Effects of the sound of the bite on apple perceived crispness and hardness

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Abstract

The effects of the manipulation of the sound produced while biting into apple samples, a non-dry food, was investigated. In Experiment 1, participants rated the perceived crispness of flesh cylinders obtained from three apple cultivars differing in their texture profile: ‘Renetta’ (white ‘Renetta Canada’), ‘Golden’ (‘Golden Delicious’), and ‘Fuji’. Participants might hear the veridical sounds they made when biting into an apple cylinder without any frequency adjustment (0 dB filter) or with high frequencies attenuated (either by –12 dB or by –24 dB). Perceived crispness was significantly lower when any of the reductions were applied than when no filter (0 dB) was used. In Experiment 2, new participants rated both crispness and hardness of ‘Renetta’ and ‘Fuji’ cylinders. The sound of the bite could be unfiltered (0 dB), reduced in its high frequencies (–24 dB), or globally reduced (the microphone was switched off). Crispness, again, was perceived as significantly lower with any of the sound reductions. Interestingly, perceived hardness was significantly affected by the sound information as well: Hardness was rated as being significantly lower when a global sound reduction was applied than when the sound was unfiltered. We demonstrated, for the first time, that sound information plays an important role even for the evaluation of hardness, a property believed to be primarily oral/mechanical.

Introduction

Sensory quality is identified as the most important driver of consumers’ choices when it comes to fruit product selection (Harker, Gunson, & Jaeger, 2003). This seems particularly true for consumers’ choices when it comes to fruit product selection (Harker et al., 2002), as well as to the strength needed to obtain such fracture (Seymour & Hamann, 1988). Hardness, instead, appears to be a more defined property as it is related to the resistance of the apple flesh when the biting action is exerted by the teeth (Daillant-Spinnler et al., 1996). Still, there are authors suggesting that hardness would also share some properties with crispness (see Fillion & Kilcast, 2002; Vincent, 1998).

Although the number of studies focusing on the description of crispness sensation is remarkable, still an unambiguous and universally agreed definition is missing. Crispness would refer to some sound characteristics of the noise produced by the apple when it is bitten with the front teeth (Harker et al., 2002), as well as to the vibrations produced by the apple when it breaks (Christensen & Vickers, 1981; Szczesniak, 1988), and to the strength needed to obtain such fracture (Seymour & Hamann, 1988). Hardness, instead, appears to be a more defined property as it is related to the resistance of the apple flesh when the biting action is exerted by the teeth (Daillant-Spinnler et al., 1996). Still, there are authors suggesting that hardness would also share some properties with crispness (see Fillion & Kilcast, 2002; Vincent, 1998).

The role of sound in judgments of food texture was first investigated by Drake (1963, 1965). Drake demonstrated that the sounds produced by chewing or crushing a variety of foodstuffs (or the same foodstuff prepared to have different textures) varied in their amplitude, frequency, and temporal characteristics. In following years, Vickers and collaborators went onto investigating the role of sound on the perception of some textural characteristics of food like crispness and crunchiness (for an early review, see Vickers & Bourne, 1976a). Initially, the crucial role played by sound
was unveiled, observing for instance that foods differing in their crispness level also significantly differed in their produced noise pattern when they were crushed (Vickers & Bourne, 1976b; for instrumental data, see Zdunek, Konopacka, & Jesionkowska, 2010). In subsequent studies, Vickers and colleagues proposed that the nature of crispness could be more complex. According to them, this property would not only be evaluated by measuring some sound characteristics during food crushing (Vickers & Bourne, 1976a), but would also be related to the tactile sensations produced by the vibrations generated during the action of biting into the food (Christensen & Vickers, 1981). As a matter of fact, Vickers and Bourne found evidences that food crispness could be correctly estimated even when the sound generated by the bite and the chew was masked.

