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The effect of a crunchy pseudo-chewing sound on perceived texture of softened foods

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HIGHLIGHTS

- A masseter EMG signal was delivered as a "crunchy" pseudo-chewing sound.
- Softened foods were evaluated as 'stiffer' in the EMG chewing sound condition.
- Physical food properties are more likely to be influenced by altered auditory input.
- A modified chewing sound presentation may help those on texture-modified diets.

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ABSTRACT

Elderly individuals whose ability to chew and swallow has declined are often restricted to unpleasant diets of very soft food, leading to a poor appetite. To address this problem, we aimed to investigate the influence of altered auditory input of chewing sounds on the perception of food texture. The modified chewing sound was reported to influence the perception of food texture in normal foods. We investigated whether the perceived sensations of nursing care foods could be altered by providing altered auditory feedback of chewing sounds, even if the actual food texture is dull. Chewing sounds were generated using electromyogram (EMG) of the masseter. When the frequency properties of the EMG signal are modified and it is heard as a sound, it resembles a "crunchy" sound, much like that emitted by chewing, for example, root vegetables (EMG chewing sound). Thirty healthy adults took part in the experiment. In two conditions (with/without the EMG chewing sound), participants rated the taste, texture and evoked feelings of five kinds of nursing care foods using two questionnaires. When the "crunchy" EMG chewing sound was present, participants were more likely to evaluate food as having the property of stiffness. Moreover, foods were perceived as rougher and to have a greater number of ingredients in the condition with the EMG chewing sound, and satisfaction and pleasantness were also greater. In conclusion, the "crunchy" pseudo-chewing sound could influence the perception of food texture, even if the actual "crunchy" oral sensation is lacking. Considering the effect of altered auditory feedback while chewing, we can suppose that such a tool would be a useful technique to help people on texture-modified diets to enjoy their food.

1. Introduction

The ability to chew and swallow deteriorates with age, which increases the risk of aspiration and can lead to asphyxia or pneumonia. In order to avoid aspiration – the breathing in of food – elderly individuals whose eating functions have declined can only eat soft food with a consistent texture [1–5]. However, these modified diets are not always pleasant and can result in a loss of appetite [6–9]. The principal aim of this investigation was thus to explore how dissatisfaction with food texture can be reduced. One possibility is altering the auditory feedback of the sounds made when eating.

Although we do not usually pay conscious attention to the sounds emitted when we chew food, chewing sounds can influence the perception of food texture, especially the perception of crispness and crunchiness (for reviews, [10–13]). For instance, Zampini et al. reported that the perception of crispness and staleness of potato chips can be altered by varying the loudness or frequency composition of the first bite sound [14]. The effect of sound modulation on crispness perception has been subsequently replicated by other researchers [15–17]. Thus, the perception of food texture involves not only oral sensation, but also auditory feedback. It might be therefore possible to alter people's experience of food texture via altered auditory feedback of chewing sounds, thereby

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ameliorating dissatisfaction with food texture in individuals who are obliged to follow restricted diets.

The effect of auditory modification on crispness perception in previous studies has been explained by the principle of crossmodal integration [18,19], whereby oral sensation and chewing sounds are said to be integrated unconsciously [13]. This model has been used to describe results in which there is no dissociation between the oral somatosensory and auditory sensations. However, the foods in texture-modified diets are very soft and so do not elicit the oral sensation of crispness or crunchiness when eaten; we therefore created a dissociation using altered auditory feedback of chewing sounds. In this way, our study aimed to investigate whether the modified chewing sound can influence the perception of food texture, even if the actual oral sensation is lacking. Although the principal aim of our investigation was to enhance the eating experience of elderly people obliged to follow texture-modified diets, it is important to first confirm an effect with normal subjects. The present study thus assessed the effect of modified chewing sound in healthy adults. In this report, we also propose a method that can provide a pseudo-chewing sound in a simple and practical way.

2. Materials and methods

2.1. Pseudo-chewing sound using EMG signals

The foods in texture-modified diets are very soft and do not emit crispy or crunchy chewing sounds. Therefore, it is impossible to alter the real chewing sound, and chewing sounds must be provided from outside the oral cavity, i.e., from an external source. Previous studies have detected mastication by monitoring real chewing sounds or jaw movements and playing pre-recorded chewing sounds [15,16,20]. However, because real chewing sounds are hardly emitted while eating foods from texture-modified diets, it is difficult to detect mastication from the real chewing sounds. Besides, jaw movements during mastication can also be mixed with those due to speech, which must therefore be distinguished in some sophisticated way [16]. Because the final goal of our study is to help elderly people obliged to follow texture-modified diets in their daily lives – and not in a laboratory setting – we decided to detect mastication in a simple way. To achieve this, we used the electromyogram (EMG) of the masseter muscle, an agonist of mastication whose contractions are synchronous with the closing of the mouth [21–23]. By monitoring the EMG of the masseter, it is possible to provide chewing sounds that are synchronous with chewing behavior, which is what differentiates the present study to previous research.

