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Sensitive to music? Examining the crossmodal effect of audition on sweet taste sensitivity

David Guedes [a,*], Marília Prada [a], Margarida V. Garrido [a], Inês Caeiro [b], Carla Simões [b], Elsa Lamy [b]

[a] Iscte - Instituto Universitário de Lisboa, CIS_Iscte, Portugal

[b] MED - Mediterranean Institute for Agriculture, Environment and Development & CHANGE - Global Change and Sustainability Institute, University of Évora, Évora, Portugal

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ABSTRACT

Previous research has shown that music can influence taste perception. While most studies to date have focused on taste intensity ratings, less is known about the influence of musical stimuli on other parameters of taste function. In this within-subjects experiment (N = 73), we tested the effects of three sound conditions (High Sweetness soundtrack – HS; Low Sweetness soundtrack – LS; and Silence – S) on sweet taste sensitivity, namely, detection and recognition. Each participant tasted nine samples of sucrose solutions (from 0 g/L to 20 g/L) under each of the three sound conditions in counterbalanced order. We assessed the lower concentrations at which participants were able to detect (detection threshold) and correctly identify (recognition threshold) a taste sensation. Additionally, the intensity and hedonic ratings of samples above the recognition threshold (7.20 g/L) were analyzed. Affective variations (valence and arousal) in response to the sound conditions were also assessed. Although music did not lead to significant differences in mean detection and recognition thresholds, a larger proportion of sweet taste recognitions was observed at a near-threshold level (2.59 g/L) in the HS condition. The intensity and hedonic ratings of supra-threshold conditions were unaffected by the music condition. Significant differences in self-reported mood in response to the sound conditions were also observed. The present study suggests that the influence of music on the sweet taste perception of basic solutions may depend on the parameter under consideration.

1. Introduction

Music influences food perception in myriad ways (for a recent review, see Guedes, Garrido, et al., 2023). In the past decades, several studies have found links between faster tempo and higher drinking rates (Mathiesen et al., 2020; McElrea & Standing, 1992; Roballey et al., 1985), higher loudness and faster drinking and eating speed (Guéguen et al., 2008; McCarron & Tierney, 1989), or between music ethnicity and product choices (e.g., French-style accordion music leading to higher purchases of French wines, North et al., 1997, 1999; or Flamenco-style music favoring the choice of paella, Zellner et al., 2017). Notably, music may impact not only how individuals behave towards foods and drinks but also how they perceive the sensory attributes of those products. In this line of inquiry, music has been selectively employed to modulate attributes such as taste, flavor, or the mouthfeel of foods and drinks (Spence, 2020). In this study, we take on this multisensory framework to explore whether music influences different parameters of sweet taste perception.

1.1. The crossmodal influence of music on taste perception

The recent scientific interest in audition-gustation interactions has allowed for a deeper understanding of the contributions of sound in modulating taste perception and the overall eating experience. To date, several experiments have explored the ability of music to convey taste-like attributes and, consequently, to influence how individuals rate the taste of foods and drinks (Spence et al., 2019a). In one of the earliest examples of a crossmodal taste enhancement experiment, participants tasted a bittersweet cinder toffee while listening to either a low-pitched brass (i.e., "bitter") soundtrack or a high-pitched piano (i.e., "sweet") soundtrack (Crisinel et al., 2012). In this experiment, the taste of the toffee sample was significantly influenced by the background music,

* Corresponding author at: Iscte - Instituto Universitário de Lisboa, Av. das Forças Armadas, Room 2W08, 1649-026 Lisboa, Portugal.
E-mail address: dhfgs@iscte-iul.pt (D. Guedes).

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with participants evaluating the samples as sweeter while listening to the sweet (vs. the bitter) soundtrack.

Several studies have also explored the potential use of customized soundscapes (e.g., Wang et al., 2015), as well as of familiar music (e.g., pop or classical music; Hauck & Hecht, 2019; Kantono et al., 2016, 2019; Spence et al., 2013; Wang et al., 2019; Wang & Spence, 2015; Reinoso-Carvalho, Dakduk, Wagemans, & Spence, 2019), in shaping the taste of foods and drinks. While most of these studies seem to support a modulatory role of audition in perceived taste intensities of foods and drinks, less is known about its effects on other parameters of taste perception, namely taste sensitivity.

1.2. Multisensory influences on taste sensitivity

Several studies in sound-taste interactions have examined the influence of auditory stimuli on taste intensity ratings. Typically, these studies focus on the perceived intensity of basic tastes in common foods and beverages, such as chocolate (Reinoso-Carvalho et al., 2017; Reinoso-Carvalho, Gunn, Molina, et al., 2020; Reinoso-Carvalho, Gunn, ter Horst, et al., 2020; Reinoso-Carvalho, Van Ee, Rychtarikova, Touhafi, Steenhaut, Persoone, & Spence, 2015; Reinoso-Carvalho, Van Ee, Rychtarikova, Touhafi, Steenhaut, Persoone, Spence, et al., 2015; Wang et al., 2020) or beer (Reinoso-Carvalho, Velasco, van Ee, Leboeuf, & Spence, 2016; Reinoso-Carvalho, Wang, Van Ee, & Spence, 2016; Reinoso-Carvalho, Dakduk, et al., 2019).