As for hardness, it is a textural parameter considered as being predominantly mechanical in nature (Brown, Langley, & Braxton, 1998) as it is defined as the maximum force necessary for the jaws or an instrumental probe to break the food product (Vincent, 1998). Nevertheless, there are some empirical data that suggest a possible connection to sound information: Volunteers exposed to the pre-recorded sound of different foods crushed by hand were able to extract some kind of information about food hardness from the acoustic cues (Vickers & Wasserman, 1980). There are also instrumental demonstrations that include the possibility to predict to a certain extent hardness from acoustic data generated using an acoustic emission detector (Zdunek, Cybulska, Konopacka, & Rutkowski, 2010). In addition to this, the existence of a correlation between crispness and hardness evaluations has been repeatedly reported in the literature (e.g., Brown et al., 1998; Corollaro et al., 2013). However, studies definitively understanding the role of sound in hardness perception do not exist and should be investigated.

Previous research has focused mainly on the type of information that could be derived from the sound (either recorded or in real-time) during biting and chewing of foods. However, Zampini and Spence (2004) adopted a multisensory approach for studying the role auditory cues play in food perception. These researchers investigated the possible auditory modulation of tactile, mechanical, and kinaesthetic information on food perception and evaluation by simply changing the sound the person could hear when biting into commercial potato chips (Zampini & Spence, 2004). In particular, crispness and freshness, two properties that are strongly related to food quality, were judged. These authors demonstrated that a real-time increase or decrease of specific audio frequencies resulted in a symmetrical increase or decrease of the perceived crispness and freshness of the product. These results confirmed the ability of sound feedback to significantly influence a consumer’s experience.

Zampini and Spence (2004) proved the existence of a close link between sound and specific sensory properties in dry foods, which are products strongly characterised by their level of crispness. For high moisture foods, Fillion and Kilcast (2002) investigated the perceived crispness and crunchiness in fruit and vegetable products. These authors highlighted the importance of crispness in the evaluation of high moisture food using both consumers and trained panelists. Later, Masuda, Yamaguchi, Arai, and Okajima (2008) have also described the influence of the sound produced during chewing on the perception of food moisture, thus confirming the important linkage between sound and sensory properties of foods.

The process of food evaluation focusing on the sound produced during consumption is a very complex mechanism that relies on more than one transmission path. During biting, a large amount of the acoustic information travels through the air reaching the ear of the perceiver (i.e., air-conduction mechanism). The remaining amount of sound reaches the ear from the inside through its transmission from the teeth, jaws, and bones (i.e., bone-conduction mechanism; see Vickers & Bourne, 1976b). While the jaws can act as a resonance system amplifying the frequencies of sound around 160 Hz, the soft tissues of the mouth (cheeks and tongue) dampen the high frequencies of the sound produced. Kapur (1971) recorded bone-conducted sounds during chewing at a site close to the source (i.e., the mandible near its angle) and at a distant site near the ear canal. It emerged that bone-conducted sounds that reach the ear canal are dramatically attenuated (of approximately 50%).

These findings were inspired by Zampini and Spence’s research (2004) and therefore a similar procedure was applied but with some relevant differences. While Zampini and Spence asked the volunteers to evaluate sensory differences in the acoustic domain exclusively (as the potato chips were all of the same kind), in this study the volunteers were asked to judge apples intrinsically differing in terms of their sensory properties (i.e., crispness and hardness). This was done in order to avoid any possibility to prompt the participants to preferentially attend to one sensory dimension (i.e., auditory) over the others, thus biasing their perception (e.g., see Spence & Driver, 2004), and to try and take into account the variability of the sensory properties naturally present in fresh foods.

Additionally in the present study, the attention was directed to the investigation of any possible influences of air-borne sound on the perception of texture properties of high moisture food, that is apple. Indeed, food with high moisture content behaves differently from dry foods under crushing conditions (Duizer, 2001), therefore different effects of sound might be observed. For this reason, we focused on the effects exerted by the manipulation of the acoustic information captured during the consumption of different apple varieties, based on the ratings of crispness, one of the most important driver for preference (Experiment 1). In the second test (Experiment 2), we go on to verify whether sound could be relevant also when evaluating hardness, a mainly mechanical property of food, given the inconsistent results in sensory studies literature.