Interestingly, the EMG signal is an electrical waveform that can be readily interpreted as a sound. The principal frequency range of the surface EMG is up to several hundred Hertz [24–26], and therefore does not contain the high-frequency components present in crispy and crunchy sounds [27–31]. However, the frequency range of 125 Hz to 1250 Hz was extracted as the first principal component of air-conducted crispy, crunchy, and crackly sounds [29], where the frequency range of the EMG sound overlaps. In fact, the EMG sound was close to the crunchy sound emitted by hard moist foods (e.g. root vegetables). Thus, we could use the EMG signal as an external sound source of crunchy chewing sound.

In addition to onset and offset synchrony with chewing, using the EMG signal as chewing sounds provides two practical merits. The first is that, other than individual calibration to each user to accurately detect jaw movements, no adjustment is necessary to set up the system. The second is that speech movements have less of an effect on the modified chewing sound. Because the amplitude of presented chewing sound changes depending on the intensity of the masseter activity, and the masseter activity during speech is smaller than that during mastication [32,33], a chewing sound evoked by speech movements is hardly emitted.

As shown in Fig. 1, the EMG was recorded using surface electrodes. A pair of bipolar Ag/AgCl surface electrodes 5 mm in diameter was attached to the skin overlying the right masseter. One electrode was located over the maximum distended muscle belly, which was determined by palpation, and the other was attached parallel to the direction of muscle fibers with an inter-electrode distance of 20 mm; a ground electrode was attached to the forehead. Myoelectric signals were amplified (BioAmp FE132, AD Instruments) with a low-pass filter (LPF) at 5 kHz and a high-pass filter (HPF) at 10 Hz, and recorded at a sampling rate of 10 kHz (PowerLab8/35, AD Instruments).

The analog output voltage of the amplifier was sent to a mixer/graphic equalizer (ZMX124 FX USB, ALTO Professional). To reduce noise, the input signal was filtered with a HPF at 75 Hz (18 dB/oct) and high-frequency attenuation over 12 kHz (−15 dB). In order to match the frequency characteristics to the first principal component of the real chewing sound, the amplitudes of each frequency band were adjusted using the function of the graphic equalizer with one-octave resolution: frequencies <125 Hz and over 2 kHz were attenuated by

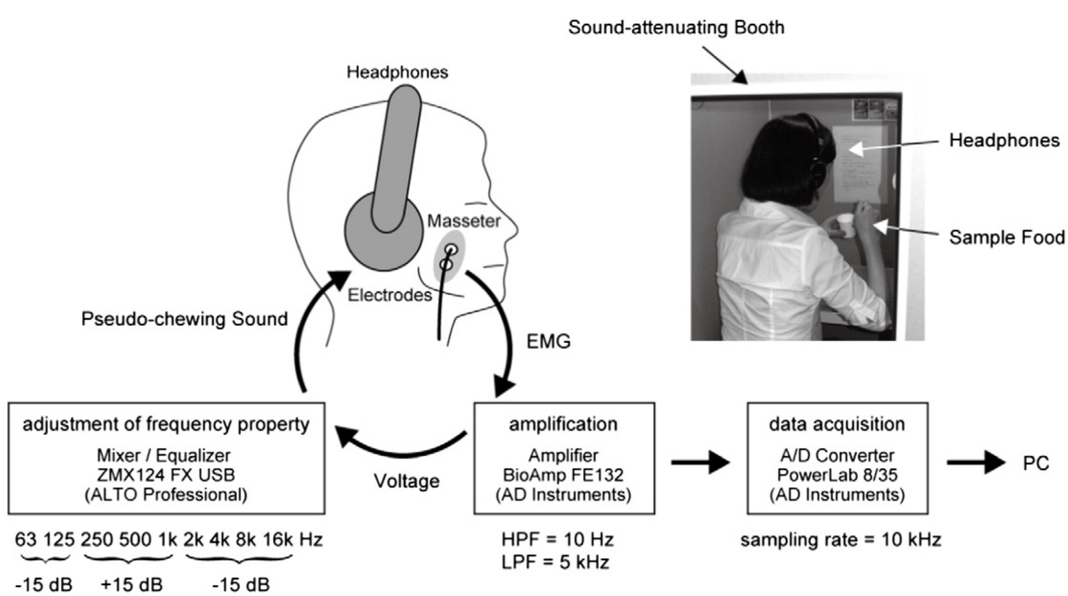

Fig. 1. EMG chewing sound presentation system and experimental setup. The EMG signal of the masseter was fed back to headphones through an amplifier and graphic equalizer to provide a pseudo-chewing sound. The EMG signal was also recorded by a personal computer for further analysis. Experiments were conducted in a sound-attenuating booth.