While these studies seem to support a modulatory role of music and sound at the supra-threshold level, less is known regarding its impact on other attributes of taste perception, such as detection and recognition thresholds. Research with other sensory modalities seems to suggest that taste sensitivity is liable to crossmodal influences. In the visual modality, the color in which basic taste solutions are presented may impact participants' ability to recognize certain tastes (e.g., sweetness was identified earlier in a green-colored solution than in red or yellow; Maga, 1974). More recently, Liang et al. (2013) found that individuals exposed to images of rounded shapes (e.g., circles, ellipses) exhibited higher recognition rates of sweetness at near-threshold levels compared to angular shapes (e.g., stars, triangles). Presenting contrasting olfactory stimuli (i.e., strawberry vs. ham odor) during a taste detection task was also found to influence sweet taste detection (with higher sensitivity when the strawberry taste was presented, Djordjevic et al., 2004), whereas adding capsaicin (a trigeminal stimulant known for the irritative sensations caused by products like chili peppers) led to significantly lower recognition thresholds in sweet, sour, salty, and bitter solutions (Han et al., 2021).

With respect to audition, there is still uncertainty regarding how this sensory modality may contribute to taste sensitivity. The current evidence is predominantly associated with the impacts of exposure to noisy conditions on gustatory function. For example, Rahne et al. (2018) found that white noise may affect the identification of some basic tastes but not others. Notably, the noisy condition seemed to increase sweetness recognition but impair sourness perception. More recently, Lorentzen et al. (2021) found no effect of loud fMRI noise on identification scores for any of the basic tastes. In addition to noise, more research is needed to understand how other types of auditory stimuli may influence taste sensitivity. Particularly, music has been shown to improve the perceived intensity of basic tastes and has been proposed as a form of sonic "sweetener" for different products (e.g., Guedes, Prada, Lamy, & Garrido, 2023). Currently, it is still unknown whether music may also improve sensitivity, similar to what has been observed for other multisensory influences (Djordjevic et al., 2004; Han et al., 2021; Liang et al., 2013; Maga, 1974).

1.3. The current study: aims and hypotheses

In this study, we sought to extend the existing evidence regarding the influence of audition on taste perception by testing the influence of musical stimuli on taste sensitivity using sucrose solutions. Specifically, we examined the impact of contrasting sound conditions (high sweetness versus low sweetness soundtracks, and silence) on taste detection and sweet taste recognition. Detection and recognition thresholds were determined for each condition, and the proportions of detection and recognition at each sucrose concentration were examined. For supra-threshold concentrations, ratings of liking and perceived intensity were also analyzed. Changes in mood in response to the experimental manipulation were assessed by measuring self-reported valence and arousal across the three conditions. We hypothesized that the congruent pairing of auditory and gustatory stimuli (i.e., sweet soundtrack and sweet taste) would lead to earlier sweet taste recognition (H1). Moreover, we expected sucrose solutions in the HS condition to be perceived as sweeter (H2) and liked more (H3) than in LS and Silence conditions.

2. Materials and methods

This study was approved by the ethical review board of Iscte – Instituto Universitário de Lisboa (Approval #117/2020).

2.1. Participants

A sample size of 78 participants was estimated using GPower version 3.1.9.6 (power = 0.80, alpha = 0.05, effect size f = 0.25) for repeated measures ANOVA. A total of 79 individuals were recruited to participate in this study. Six participants reported that at least one of the musical stimuli did not reproduce correctly and thus were excluded from the analyses. The 73 participants retained for analysis were aged 18–49 (M = 31.66, SD = 9.26). There were 50 women and 23 men. Mean Body Mass Index was 23.64 kg/m^2, with 59 % of participants within the normal weight range (18.5–24.9). Most participants followed an omnivore diet (92 %) and described themselves as non-smokers (92 %). All participants reported normal hearing, tasting, and smelling abilities. Participation was compensated with 5€ gift cards.

2.2. Stimuli

2.2.1. Taste stimuli

Taste stimuli consisted of nine aqueous solutions with increasing sucrose concentration. All samples were prepared with still mineral water (pH 6.0) and sucrose. Sucrose concentration levels were determined based on the values provided in standard ISO 3972 (for a similar procedure, see Rodrigues et al., 2017). The first sample consisted solely of water, and the following samples were prepared with sucrose concentrations of 0.55 g/L, 0.94 g/L, 1.56 g/L, 2.59 g/L, 4.32 g/L, 7.20 g/L, 12.0 g/L, and 20.0 g/L. The samples were served at room temperature in opaque, disposable paper cups (see Fig. 1). This set of solutions ranged from low to high concentrations in order to adequately cover interindividual differences in taste sensitivity, as well as to allow for a sufficient number of samples with detectable sucrose levels for adequately evaluating sweet taste intensity and liking.