**Experiment 1**

**Method**

**Participants**

Seventeen untrained participants (13 females and 4 males, mean age = 26 years old) took part in this study. There were no reported hearing problems from participants. All of the participants were naïve as to the purpose of the experiment and an informed consent was signed before starting the experimental session.

**Stimuli**

Three apple varieties were used as stimuli: ‘Renetta’ (white ‘Renetta Canada’), ‘Golden’ (‘Golden Delicious’), and ‘Fuji’. These varieties were selected on the basis of an extensive characterisation by descriptive sensory analysis (Corollaro et al., 2013) that classified these apples as differing in terms of the textural
parameters of crispness and hardness: ‘Fuji’ was the crispiest and hardest, ‘Renetta’ was the least crispy and the softest, whilst ‘Golden’ placed itself more or less in between (but closer to ‘Fuji’ than ‘Renetta’). In order to avoid any possible effect of expectancy conveyed by vision, all the apples were peeled and cut into cylinders of 1.2 cm of diameter and 1.8 cm of height (for more details on samples preparation, refer to Corollaro et al., 2013). Immediately after cutting, the cylinders were arranged on plastic trays covered with food-safe plastic wrap (PVC). Numbers on the trays indicated the order in which the cylinders should be evaluated.

**Apparatus**

The sound equipment (cf., Zampini & Spence, 2004) consisted of a microphone and a pair of headphones connected to an audio card controlled by the software Reaper 4.02 (Cockos Inc., San Francisco, CA, USA; [www.reaper.fm](http://www.reaper.fm)). The microphone (C451B, AKG, Vienna, Austria) was used to capture the sound produced by the participants while biting into the apple cylinders that was delivered to her/him in real-time through the headphones (DT100, BeyerDynamic, Heilbronn, Germany). The audio card (Edirol FA-66, Roland, Shizuoka, Japan) was used for sound manipulation and filtering: Frequencies between 2 and 20 kHz were either left unmodified and the real sound was used (0 dB condition), or were reduced by 12 or 24 decibels (−12 dB and −24 dB conditions). The rationale behind the choice of which frequencies to modify was that this reflects the range of sound frequencies mostly associated with food crispness (Duizer, 2001; for dry foods, see Zampini & Spence, 2004; for apple, see De Belie, Harker, & De Baerdemaeker, 2002). Instructions and response collection were computer-controlled by means of the software E-Prime 2.0 (PST Psychology Software Tools Inc., Sharpsburg, PA, USA).

**Design**

There were two within-participants factors: apple variety (‘Renetta’, ‘Golden’, and ‘Fuji’) and sound manipulation (−24 dB, −12 dB, and 0 dB/real sound). The session consisted of a brief practice block and three experimental blocks of 18 trials each (every block consisted of the nine conditions replicated twice), resulting in a total of 54 presented trials (each condition was presented in a total of six replicates). Each experimental block lasted less than five minutes. The session (including participant’s welcome, instruction, informed consent filling, breaks between blocks, and final debriefing) lasted for approximately 30 min overall. The presentation of the trials was randomised with the constraint that the same apple-sound condition was never presented on consecutive trials.