−15 dB, and frequencies between 250 Hz and 1 kHz were amplified by +15 dB. Ultimately, we used the frequency range from 250 Hz to 1 kHz from the EMG signal to generate the pseudo-chewing sound. The pseudo-chewing sound was delivered via headphones (MDR-NC60, Sony). Therefore, we were able to deliver a "crunchy" pseudo-chewing sound synchronously to the chewing behavior by directly feeding back the altered EMG signal (EMG chewing sound).

2.2. Participants and sample foods

Thirty healthy participants (9 male and 21 female, age range 20–58 years, mean 38 ± 12 (SD) years) without signs of oromandibular or auditory diseases took part in the experiment. All participants provided informed consent. The experiment was approved by the ethics committee of the National Institute of Advanced Industrial Science and Technology (AIST), and was conducted in accordance with the Declaration of Helsinki.

Five commercially available nursing care foods were used as sample foods (Table 1). All sample foods contained finely chopped ingredients and had been cooked until very soft. The Japan Care Food Conference classifies nursing care foods into four categories based on their hardness and viscosity, and these guidelines are used to choose foods for care recipients, depending on their ability to chew and swallow. The five food samples used in this study were classified as Universal Design Food's (UDF) category 2 ("can be broken up using the gums") or category 3 ("can be broken up by the tongue") [34]. Each food portion was 12 g and was maintained at 50 °C.

2.3. Questionnaires

2.3.1. Questionnaire 1: material-property rating

A set of 18 adjective pairs were used for the material-property rating questionnaires, most of which were selected by referring to the previous literature [35–39]. For convenience, we first divided the adjectives used for material-property ratings into three groups: adjectives related to taste (Table 2a); adjectives related to texture (Table 2b); and adjectives related to evoked feelings (Table 2c). Participant used seven-point scales to rate how well these adjectives applied to each of the food stimuli.

2.3.2. Questionnaire 2: general impressions of the eating experience

A set of four questions was used to measure more general impressions of the eating experience (Table 3). Participants rated the naturalness of sound/food combinations, how comfortable the sound was, the number of perceived ingredients, and their subjective observation regarding whether they were able to masticate regularly. As in Questionnaire 1, seven-point scales were used, but evaluations were performed by comparing two sound conditions.

Table 1
Nursing care foods used in the experiment.

Food no.	Description of sample food (*Name in Japanese*)	UDF category	Product maker
1	Five spicy fried and boiled vegetables (*Go-shu-yasai-no-kinpirani*)	3	Wakodo
2	Pumpkin simmered with minced chicken (*Kabocha-no-tori-soboroni*)	3	Wakodo
3	Japanese radish simmered with minced chicken (*Daikon-no-tori-soboroann*)	3	Kewpie
4	Meat and potato stew (*Nikujaga*)	2	Kewpie
5	Shrimp and scallop with cream sauce (*Ebi-to-kaibashira-no-kurimuni*)	2	Kewpie

Table 2
Adjectives selected for material property rating.

a. Taste	b. Food texture	c. Evoked feelings
Light taste–heavy taste	Soft–hard	Unexciting–exciting
Cheap taste–expensive taste	Dry–moist	Unsatisfied–satisfied
Insipid taste–rich taste	Common–rare	Diminishes appetite–arouses appetite
Stale taste–fresh taste	Not chewy–chewy	Less involved dining experience–more involved dining experience
Simple taste–complex taste	Boring–interesting	Unpleasant–pleasant
Unpalatable–palatable	Smooth–rough	
	Bad texture–good texture	

Adjective pairs were originally presented in Japanese, and are here translated into English.

2.4. Procedure

Experiments were conducted in a sound-attenuating booth. Because the sound pressure level depended on the amplitude of the individual EMG signal, it was adjusted using a mastication evaluation gum (Masticatory Performance Evaluating Gum XYLITOL, Lotte) [40]. Each participant was instructed to adjust the volume to a comfortable level while they chewed the mastication evaluation gum. In the condition without sound feedback, no EMG chewing sound was fed back to the participant.