2.2.2. Auditory stimuli

Auditory stimuli were selected from the Taste & Affect Music Database (Guedes, Prada, Garrido, & Lamy, 2023). This dataset provides subjective norms for 100 soundtracks in basic taste correspondences and affective associations. Basic taste correspondences were evaluated according to a forced-choice paradigm, whereas affective associations were assessed using seven-point rating scales.

Two soundtracks were selected from this dataset to represent high and low sweetness correspondences and moderate valence and arousal levels. The high sweetness soundtrack (HS) was an excerpt from "Fruity Juice" composed by Jerry Lacey (Album: By the Blueprint, 2013). This soundtrack was evaluated as sweet by 62.8 % of participants in the norming study. The low sweetness (LS) soundtrack was an excerpt from "Weird Solution" composed by Cobby Costa (Album: Fiction, 2012).

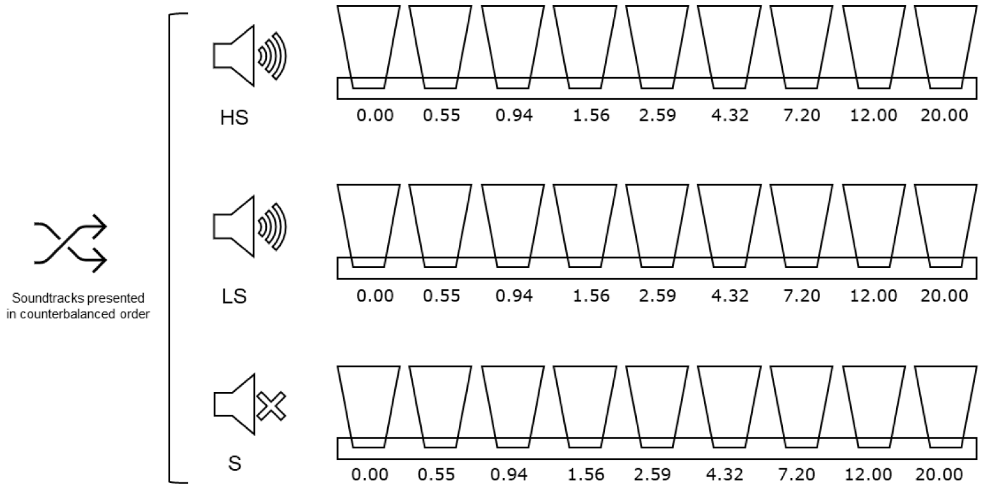

Fig. 1. Overview of the Experimental Procedure.

This soundtrack was evaluated as sweet by 7.23 % of the norming sample.

The soundtracks used in the current study consisted of 30-second excerpts played in a loop throughout the corresponding tasting series. The 30-second sound clips were the same used in the original validation study, and the corresponding files may be found in Guedes, Prada, Garrido, and Lamy (2023), identified as stimuli #58 (HS) and #12 (LS).

2.3. Procedure

To prepare for the study, participants were asked not to eat, drink, smoke, or brush their teeth one hour before the experiment. Moreover, they were asked to have similar breakfasts (i.e., bread and milk or plant-based alternative).

Informed consent was obtained prior to beginning the experiment. Participants were informed that the study involved the consumption of aqueous solutions. The consent form specified the purpose of data collection, the anonymity and confidentiality of responses, and the voluntary nature of participation. Participants were asked to indicate whether they suffered from any food allergies and/or intolerances orally and in the written consent form before beginning the experiment.

All experimental sessions were scheduled at fixed times during the morning (between 9 am and 11 am). The sessions took place in the same location, a tasting room equipped with individual sinks and opaque partitions. Each session had an average of 2–3 participants. Each participant received a tray with the samples arranged in horizontal rows and one (paper) cup of water to cleanse the palate. The water provided here was the same used to prepare the samples.

A web survey, programmed in Qualtrics, was presented on laptop computers equipped with headphones. All tasting procedures and experimental tasks were first explained by the experimenter. Participants were told that the goal of the study was to evaluate different sucrose solutions and to identify basic tastes. For that purpose, they were asked to taste and evaluate three series of solutions, not knowing that the three series were alike. In each tasting series, participants were exposed to one of the three different auditory stimuli (HS soundtrack, LS soundtrack, and silence) in counterbalanced order. Participants were blind to the goals of the study and were informed that they would be using headphones as "a way to keep focused on the task".

The first sample in each series was always the neutral sample (water), followed by the sucrose solutions in ascending order of sweetener concentration (see Fig. 1). Participants were instructed to keep the samples in their mouths for at least five seconds while gently moving the tip of the tongue. They should then spit out the samples and rinse their mouth with water. A 30-second visual timer was provided in the survey to indicate when to proceed to the following sample. After completing each series, participants answered two mood self-report items (valence and arousal). In the end of the experiment, participants were debriefed regarding the goal of the study. The overall procedure took approximately 45 min.