**Procedure**

Participants sat in individual testing booths equipped with a PC screen and a mouse. The tray containing the apple cylinders was placed on the desk of the booth. The participant was asked to wear a pair of headphones throughout the experiment in order to be properly isolated from the surrounding environment. The microphone was steadily held by the participant (with the left hand) and kept at approximately 3 cm from the mouth. She/he was instructed to carefully read and follow the instructions appearing on the screen. On each trial, a 100-point rating scale of apple crispness (0 = not at all crisp, 100 = extremely crisp) was presented on the screen. The participant was instructed to pick up (with the right hand) the apple cylinder corresponding to the number on the screen and to bite into it with the front teeth while remaining close to the microphone. The cylinder was rated for crispness with one mouse click on the scale. After the bite, the cylinder could be either eaten or spat. Between trials, the word “wait” appeared on the screen, allowing the experimenter to have the time to apply the next sound filter correctly. As soon as the experimenter was ready, he pressed a key on a keyboard and the next trial started. No time limit was imposed to the participant to perform the test.

**Data analysis**

The participant’s mean responses on the crispness scale were submitted to a 3x3 repeated-measures Analysis of Variance (ANOVA), with the factors apple variety (‘Renetta’, ‘Golden’, or ‘Fuji’) and sound manipulation (−24 dB, −12 dB, or 0 dB/real sound). Post-hoc comparisons (when appropriate) were performed by using Tukey’s unequal N HSD test. All the analyses were performed with STATISTICA 9.1 (StatSoft Inc., Tulsa OK, USA).

**Results**

**Crispness**

The results of the analysis revealed that this group of volunteers consistently evaluated the intrinsic differences in apple crispness, even when they were naïve and not specifically trained in sensory analysis [F(2,32) = 179.44, p < 0.001; see Fig. 1a]. As foreseen by the previous descriptive analysis (see Corollaro et al., 2013), ‘Renetta’ apple was perceived as being significantly less crisp [M = 25; dotted bar] than the other varieties [for both comparisons, p < 0.001]. In contrast, ‘Fuji’ apple (diagonal lines bar) was judged as the crispiest apple [M = 83; for both comparisons, p < 0.001]. The ‘Golden’ apple variety (square bar) was rated as being significantly different from the other two varieties placing itself in between [M = 67; for both comparisons, p < 0.001].

The sound manipulation applied during the test also appeared to affect apple crispness perception [F(2,32) = 4.34, p = 0.022; see Fig. 1b]. In particular, both reductions of sound [−24 dB and −12 dB, M = 57; dark and light grey bars, respectively] showed a diminished crispness evaluation as compared to the real sound condition [M = 60; white bar; for both comparisons, p < 0.05]. The interaction between the factors apple and sound was not significant [F(4,64) < 1; Fig. 1c].

**Discussion**

In Experiment 1, an effect of the sound information available during the consumption of apple on crispness evaluation was observed. All apple varieties were judged as significantly less crisp when the high frequencies of sound (i.e., those frequencies associated the most with crispness; cf. Zampini & Spence, 2004; see also De Belie, De Smedt, & De Baerdemaeker, 2000; Duizer, 2001) were reduced, as compared to the condition in which the real sound was heard. This was consistent with the literature that defines crispness as being a predominantly auditory sensation (e.g., see Vickers, 1981) but could also extend such effects to foods high in moisture content (i.e., apple). In addition to this result, it was shown that even naïve consumers have an ability to consistently discriminate between different crispness levels in food products that is comparable to that showed by trained panelists (Corollaro et al., 2013).

**Experiment 2**

Given that no difference between −24 dB and −12 dB conditions was observed in Experiment 1, in Experiment 2 the −12 dB condition was substituted by a stronger and more generalised sound reduction, obtained by switching off the microphone. This manipulation would prevent the sound conveyed by the air (but not that conducted by the bones) to reach the volunteer and this would allow to verify whether this severe acoustic reduction (less specific than that applied in Experiment 1) could still affect crispness perception. The second aim of Experiment 2 was to go further
to the investigation of the existence of similar acoustic effects on hardness, a property of food texture generally considered as being oral/mechanical (Daillant-Spinnler et al., 1996; Masuda et al., 2008; Vickers, 1981; Vincent, 1998) and for which a limited effect of the auditory information is thus expected. Despite the fact that instrumental sound-hardness relationships have been described (Vincent, 1998) and the possibility of gathering some information about hardness from recorded sounds has been put forward (Vickers & Wasserman, 1980), to date neither issues have been clearly addressed, nor the possibility of sound to cause a variation in perceived hardness has ever been investigated. What is more, it is widely known that crispness and hardness are strongly correlated parameters (e.g., see Brown et al., 1998; Corollaro et al., 2013). In previous studies, it has also been suggested that crispness would represent a property placed along a continuum of which one far end is hardness (Christensen & Vickers, 1981; Vickers, 1981).