Ten trials were carried out (five kinds of sample foods × two sound conditions), and each trial was performed once. The order of five sample foods and the three categories in Questionnaire 1 was randomized. The two sound conditions for each food were carried out sequentially. Half of the participants began with the with-sound condition, and the other half began with the without-sound condition.

In each trial, participants were informed of the food name and sound condition in advance. Because the purpose of this experiment was to examine the influences of the chewing sound, the participants were instructed to chew more than ten times on the right side of mouth (i.e., the side where the electrodes were attached). No restriction was imposed on the timing of swallowing, provided that mastication was performed over ten times. Questionnaire 1 was completed immediately after each condition. When the two sound conditions for each food were completed, Questionnaire 2 was filled out.

2.5. Evaluation of chewing behavior

In order to evaluate the influences of the EMG chewing sound on the mastication, we analyzed mastication intensity and rhythm. Mastication intensity was calculated from root mean square (RMS) values of the EMG signal during mastication, and normalized against the maximum RMS value over ten conditions. The rhythm of mastication was obtained from the first peak frequency of fast Fourier transform (FFT) analysis; the FFT spectrum was calculated from the rectified EMG signal.

2.6. Data analysis

The mastication intensity and rhythm were statistically tested using a two-way repeated-measures analysis of variance (ANOVA) and the Bonferroni multiple comparisons test. Questionnaire data were analyzed using a Wilcoxon signed-rank test. Results were considered

Table 3
General impressions of the eating experience.

General impression
Sound/food combination is unnatural–sound/food combination is natural
Uncomfortable sound–comfortable sound
Fewer ingredients–more ingredients
Unable to masticate regularly–able to masticate regularly

Questionnaire items were originally presented in Japanese, and are here translated into English.

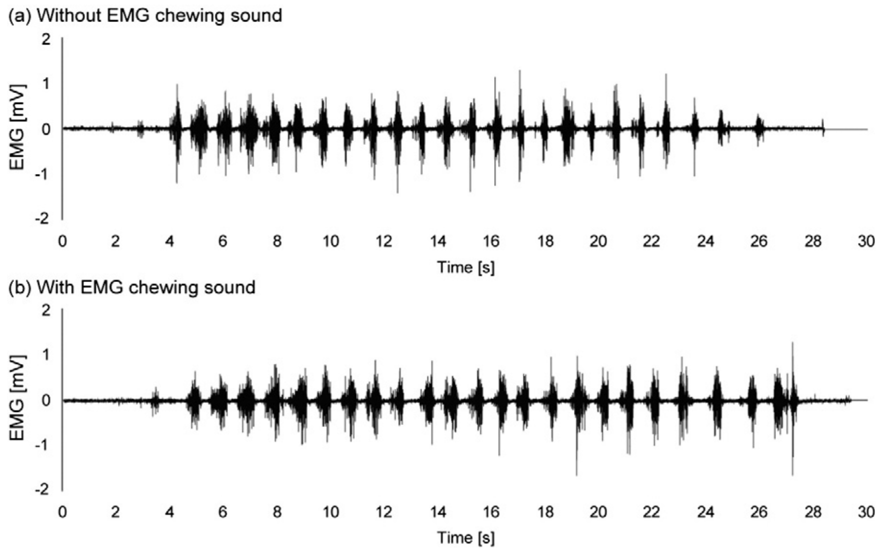

Fig. 2. Example of EMG signals. EMG signals measured during chewing of sample food 1 are shown. (a) Without EMG chewing sound. (b) With EMG chewing sound. No clear difference was observed between the two conditions.

significant when the *p*-value was <0.05 and marginal when it was between 0.05 and 0.1.

3. Results

3.1. Chewing behavior

An example of the EMG signal is shown in Fig. 2. Mastication was rhythmical, and no clear difference was observed in the presence or absence of the EMG chewing sound. The frequency characteristics of the EMG signal and EMG chewing sound are depicted in Fig. 3, which shows that lower frequency range was attenuated and the selected frequency ranges were amplified. Mastication intensity and rhythm are depicted in Fig. 4. Although the mastication intensities varied depending on the sample food, no significant difference was observed between the two sound conditions (food effect $F(4, 116) = 15.5$, $p < 0.001$; sound effect n.s.; interaction n.s.). As for the mastication rhythm, a significant difference was only observed between foods 2 and 3, and no significant difference was observed between the sound conditions (food effect $F(4, 116) = 3.97$, $p < 0.01$; sound effect n.s.; interaction n.s.).