2.4. Measures

2.4.1. Basic information and screening items

This block of questions included basic sociodemographic information (age and sex) as well as self-reported anthropometric items (weight and height). Additionally, participants answered items regarding smoking habits and dietary patterns.

Participants' compliance with eligibility criteria was confirmed by a block of screening items. Individuals were asked to indicate whether they suffered from any compromise to hearing, tasting, or smelling and if they ate, smoked, drank coffee, or brushed their teeth before the experiment (Yes/No).

2.4.2. Sample evaluation

All items and corresponding response scales are presented in Table 1. For each sample, participants were asked to indicate whether they were able to detect any sensation different from water (Yes/No). If no, participants proceeded to the next sample after 30 s. If yes, participants were asked if they were able to identify what distinguished the solution from water (Yes/No). For those who were able to identify the taste

Table 1
Sample Assessment Items and Response Options.

Taste Variable	Item	Response options
Detection	1. Are you able to identify any taste sensation other than the taste of water?	Yes/No
Recognition	2. Are you able to identify what taste distinguishes this sample? [a]	Yes/No
	3. If yes, please indicate which taste that is [b]	Multiple choice: sweet, bitter, sour, salty, other [text entry]
Intensity	4. Please, indicate the level of the scale that best represents the intensity of the taste you've just detected [b]	9-point scale (1 = *Not intense at all*; 9 = *Extremely intense*)
Liking	5. Please, indicate how much you like the taste you've just detected [b]	9-point scale (1 = *Disliked very much*; 9 = *Liked very much*)

[a] Displayed if item 1 was answered "yes".
[b] Displayed if item 2 was answered "yes".

sensation, an additional block of questions was displayed. First, participants were asked to identify the taste sensation on a multiple-choice question with four basic taste alternatives (sweet, bitter, salty, sour) and an open-ended ("other") option. Second, participants were asked to rate the intensity and liking of the taste sensation using nine-point scales (see Table 1).

2.4.3. Mood self-report

Participants were asked to describe their mood (valence and arousal) at the end of each condition, using two 9-point scales ("Please, describe your current mood using the provided scales"). Valence was assessed with one item ranging from 1 (*Negative*) to 9 (*Positive*), and Arousal was assessed with one item ranging from 1 (*Not at all intense*) to 9 (*Very intense*).

2.4.4. Manipulation check

After completing the taste sensitivity task, participants were asked to rate the two soundtracks that were presented before using nine-point scales for sweetness (1 = *not at all sweet* to 9 = *very sweet*), valence (1 = *not at all pleasant* to 9 = *very pleasant*), and arousal (1 = *not at all intense* to 9 = *very intense*).

2.5. Data analysis

Data were analyzed using IBM SPSS Statistics version 26. Two separate repeated-measures (RM) ANOVA were conducted with detection and recognition thresholds as dependent variables, respectively, and sound condition (HS, LS, S) as the independent variable.

Detection thresholds were determined as the lower concentrations at which a taste sensation (i.e., a taste different from water) was detected. Recognition thresholds were determined as the lower concentration at which sweetness was successfully identified (i.e., when participants selected the option "sweetness" in the multiple-choice item). In both cases, a threshold level was only considered valid if it was followed by another consonant response (i.e., two consecutive detections and two consecutive correct recognitions, respectively) and no more than one dissonant response (i.e., two or more non-detections or incorrect taste recognitions in the following samples). If participants could not recognize the sweet taste at the highest concentration (20.00 g/L), they received a score corresponding to what would be the next concentration level in the series (33.00 g/L), following the procedure described in Han et al. (2021).

Additionally, the proportion of participants detecting a taste other than water (detection) and the proportion recognizing sweet taste (recognition) were calculated for each of the nine sucrose concentration levels and compared between conditions with Cochran's Q (with "1" for correct detection/recognition and "0" for no detection/recognition). Average taste intensity and hedonic ratings were calculated for supra-threshold samples (i.e., samples where at least 50 % of participants were able to identify the sweet taste) in each of the three soundtrack conditions. Mean differences in intensity and liking ratings of supra-threshold levels were analyzed with RM-ANOVA.

To test the validity of the experimental manipulations, the HS and LS soundtracks were compared using pairwise *t*-tests for sweetness, valence, and arousal ratings. Additionally, differences in self-reported mood (valence and arousal) were compared with RM-ANOVA. Effect sizes are reported as partial eta squared, and Bonferroni correction was applied to all pairwise comparisons.

3. Results

3.1. Experimental manipulation

The HS soundtrack was rated as significantly sweeter ($M = 6.15$, $SD = 2.10$) than the LS soundtrack ($M = 2.49$, $SD = 1.50$), $t(70) = 11.71$, $p < .001$. The HS soundtrack was also evaluated as more pleasant ($M = 6.63$, $SD = 2.18$) than the LS ($M = 4.82$, $SD = 2.08$), $t(72) = 5.66$, $p < .001$, whereas arousal ratings were higher in the LS soundtrack ($M = 6.00$, $SD = 1.97$) than in the HS ($M = 4.07$, $SD = 1.89$), $t(71) = 8.55$, $p < .001$.