Methods

Participants

Twenty-seven new untrained participants (13 females and 14 males, mean age = 29 years old) took part in this experiment. None of them declared to suffer from any auditory dysfunctions. All of the participants were naïve as to the purpose of the experiment and gave their informed consent before starting the experimental session.

Stimuli and apparatus

The sound equipment used in the second test was the same as in Experiment 1. However, only two apple varieties were used in Experiment 2: ‘Renetta’ (white ‘Renetta Canada’) and ‘Fuji’, that is the least crisp and the softest apple vs. the crispiest and hardest apple (see also Corollaro et al., 2013). Cylinder preparation and presentation procedure were exactly the same as in the previous experiment. However, sound manipulation this time consisted of a reduction of 24 decibels (−24 dB condition), a global reduction obtained by switching the microphone off (microphone off condition), or an unfiltered real sound condition (0 dB). Instructions presentation and response collection were managed using the software E-Prime (PST Psychology Software Tools Inc., Sharpsburg, PA, USA).

During a preliminary pilot test, fourteen people were asked to freely give a definition of the meaning of food crispness and hardness: For crispness, eight of them referred to both sound and force information, four of them to sound information only, while the remaining two referred to force information only. For hardness evaluation, instead, no one mentioned any sound information: All fourteen referred to mechanical/force information. On the basis of these results, a brief questionnaire was developed with which, during the post-experimental phase of Experiment 2, all the participants were asked to rate how much force and sound information were important during the evaluation of the apple cylinders. They were asked to think about how they had evaluated crispness and hardness during the test and to give a score (from 1 = not at all to 9 = extremely) as a function of how important the following information had been: – the force required for the bite/the resistance offered by the sample; – the sound/noise produced by the bite.

Design and procedure

The test consisted of a within-participants repeated-measures design, with the factors of apple variety (‘Renetta’ and ‘Fuji’) and sound manipulation (microphone off, −24 dB, and 0 dB/real sound). This time, participants expressed ratings for apple crispness and hardness. In order to avoid any halo effects, the order of scale presentation (i.e., crispness scale or hardness scale) was fixed between blocks and counterbalanced between participants. Thus, the session consisted of two blocks performed with one scale (e.g., crispness), and the last two blocks performed with the other scale (e.g., hardness). Before starting with the first block a brief practice block was performed, followed by four experimental blocks (two blocks per scale) of 18 trials each (every block consisted of the six conditions replicated three times), resulting in a total of 72 presented trials (each condition was presented in six replicates in total). At the end of the test, a paper questionnaire was given to each participant. The session that included four practice block was performed, followed by four experimental blocks (two blocks per scale) of 18 trials each (every block consisted of the six conditions replicated three times), resulting in a total of 72 presented trials (each condition was presented in six replicates in total). At the end of the test, a paper questionnaire was given to each participant. The session that included four experimental blocks (one for each tray) but also the participant’s welcome, the filling of the questionnaire and the informed consent, the breaks between blocks, and the final debriefing lasted for approximately 45 min overall. The presentation of the trials was

![Fig. 1. Mean crispness ratings collected in Experiment 1 (a) main effect of the factor apple variety (‘Renetta’ – dotted bar, ‘Golden’ – squared bar, or ‘Fuji’ – diagonal lines bar) across the sound conditions; (b) main effect of sound manipulation (−24 dB – dark grey bar, −12 dB – light grey bar, or 0 dB/real sound – white bar) across the apple conditions; (c) interaction between the factors apple variety and sound manipulation. Bars represent the standard error of the means. Asterisks indicate significant comparisons and p-value (Tukey’s HSD test; *** = p < 0.001; * = p < 0.05).](image-url)
randomised with the constraint that the same apple-sound condition was never presented on consecutive trials. The experimental procedure was the same as that adopted in the previous test, with the exception of the rating scale used.