3.2. Questionnaires

The results of Questionnaire 1 in the condition without the EMG chewing sound are shown in Fig. 5. Although all sample foods were classified into UDF categories 2 and 3, there were some food-dependent differences in the participants' subjective evaluations. In particular, food No. 2, which was almost pureed, differed from other foods in the questionnaire items related to food texture and evoked feelings.

The differences in evaluation scores of Questionnaire 1 between the sound conditions are shown in Fig. 6. The graph shows the differences in scores of the with and without EMG chewing sound conditions. Several questionnaire items were significantly different. Food texture and evoked feelings seemed to change more than taste.

Regarding food texture, the perceived chewiness (questionnaire item: “not chewy–chewy”) was greater in the condition with the EMG chewing sound for four out of five sample foods. Although no difference in perceived chewiness was found for food No. 5, there was a marginal difference in perceived hardness (“soft–hard”). The judged roughness of foods No. 2 and No. 4 was significantly greater in the condition with the EMG chewing sound (“smooth–rough”), and that of food No. 1 was marginally greater. Moreover, texture was perceived as more interesting for food No. 3 and No. 5 in the condition with the EMG chewing sound (“boring–interesting”), and there was a marginal difference in the interestingness of texture for food No. 1. Thus, perceived food texture appeared to be effected by the altered auditory feedback of chewing in the majority of the food samples.

Regarding evoked feelings, enjoyment and excitement (“unexciting–exciting”), satisfaction (“unsatisfied–satisfied”), the feeling that the participant was engaged in an actual eating experience (“less involved dining experience–more involved dining experience”), and pleasantness (“unpleasant–pleasant”) were significantly greater for several foods in the condition with the EMG chewing sound (food No. 1, No. 4, and No. 5 for excitement, food No. 3 for satisfaction, food No.

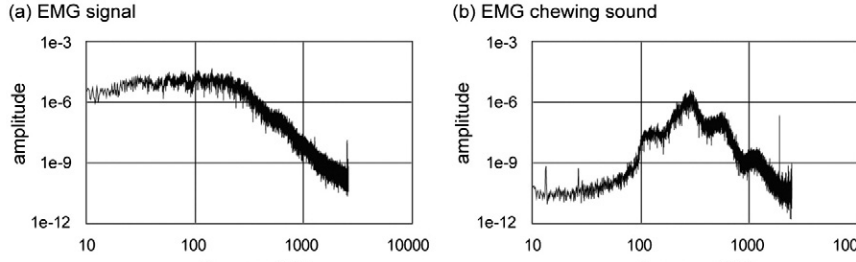

Fig. 3. Frequency characteristics of EMG signal and EMG chewing sound. (a) The raw EMG signal. (b) The EMG chewing sound created from the EMG signal. This was a voltage signal recorded at the ‘headphone out’ socket of the equalizer.

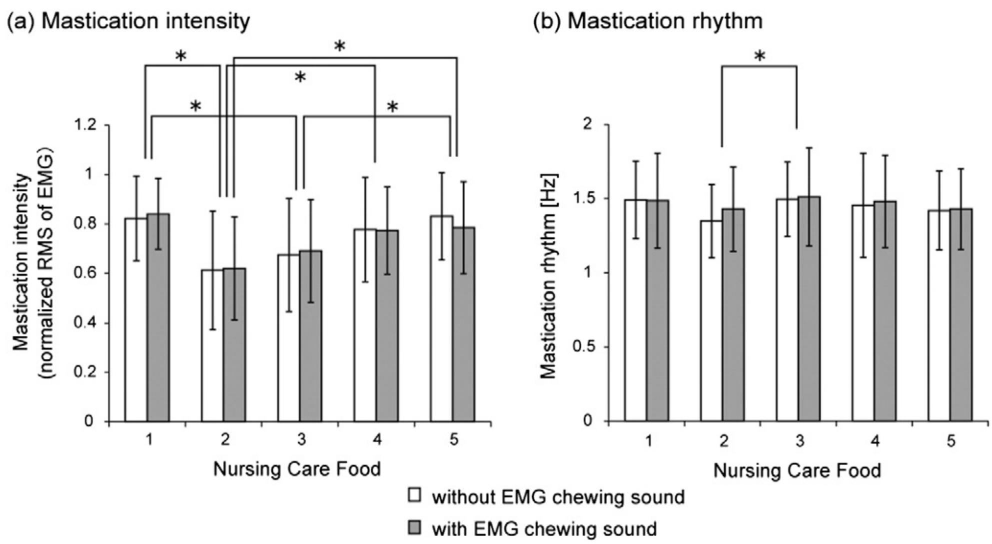

Fig. 4. Mastication intensity (a) and rhythm (b). White bars indicate the condition without the EMG chewing sound, and gray bars indicate the condition with the EMG chewing sound. There were no differences between with/without EMG chewing sound conditions, only differences between food samples. $^{*}p < 0.05$.