Regarding participants' self-reported mood in each of the three conditions (HS, LS, S), a significant difference was observed in the valence dimension, $F(1.82,130.81) = 3.74$, $p = .030$, $\eta_p^2 = 0.05$. Pairwise comparisons with Bonferroni correction showed a significant difference ($p = .026$) between the HS and the LS conditions, with the HS soundtrack leading to more positive felt valence ($M = 6.73$, $SD = 1.64$), compared to the LS soundtrack ($M = 6.38$, $SD = 1.91$). No differences were observed for felt arousal, $F(2,144) = 0.57$, $p = .565$, ${\eta_p}^2 = 0.01$.

3.2. Effects of experimental condition on taste sensitivity (detection and recognition thresholds)

We did not find a significant impact of experimental condition on detection thresholds, $F(2,144) = 1.23$, $p = .296$, ${\eta_p}^2 = 0.02$. On average, taste detection thresholds were 2.62 ($SD = 3.11$ g/L) in the Silence condition, 3.22 ($SD = 3.75$ g/L) in the LS condition, and 3.34 ($SD = 4.51$ g/L) in the HS condition.

The main effect of sound condition on recognition thresholds was also not significant, $F(2,144) = 0.04$, $p = .964$, ${\eta_p}^2 = 0.00$. In this case, recognition thresholds were 9.44 ($SD = 7.35$ g/L) in the HS condition, 9.62 ($SD = 5.86$ g/L) in Silence, and 9.68 ($SD = 6.52$ g/L) in the LS condition.

3.3. Variation of detection and recognition rates across sucrose concentration levels

Fig. 2 presents the proportion of taste detections (i.e., perception of a taste sensation different from water) obtained for each sucrose concentration for the three sound conditions (Detailed data is available in Supplementary Table 1). Detection rates increased with sucrose concentration, starting with lower proportions of detection in the first sample (between 39.7 % [LS] and 46.6 % [HS] in the 0 g/L sample) until full detection across the three conditions in the most concentrated sample (20 g/L). There were no significant differences between the three conditions for none of the concentration levels.

Fig. 3 presents the variation in recognition rates across the samples for the three conditions (Detailed data is available in Supplementary Table 1). The identification of a sweet taste sensation was lower for the first sample (0 g/L). Although this sample consisted only of water, four participants reported identifying a sweet taste sensation under the HS soundtrack, one in the Silence condition and none in the LS condition. The higher recognition rates were found in the more concentrated sample (20 g/L), albeit no full recognition was achieved in either of the samples. The recognition curves presented in Fig. 3 show a pattern of increase in the correct identification of sweet taste with increasing sucrose concentration. While sweetness was barely recognizable in the least concentrated samples (0.55 g/L – 1.56 g/L), an increase in recognition rates was observable from 2.59 g/L onward. This rise in recognition was achieved earlier in the HS condition, with a significantly larger proportion of participants (23 %) identifying sweetness at 2.59 g/L, compared to 11 % at the LS and S conditions, $\chi^2(2) = 6.000$, $p = .05$.

3.4. Intensity and hedonic ratings of suprathreshold concentrations

Intensity and hedonic ratings were compared for the three most concentrated solutions since 7.20 g/L was the level at which at least 50 % of participants were able to identify the sweet taste, regardless of condition. No significant differences were observed here, with both attributes being rated similarly across conditions in either of the three concentration levels (all $p > .155$).