Data analysis

The participant’s mean responses on the scales were submitted to two $2 \times 3$ repeated-measures ANOVA, one for crispness and the other for hardness, with the factors of apple variety (‘Renetta’ or ‘Fuji’) and sound manipulation (microphone off, –24 dB, 0 dB/real sound). Post-hoc comparisons (when appropriate) were performed using Tukey’s HSD test. Means computed from the scores expressed by the participants in the questionnaire were analysed by means of t-tests. All the analyses were performed with STATISTICA 9.1 (StatSoft Inc., Tulsa OK, USA). Due to missing responses, data obtained by one participant were not considered in crispness analysis whilst those of a different volunteer were not included in hardness analysis.

Results

Crispness

The results confirmed the ability of the naïve participants to discriminate between apples differing in crispness [$F(1,25) = 158.07, p < 0.001$; Fig. 2a]. As expected, ‘Fuji’ apples were judged as being crispier [$M = 67$; diagonal lines bar] than ‘Renetta’ apples [$M = 31$; dotted bar]. Sound appeared again to play a role in the evaluation of apple crispness [$F(2,50) = 22.27, p < 0.001$; Fig. 2b]. Apples presented with the real unfiltered sound (0 dB; white bar) were rated as crispier [$M = 55$] than apples presented with any form of sound reduction (for –24 dB, $M = 48, p < 0.001$; for microphone off, $M = 47, p < 0.001$; dark grey and black bars, respectively), thus independently from the specific auditory reduction. Again, no significant interaction between the factors apple and sound was observed [$F(2,50) < 1$; Fig. 2c].

Hardness

The results confirmed that naïve participants have the ability to perceive differences in apple hardness [$F(1,25) = 98.80, p < 0.001$; Fig. 3a]. ‘Fuji’ apples were judged as being significantly harder [$M = 58$; diagonal lines bar] than ‘Renetta’ apples [$M = 33$; dotted bar], as indicated by previous study with trained panelists (Corollar et al., 2013). Interestingly, sound appeared to also play a significant role in this evaluation [$F(2,50) = 3.65, p = 0.033$; see Fig. 3b]. Particularly, apples presented with the real unfiltered sound (0 dB; white bar) were perceived once again as being harder [$M = 47$] than apples presented with the global sound reduction (microphone off, $M = 44, p < 0.05$; black bar). The application of the –24 dB filter, however, did not show any difference in the evaluations [$M = 45$; dark grey bar] as compared to the other conditions. No significant interaction between factors was observed [$F(2,50) < 1$; Fig. 3c].

Questionnaire

Responses collected with the questionnaire revealed that, for the participants, force was the most important information for hardness evaluation [$M = 8, SD = 1.4$; sound information, $M = 4, SD = 1.8$; $t(26) = 7.96, p < 0.001$]. However, no difference was found between the impact of force and sound on crispness evaluation [force information, $M = 7, SD = 1.5$; sound information, $M = 7, SD = 1.4$; $t(26) = 1.38, n.s.$].