1 and No. 2 for feelings of involvement in eating experience, and food No. 1 and No. 5 for pleasantness). As shown in Fig. 6, food No. 1 exhibited increased changes in the questionnaire items related to evoked feelings.

With regard to taste, scores related to expensive taste, complex taste, and palatability were significantly greater in the condition with the EMG chewing sound, although the results were not consistent (food No. 5 for expensive taste, food No. 3 for complex taste and palatability).

Fig. 7 shows the results of Questionnaire 2. For food No. 2, although the food/sound combination was felt to be unnatural and the sound was perceived as uncomfortable, both perceived chewiness and the feeling of having a real dining experience were significantly greater in the condition with the EMG chewing sound (Fig. 6). Moreover, significant

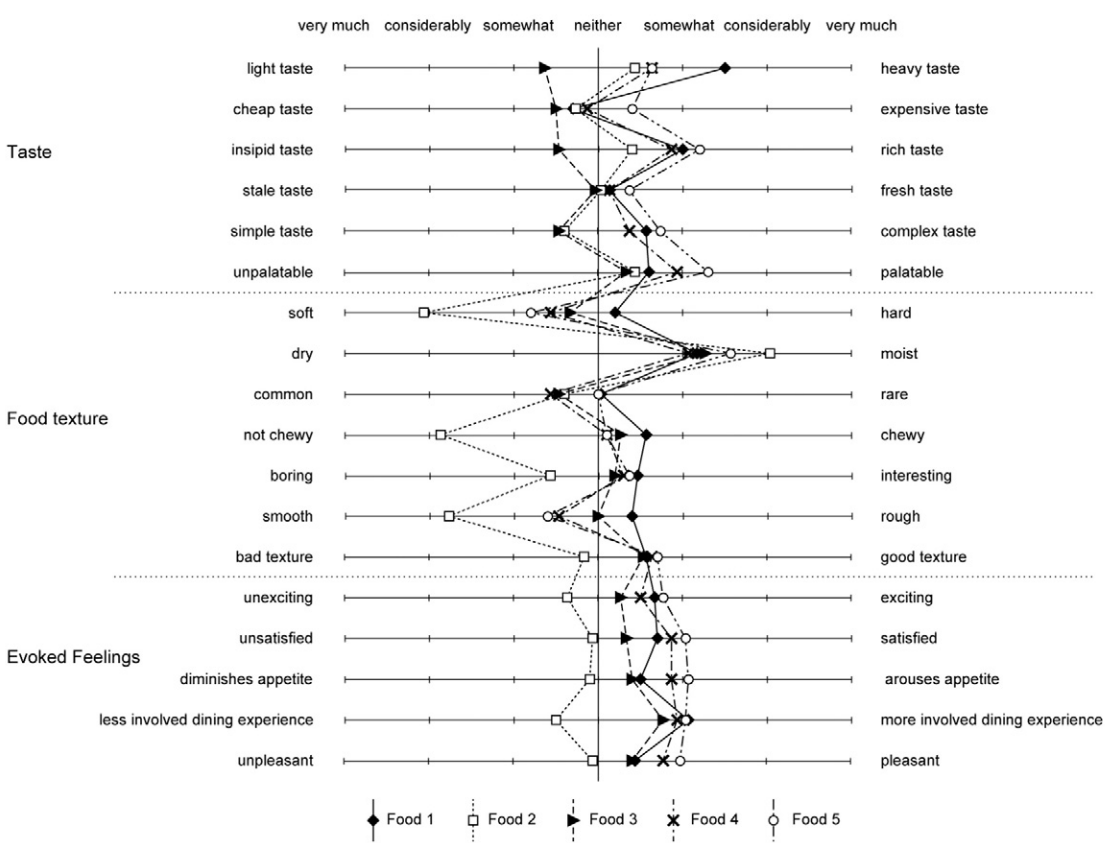

Fig. 5. Results of subjective evaluations in Questionnaire 1 in the condition without the EMG chewing sound. Different symbols represent the different sample foods.