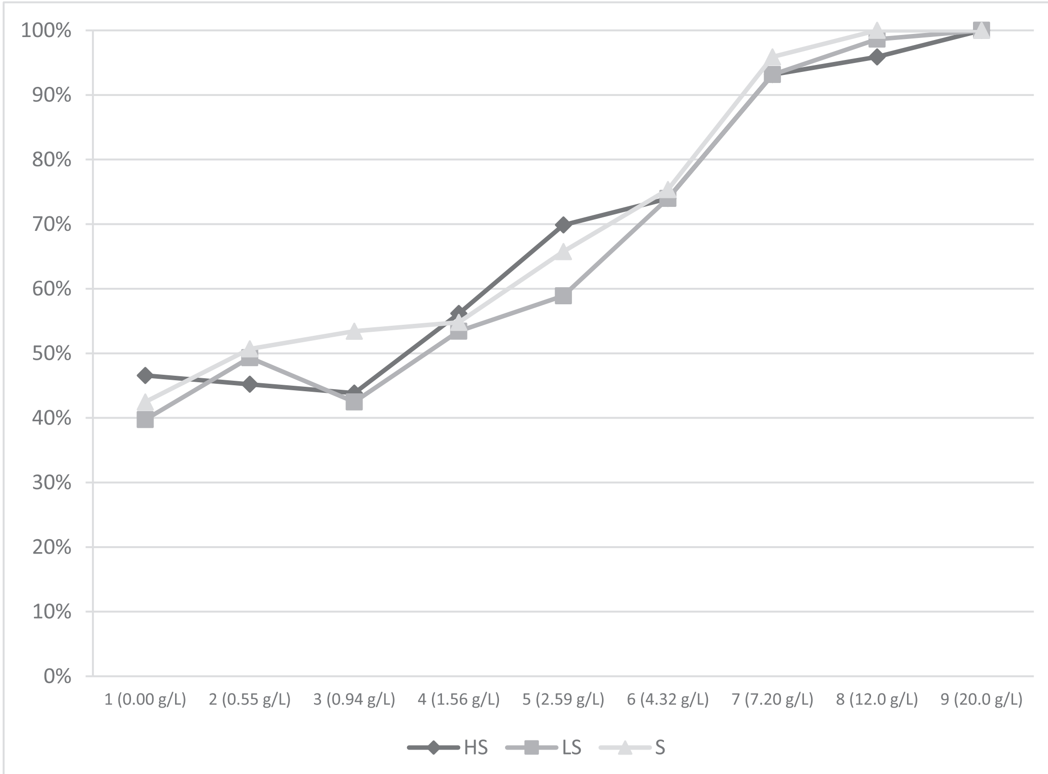

Fig. 2. Variation In the Percentage of Participants Detecting the Presence of a Taste, for Each Sucrose Concentration, in High Sweetness, Low Sweetness, and Silence Conditions. Note. HS = High sweetness; LS = Low sweetness; S = Silence.

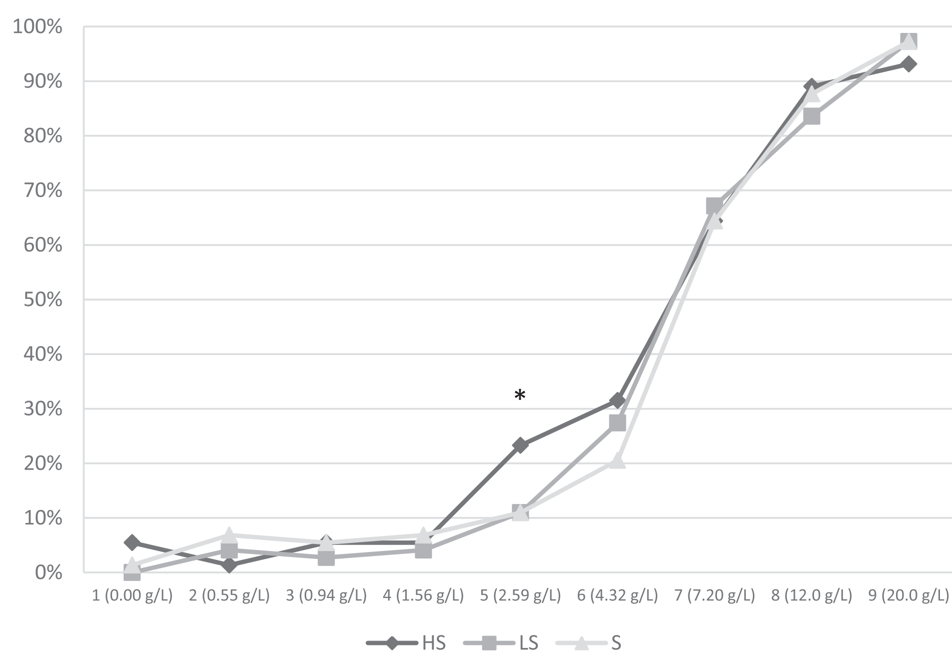

Fig. 3. Variation In the Percentage of Participants Recognizing the Sweet Taste, for Each Sucrose Concentration, in the High Sweetness, Low Sweetness, and Silence Conditions. Note. HS = High sweetness; LS = Low sweetness; S = Silence.

4. Discussion

Despite the growing evidence that music shapes the intensity at which tastes are perceived, less is known about the effect of music on taste sensitivity. In this study, we explored the effects of exposure to three auditory conditions on the ability to detect taste sensations and recognize sweetness in sucrose solutions. Participants completed a taste sensitivity task while listening to soundtracks varying in taste correspondences (highly associated with sweetness vs. lowly associated with sweetness) and in silence. The results support the notion that individuals are able to associate taste and sounds. Indeed, the sweetness ratings of the two soundtracks differed significantly, thus supporting the results previously obtained in the norming study (Guedes, Prada, Garrido & Lamy, 2023). It is worth noting that the crossmodal correspondence patterns observed in this study were observable despite the option for a quantitative measurement strategy instead of a forced-choice paradigm, as is often the case in sound-taste pairings (Guetta & Loui, 2017; Mesz et al., 2011, 2012; Wang et al., 2015).