Discussion

Experiment 2 demonstrated that the application of a global reduction to the acoustic information available when consuming food influences apple crispness perception in a similar way as the reduction of 24 dB of the sole high frequencies. More interestingly, sound information revealed to be able to modulate apple hardness ratings, demonstrating for the first time that this textural property is much more related to cues not exclusively oral/mechanical than what was previously thought. However in order to observe this effect, it is necessary to apply a heavier manipulation of sound (i.e., an overall reduction eliminating air-borne sounds) than that required for crispness modulation. As a matter of fact, a significant reduction of the perceived hardness of apple was observed only when the amount of sound information

![Fig. 2. Mean crispness ratings collected in Experiment 2 (a) main effect of the factor apple variety (‘Renetta’ – dotted bar vs. ‘Fuji’ – diagonal lines bar) across the sound conditions; (b) main effect of sound manipulation (microphone off – black bar, –24 dB – dark grey bar, or 0 dB/real sound – white bar) across the apple conditions; (c) interaction between the factors apple variety and sound manipulation. Bars represent the standard error of the means. Asterisks indicate significant comparisons and p-value (Tukey’s HSD test; *** = p < 0.001).](image-url)
The influence that one sensory modality has on the perception of stimuli through another sensory modality is suggested to be compatible with what has been described about the effects that one sense could exert over another sensory modality (e.g., see Shimojo & Shams, 2001; Welch & Warren, 1980). In particular, one modality would be able to modulate the perception originating from a different sense only if the stimulus has enough strength and reliability. This hypothesis appears to be very suitable for describing the influence exerted by a substantial sound reduction on crispness evaluation in potato chips (Zampini & Spence, 2004). Here, a high moisture and more variable product (than industrially produced potato chips) was used, that is apple. Additionally, apples were selected as a function of their intrinsic crispness and hardness difference, thus making the task to perform as natural and feasible as possible. That is, the evaluation of existing differences between the cylinders would allow the volunteer to focus on the whole experience with the product, avoiding any cues about the only source of differences available (i.e., the acoustic domain, like in Zampini and Spence’s experiment).

The results described here give additional information supporting what was known about food crispness perception. Crispness is strongly affected by the sound information available while consuming the food, as it represents one of the texture properties that are associated the most with the sound produced when crushed (Christensen & Vickers, 1981; Vickers & Bourne, 1976a, 1976b). What is interesting to note though is that an additional reduction of the sound information available during apple evaluation did not result in a further decrease of its perceived crispness. This could be related to the nature of the sound manipulations adopted: When the frequencies typical of crisp foods are filtered then a reduction in that perception is observed, while when the sound information is severely reduced (including more frequencies than only those classically associated to crispness) no additional effect is observed. Once the crucial information is altered, a floor effect is reached and no further decrease in crispness intensity is obtainable. It is important to remember here that bone-conducted sounds were not blocked in this study, as this went beyond the purposes of the investigation. Nevertheless, these results appear to be consistent with the stronger role played in crispness perception by the air- than the bone-conduction mechanism described by Dacremont et al. (1991).

The case of hardness perception, on the contrary, is different. On the one hand, there were some data indicating the existence of some sort of link between the sound of food and hardness scores (Vickers & Wasserman, 1980). What is more, Vickers (1981) observed that people are able to effectively evaluate food hardness by simply hearing the sound produced during fracture. On the other hand, hardness is mainly considered to be a dimension related to oral and force properties (Vickers, 1981; Vincent, 1998; see also the results obtained from Experiment 2 questionnaire). Crucially, the present study demonstrates for the first time that the evaluation of hardness levels of different apple varieties can be systematically modulated by the sound information produced while biting into them. Therefore for hardness evaluation, acoustic cues seem to be taken into account more than what was previously thought. Differently from crispness though, hardness judgements appear to be sensitive to a stronger sound reduction than that caused by a decrease only in the range of frequencies related to crispness. This would supply a possible explanation for the uncertain results described in the past; that is hardness would only be affected by a powerful sound information. This would be compatible with what has been described about the effects that one sense could exert over another sensory modality (e.g., see Shimojo & Shams, 2001; Welch & Warren, 1980). In particular, one modality would be able to modulate the perception originating from a different sense only if the stimulus has enough strength and reliability. This hypothesis appears to be very suitable for describing the influence exerted by a substantial sound reduction on tactile/mechanical perception related to apple hardness.