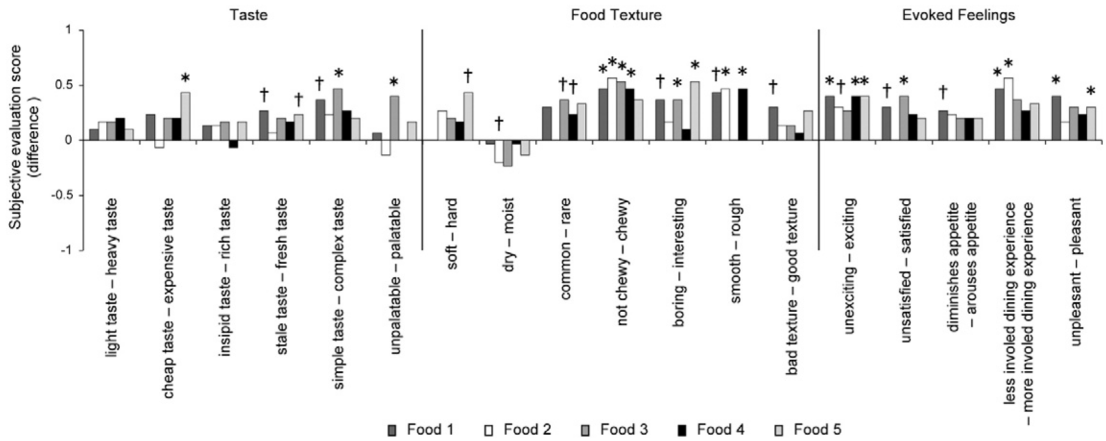

Fig. 6. Differences in subjective evaluation scores in Questionnaire 1. Scores in the condition with the EMG chewing sound were subtracted from scores in the condition without the EMG chewing sound. Positive scores indicate that there was a greater evaluation score for the EMG chewing sound condition toward the adjectives shown on the right side in Fig. 5. Results of Wilcoxon signed-rank test are also shown: $^{*}p < 0.05$, $†p < 0.1$.

differences were more obvious for food No. 1 (Fig. 6), for which the food and sound were perceived as most highly matched. For food No. 1 and No. 5, the number of perceived ingredients was greater, and mastication was considered to be more regular in the condition with the EMG chewing sound.

4. Discussion

This study examined whether the perceived texture of nursing care foods could be modified by presenting a "crunchy" pseudo-chewing sound generated from masseter EMG signals. When the EMG chewing sound was provided, participants were more likely to evaluate a food as having the property of stiffness. Although the effects of the EMG chewing sound were complex and inconsistent differences were also observed, we considered that the observed effects can be attributed to an effect inherent to crispy and crunchy sounds. In the following sections, we discuss 1) influences of the EMG chewing sound on chewing behavior, 2) the influence of the EMG chewing sound on the perception of food texture and evoked feelings, and 3) potential underlying mechanisms and further considerations.

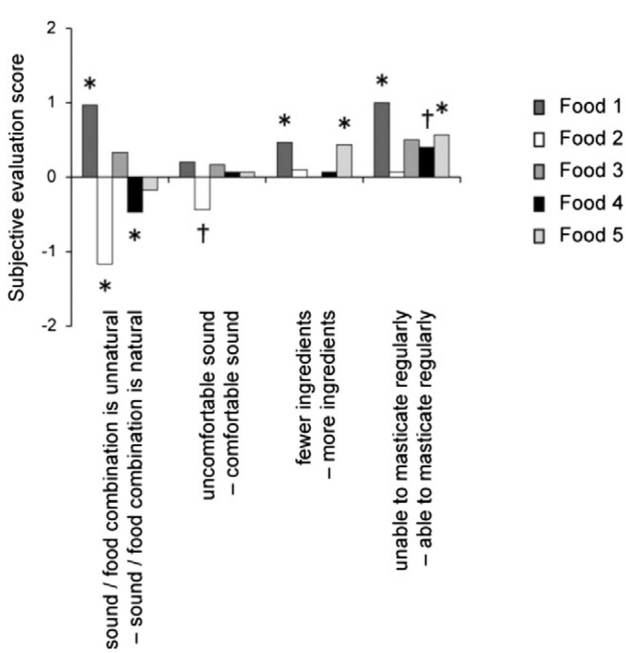

Fig. 7. Subjective evaluation scores in Questionnaire 2. Results of Wilcoxon signed-rank test are also shown: $^{*}p < 0.05$, $†p < 0.1$.

4.1. Influences of the EMG chewing sound on chewing behavior

We found no effect of sound condition on mastication intensity and rhythm. The significant differences of mastication intensity and rhythm were only observed among the sample foods individually. Since mastication is a semi-automatic rhythmic movement, where mastication rhythm is controlled by the masticatory central pattern generator in the brainstem and bite force is modulated by sensory input [41–44], actual food hardness increases muscle activity but does not influence chewing rhythm [23,45,46]. The results are consistent with previous studies. Importantly, the intensity and rhythm of mastication did not differ between the sound conditions, and there was no influence of EMG chewing sound on mastication.

