chews are more equalized than the bites. At 160 Hz there is no significant difference between global attenuation of bites and chews. At 3,500 Hz, amplification added to the bites is smaller than to the chews.

The high-frequency content of air-conduction records of chew sounds is low because sounds were muffled by the cheek before they were recorded. High frequencies are largely masked by low frequencies. The attenuation of low frequencies by the middle-ear muscle action during eating favours hearing of the

TABLE 4.
MEANS OF EQUALIZATIONS IN dB

	bone-conduction	air-conduction	
	160 Hz	160 Hz	3 500 Hz
Bite	− 2.0 ^{a} *(5.1)*	− 0.7 ^{a} *(2.9)*	+ 1.2 ^{a} *(2.7)*
Chew	− 3.6 ^{a} *(6.4)*	− 3.4 ^{b} *(5.7)*	+ 4.0 ^{b} *(4.0):*

n = 36, *in brackets* = *standard deviation* (for each frequency, means indexed with the same letter are not significantly different at P = 0.01).

TABLE 5.
MEANS OF GLOBAL GAIN + RECORD GAIN + ADDED EQUALIZATION IN dB

	bone-conduction	air-conduction	
	160 Hz	160 Hz	3 500 Hz
Bite	− 23.4 ^{a} *(11.5)*	− 20.1 ^{a} *(6.6)*	− 18.2 ^{a} *(8.1)*
Chew	− 33.9 ^{b} *(12.9)*	− 18.0 ^{a} *(8.4)*	− 10.6 ^{b} *(5.3)*

n = 36, *in brackets* = *standard deviation* (for each frequency, means indexed with the same letter are not significantly different P = 0.01).

high-frequency components. This does not occur during playback of the records. The equalizations attempt to imitate this process. The bite records are lightly equalized because the bite sounds have a higher high-frequency content than the chew sounds, and they are less sensitive to masking.

CONCLUSION

The air and bone-conduction components of the sound that is heard during direct evaluation of food strongly depends on the acoustic surrounding. Sound propagation in air is different between a bite (with incisors, lips open) and a chew (with molars, lips closed). The contact area between the food and the teeth is not identical, and the amount of vibration through the bones is different. Differences are observed among panelists because their dentition, shape and dimension of buccal and nasal cavities are different. Although the composition of bite sounds differs from food to food, it does not clearly distinguish between *croustillant* (crispy), *craquant* (crackly) or *croquant* (crunchy).

Mixing is needed to equalize records, particularly air-conduction records, where the low-frequencies (160 Hz) are attenuated and the high-frequencies (3,500 Hz) are amplified.

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