The influence that one sensory modality has on the perception of stimuli through another sensory modality is suggested to be the cause of the effect observed by Barnett-Cowan (2010) in a freshness and crispness evaluation task. In that study, participants were presented with pretzels having different degree of moisture decrease in perceived crispness is obtained. This result is consistent with what has been previously described in the literature about the influence exerted by sound on crispness evaluation in potato chips (Zampini & Spence, 2004). Here, a high moisture and more variable product (than industrially produced potato chips) was used, that is apple. Additionally, apples were selected as a function of their intrinsic crispness and hardness difference, thus making the task to perform as natural and feasible as possible. That is, the evaluation of existing differences between the cylinders would allow the volunteer to focus on the whole experience with the product, avoiding any cues about the only source of differences available (i.e., the acoustic domain, like in Zampini and Spence’s experiment).

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The influence that one sensory modality has on the perception of stimuli through another sensory modality is suggested to be the cause of the effect observed by Barnett-Cowan (2010) in a freshness and crispness evaluation task. In that study, participants were presented with pretzels having different degree of moisture
and were asked to rate the perceived freshness and crispness of the pretzels with a single bite. Half of the trials were incongruent: The part of pretzel that was held by the participant and the part that she/he actually bit differed in terms of treatment (i.e., the pretzel was moist on the holding site but fresh on the biting site, or the other way round). Interestingly, freshness and crispness ratings decreased with the incongruent information than when congruent trials were presented. Here, the tiny size of the samples probably prevented such an interaction to happen. As a matter of fact, from one side the samples were not discriminable in terms of hand feel (while the difference in moisture in the pretzel was clearly perceivable by touch), while on the other side no difference in the effect of the sound was observed in the ‘incongruent’ condition (e.g., ‘Fujii’ apple presented with the −24 dB manipulation) as compared to the ‘congruent’ condition (e.g., ‘Renetta’ apple with −24 dB manipulation).

A final additional result observed in this study is the ability of untrained naive volunteers to consistently discriminate between food products in terms of their crispness or hardness. In both experiments, the volunteers have been able to reliably distinguish between the different variables expressing scores similar to those produced by a trained panel (Corollaro et al., 2013). This supports the notion that these textural properties are straightforward and easy to assess even for people lacking of any specific sensory training. Additionally, it was shown for the first time that also during experiments, the volunteers have been able to reliably distinguish food products in terms of their crispness or hardness. In both experiments, the volunteers have been able to reliably distinguish among the different variables expressing scores similar to those produced by a trained panel (Corollaro et al., 2013). This supports the notion that these textural properties are straightforward and easy to assess even for people lacking of any specific sensory training, despite maybe their higher difficulty in finding a consensual and unambiguous definition of those properties (Szczesniak, 1988).

In conclusion, the perceived crispness of a high moisture food like apple can be modulated systematically by the manipulation of crispness-related frequencies of the sound produced while biting. Additionally, it was shown for the first time that also during the evaluation of hardness the sound information available is taken into account. Additionally, it was observed that naïve people have the ability to perform a correct discrimination of these texture properties in apple, even without any specific training in sensory analysis. Finally, these results suggest that the predicting ability of models of texture properties could improve if sound parameters were taken into account together with mechanical information (Costa et al., 2011) since both parameters have shown to have an influence on both crispness and hardness. As a final remark, it should be underlined that in the present study the focus was maintained on the effects of sound on the air-conduction mechanism, whilst keeping the bone-conducted information constant. It would be interesting in future studies to deepen the investigation of such effects by acting on the information reaching the perceiver through the bones, like for example using vibrational masking techniques, and to get more insight about the dampening effects naturally exerted by the soft tissues present in the mouth (e.g., see Chordekar, Kriksunov, Kishon-Rabin, Adelman, & Sohmer, 2012).

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