Notwithstanding the differences in how the musical stimuli were perceived, taste associations did not lead to significant differences in average detection and recognition thresholds. However, a closer inspection of recognition rates at each concentration level showed a significantly higher percentage of participants recognizing the sweet taste at a near-threshold level (2.59 g/L) under the HS music condition. The higher recognition percentage at the near-threshold level seems to align with what Liang and colleagues (2013, 2016) described for the crossmodal effects visual shapes and familiar words had on taste sensitivity. The authors note that the effects of visual information evident at near-threshold levels are no longer significant at lower or higher sucrose concentrations. Thus, these findings seem to suggest that the influence of extrinsic sensory cues in recognition may be more pronounced when the taste stimulus' identity is more "ambiguous". In other words, these extrinsic sensory cues could aid in disambiguating situations when the sweet taste sensation is neither barely recognizable nor clearly recognizable. This result is also consistent with the notion that multisensory integration may aid in solving perceptual ambiguities (Plass et al., 2017). For example, in the famous Rubin face-vase task (an ambiguous, black-and-white image where a vase or two faces may be perceived as dominant), participants are more likely to perceive the white element (faces or vase) as dominant when a high-pitched sound is presented, whereas a low-pitched sound leads individuals to perceive the black element as dominant (Zeljko et al., 2021). This perceptual shift may be attributed to the underlying crossmodal association between higher (vs. lower) pitched sounds and lightness (vs. darkness).

The subtle effect of music on taste perception may be partly explained by its extrinsic influence on oral perception. Unlike odors (Djordjevic et al., 2004) and trigeminal sensations (Han et al., 2021), visually presented shapes and words (Liang et al., 2013, 2016) and musical stimuli are extrinsic sensory cues, rather than attributes of the foods or drinks themselves (Piqueras-Fiszman & Spence, 2015; Spence et al., 2019b). More importantly, the olfactory and trigeminal modalities are considered constitutive (rather than simply modulatory) of flavor perception (Delwiche, 2004; Spence et al., 2015). Although extrinsic auditory stimulation is undoubtedly influential for individuals' experience with foods and drinks, the extent to which it affects taste sensitivity requires further investigation.

It is also interesting to note that the auditory stimuli used in this study did not seem to influence hedonic and intensity ratings of supra-threshold solutions to a significant extent. Most of the existing literature suggests that music may shape how individuals perceive the taste of foods and drinks (De Luca et al., 2019; Guedes, Prada, Lamy, & Garrido, 2023; Hauck & Hecht, 2019; Kantono et al., 2016, 2019; Reinoso-Carvalho et al., 2019; Reinoso-Carvalho, Velasco, et al., 2016; Spence et al., 2013; Wang et al., 2019; Wang & Spence, 2015). However, these effects have been described predominantly for highly palatable products (e.g., chocolate, ice cream) and alcoholic beverages (e.g., wine, beer). Indeed, it has been previously suggested that the effects of music on the evaluation of food products may depend on the product's desirability. For instance, Fiegel et al. (2014) found that music genre affected individuals' impression of an emotional food (chocolate) but not of a non-emotional food (bell peppers). One may hypothesize that this could also be the case with basic taste solutions, which are expected to have a lower hedonic value than familiar foods or drinks. In a previous study, music (in this case, classical music pieces by Tchaikovsky and Berg) was also ineffective in enhancing the sweetness perception of aqueous solutions (Hauck & Hecht, 2019). Of particular importance to our case was that perceived sweetness was unaffected even though the two soundtracks in Hauck and Hecht's (2019) study had been previously evaluated as differing significantly in sweetness correspondences in a pilot experiment.

Previously, it has been argued that some crossmodal correspondences may be relative in nature (Spence, 2019). As such, a direct contrast between soundtracks could be needed to evoke a significant shift in perception (although see also Reinoso-Carvalho, Gunn, ter Horst, et al., 2020). In our study, it is possible that participants' efforts in differentiating each sample from the previous solutions in the series may have somewhat overshadowed the contrast between soundtrack conditions.

One hypothesis for explaining the effect of music on sweet taste ratings has been a sensation transference effect (Reinoso-Carvalho, Wang et al., 2016). According to this view, positive feelings toward music may carry over to the evaluation of foods and beverages. This hypothesis has been put forward to explain why music may enhance (the usually pleasant) sensation of sweetness, as well as contribute to the hedonic experience (Reinoso-Carvalho et al., 2019). However, this does not seem to have occurred in our study as, despite being evaluated differently in valence and arousal dimensions, the affective attributes of the soundtracks did not carry to the ratings of the aqueous samples. Notably, the hedonic ratings of supra-threshold samples remained slightly below the scale's midpoint, suggesting that aqueous samples (unlike food products with more complex food matrices and, perhaps, different hedonic appeal) may be less liable to changes in hedonic ratings. To a certain extent, these findings may express a floor effect, whereby the overall low desirability of aqueous solutions may have motivated a larger convergence around the lower values of the scale.