4.2. Influences of the EMG chewing sound on perception of food texture

When the "crunchy" pseudo-chewing sound was provided, participants were more likely to evaluate a food as having the property of stiffness (questionnaire items "not chewy–chewy" and "soft–hard"). Moreover, this seemed not to be affected by the perception of an unnatural combination between the chewing sound and food ("sound/food combination is unnatural–sound/food combination is natural"). Food No. 1 was evaluated as the food best matched to the EMG chewing sound, whereas food No. 2 was evaluated as the most mismatched (Fig. 7). However, the evaluation of chewiness of both foods was significantly greater in the condition with the EMG chewing sound. In addition, the evaluation of roughness was also greater in the condition with the EMG chewing sound for several foods (significant differences in food No. 2 and No. 4 and a marginal difference in food No. 1). Perceived crispness is affected by the frequency composition and loudness of the accompanying sound [14,17]; similarly, in haptic texture perception, the perception of texture is also influenced by sound [47,48]. Considering these effects, we can suppose that the participants perceived a greater stiffness and roughness in response to the "crunchy" chewing sound.

Although the results were not consistent across all foods, differences between the two sound conditions were also observed in taste complexity ("simple taste–complex taste") and the number of perceived ingredients ("fewer ingredients–more ingredients"). Perhaps the presence of the "crunchy" chewing sound made participants suppose that the property of crunchy ingredients varied, or that crunchy ingredients had been added. Taken together, the results indicate that the “crunchy” chewing sound did not influence the perception of chemical sense, such as judgments about heaviness or richness, but did influence the perception of food physical properties, such as stiffness or roughness.

4.3. Influences of the EMG chewing sound on evoked feelings

With regard to the effect of altered auditory feedback on evoked feelings, we made an interesting observation. The evaluations of food No. 1, which was perceived as best matched to the EMG chewing sound, were more positive in most questionnaire items when the EMG chewing sound was provided. Though the results were limited to one sample food, it is natural to consider that sound/food combination influences evoked feelings. A better combination is considered to lead to more positive evoked feelings. Thus, it may be important to consider the contribution of sound/food congruence to psychological effects such as satisfaction and pleasantness.

4.4. Underlying mechanisms and further considerations

Although acoustic information is an important cue to evaluate crispness [49], so is the oral somatosensory sensation of vibration produced by fracturing or crushing foods [50]. In the absence of the oral somatosensory sensation of crispness, the attentional capture of auditory cues might enhance the effect of altered auditory feedback. If auditory cues capture attention more effectively than do oral-somatosensory cues [13], the attentional capture of auditory cues might enhance the judged crunchiness of food eaten in the presence of the “crunchy” EMG chewing sound. In addition to this, participants were informed about the sound conditions (with and without the EMG chewing sound) in advance, which is one limitation of the current study. Because texture properties of food can be estimated from sound alone, even when no food is in the mouth [49,51], participants in the present experiment may thus have anticipated the crunchiness of the sample food and judged the crunchiness to be greater. Thus, further studies should aim to determine the relative contributions of auditory bias and crossmodal integration.

In elderly persons whose eating functions have declined, the EMG signal might not be so clear. In the case where eating functions have seriously declined, they might not even be able to chew. Therefore, it may be difficult to apply the current method to patients without further investigations and modifications. In a small pilot study, for instance, we confirmed that the current method can be applied to healthy elderly participants, and found that the perceived chewiness and the feeling that the participant was engaged in an actual eating experience were influenced by altered auditory feedback [52]. The clarity of the EMG signal is considered to depend on the degree to which eating functions have declined, and if participants cannot execute masticatory jaw movement, it might be difficult to apply this method. Therefore, in future research, we plan to apply the current method to elderly persons who show sufficiently clear EMG signals. However, in most cases, even if eating functions have declined, elderly persons can nonetheless execute masticatory jaw movement. Therefore, the necessity of our method is to be able to present the chewing sound, regardless of whether a clear EMG signal is acquired.

5. Conclusion

A masseter EMG signal was delivered as a “crunchy” pseudo-chewing sound, and foods were evaluated as ‘stiffer’ with presentation of the EMG chewing sound. Therefore, it was shown that a modified chewing sound can influence the perception of food texture, even if the actual oral sensation is lacking. Providing altered auditory feedback is therefore a potentially useful technique for helping people experience varied food textures.

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