Previous studies have suggested that taste perception is liable to the influence of mood (Noel & Dando, 2015). For example, exposure to acute stress has been shown to impair sweet taste perception at the intensity level (Al'absi et al., 2012). Exposure to pleasant stimuli, such as pictures or music, may increase the perceived intensity of sweet taste (e.g., Wang & Spence, 2018), and even subtle affective cues, like emoticons, may affect the ability to detect sweet taste. Although the role of the affective value of musical stimuli in taste perception is still a matter of debate (Reinoso-Carvalho, Gunn, ter Horst, et al., 2020), it is likely that the differences in mood reported by participants in this study may have contributed to the higher sweetness detection at the near-threshold level.

4.1. Limitations and future directions

In this study, we sought to extend the current understanding of the crossmodal implications of audition for taste perception by examining the influence of music on taste detection and recognition parameters. Although these findings hint at how sound and taste may interweave at a more basic level of perception, further research is needed to clarify how this relationship may unfold. For instance, here we explored a broad range of sucrose concentrations, spanning very low (barely detectable) levels to higher (clearly detectable) levels. Future studies may wish to explore whether soundtracks may have more profound effects on a narrower range of near-threshold solutions. That was the case in the aforementioned studies of Liang and colleagues (2013, 2016), where smaller intervals between concentration levels were explored. It is also possible that different results would be obtained with products with different familiarity and hedonic appeal (e.g., yogurts, juices), as this may lead to differences, for instance, in acceptance dimensions (e.g., Fiegel et al., 2014).

One important limitation when discussing these results in light of previous findings is that procedures for taste sensitivity analysis often differ among studies. For example, while in our study participants were blind to the content of the samples, participants in Liang's et al. (2013, 2016) experiments were instructed to indicate whether sweetness was present or absent. In Djordjevic's et al. (2004) study, taste detection was determined using a modified staircase method, in which participants were provided two different samples (one blank and one containing sucrose) and were asked to indicate which had a stronger taste. The diversity in assessment methods may, thus, caution against direct comparisons among multisensory studies. Moreover, while this research offers clues about how music may influence taste sensitivity, it is unknown whether these results are generalizable to different music styles or other categories of auditory stimuli (e.g., soundscapes). From that perspective, more empirical inquiry is needed to understand what role may hearing play in the context of taste perception in general and taste sensitivity in particular.

Although the sample size for this study was determined *a priori*, some cases had to be excluded from the data analysis. Thus, the results should be interpreted considering that the number of participants was slightly below the ideal sample size. Furthermore, the higher percentage of women in the sample should also be taken into account, considering the literature suggesting potential sex differences in sweet taste liking (Laeng et al., 1993; Yang et al., 2020), intensity evaluation (Michon et al., 2009) and sensitivity (Rodrigues et al., 2017). An additional limitation concerns the potential complexity (e.g., number of trials) of the experimental task for non-trained participants, which may have resulted in fatigue.

Understanding the crossmodal influence of sound on taste perception is relevant not only from a fundamental science perspective but also from an applied standpoint. Recent evidence suggests that sonic "sweetening" may improve taste perception and increase acceptance of healthier food products, such as vegetables or cookies with reduced sugar content (Guedes, Prada, Lamy, & Garrido, 2023). Extrinsic auditory stimuli may also contribute to increasing the commercial appeal of food products or to creating engaging dining experiences, for instance, by harmoniously pairing flavors and sounds (for a review, see Spence, 2020). Thus, more research is needed to understand if crossmodal effects are generalizable across auditory and gustatory stimuli. Based on the current findings, it appears that the crossmodal contribution of sound on sweet taste perception could depend on the samples' sweetness level and potentially their hedonic value as well.

5. Conclusions

According to multisensory research, taste perception is liable to the influence of all sensory modalities (Spence, 2015). In this study, sweet taste recognition patterns were influenced by the auditory manipulation, whereas taste detection thresholds, as well as intensity and hedonic ratings of supra-threshold samples remained unaltered. These findings suggest that although audition (in this case, musical stimuli) may influence taste perception, its influence may differ according to the perceptive parameter under analysis. Importantly, it appears that sonic cues may aid in disambiguating a gustatory percept, whereas their contribution may be less determinant when the sweet taste sensation is more evident.

This research contributes to a better understanding of the crossmodal role of audition for taste perception, particularly for sweet taste. Understanding the multisensory integration mechanisms underlying sweetness perception may inform future research and intervention targeting sugar consumption.

CRediT authorship contribution statement

David Guedes: Conceptualization, Investigation, Formal analysis, Methodology, Writing – original draft. **Marília Prada:** Conceptualization, Methodology, Writing – review & editing. **Margarida V. Garrido:** Conceptualization, Methodology, Writing – review & editing. **Inês Caeiro:** Investigation. **Carla Simões:** Investigation. **Elsa Lamy:** Conceptualization, Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Ethical statement

This study was approved by the ethical review board of Iscte – Instituto Universitário de Lisboa, Reference number 117/2020, date 18/12/2020.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodres.2023.113256.

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