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Bidirectionality in multisensory perception: Examining the mutual influences between audition and taste

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ABSTRACT

Previous research suggests that people reliably associate sounds and tastes. One important and often-cited implication of these crossmodal correspondences is the modulatory effect of sound on taste perception. In contrast, the potential impact of gustatory sensations on auditory perception has received less empirical attention. This paper presents the results of three experiments examining how listening to a sweet (vs. bitter) soundtrack shapes the sensory perception of bittersweet chocolate (Experiments 1a and 1b) and how the sweet (vs. bitter) taste of chocolate affects the perception of congruent sensory and hedonic attributes of a "bittersweet" soundtrack (Experiment 2). Experiment 1a manipulated the soundtrack type between participants and found no significant effect of music on taste perception. Experiment 1b followed a similar procedure but with a within-participants design. Here, the chocolate sample was perceived as sweeter and more positive when paired with the sweet soundtrack. In Experiment 2, tasting sweet chocolate shifted the evaluation of the bittersweet soundtrack toward higher sweetness and pleasantness and lower bitterness ratings. These findings suggest that sound-taste correspondences may have bidirectional effects on gustatory and auditory stimuli perception. However, the effects of audition on taste may depend on the direct contrast between soundtracks with different crossmodal profiles. These findings contribute to a better understanding of multisensory interactions between audition and taste. The implications for future research and the challenges to real-world interventions are discussed.

1. Introduction

People reliably associate attributes of stimuli arising from different sensory modalities. In the case of audition and gustation, research has shown a considerable degree of consistency in how participants associate auditory stimuli (e.g., music) and basic taste sensations (e.g., sweetness, sourness; Guedes, Prada, Garrido, et al., 2023; Wang et al., 2015). One important implication of the crossmodal mappings between both sensory modalities is that sound may contribute to shaping taste perception in predictable ways (Guedes, Prada, Lamy, et al., 2023). For instance, listening to a music piece associated with sweetness may lead participants to perceive foods as sweeter, while music associated with bitterness may highlight the bitter attributes of the foods instead (Crisinel et al., 2012; see also Höchenberger & Ohla, 2019).

One hypothesis for the emergence of such perceptual changes suggests that sound cues may guide attention to congruent attributes in foods and drinks (Spence et al., 2019). As such, if a sound that happens to be playing in the background activates a specific gustatory association, that same attribute may appear to be more dominant in the flavor matrix (Wang et al., 2019). Music has been the most often studied stimuli in this regard, not only for its ability to embody such conceptual metaphors but also for its emotional value (Guedes, Garrido, Lamy, et al., 2023). One alternative possibility is that the feelings evoked by music somehow transfer to the evaluation of the taste sensations being processed concurrently (Reinoso-Carvalho et al., 2016, 2017; Wang & Spence, 2018). This "sensation transference" account entails that the emotional value of music somehow "contaminates" the hedonic perception of foods, but also the perception of taste or flavor properties. Specifically, it appears that pleasant or liked music may contribute to highlighting taste sensations that are also pleasant (mainly sweetness), whereas disliked music may emphasize less preferred tastes (e.g., bitterness; Kantono et al., 2016, 2019).

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Perhaps due to the intimate connection between taste sensations and the emotional experience, sweet music has been shown to affect not only the perceived sweetness of foods but also their acceptance and participants' intentions of consuming those products again in the future (Guedes, Prada, Lamy, et al., 2023). Thus, it seems likely that music selected based on its crossmodal associations and/or emotional connotations may change how sensory (e.g., taste) and hedonic (e.g., liking) attributes are perceived.

While growing empirical attention is devoted to understanding how and why such crossmodal influences of sound on taste occur, it is unknown whether similar transference effects should be expected from gustation to audition. Generally, crossmodal correspondences are considered bidirectional (Deroy & Spence, 2013), which implies that different tastes might give rise to different sound associations, as much as sounds are differentially associated with tastes. While both approaches are found in the literature on crossmodal correspondences, it is still unknown whether gustatory stimuli also result in different perceptual effects on sound evaluation, similar to the more established "sonic seasoning" effects (Spence et al., 2019; see also Guedes, Garrido, Lamy, et al., 2023).

1.1. The current work: Aims and hypotheses

The current work examines the issue of bi-directionality in sound-taste interactions by further testing the influence of auditory stimuli on taste perception and examining for the first time the symmetrical influence of taste on auditory perception. The influence of "sweet" (vs. "bitter") soundtracks on the taste of bittersweet chocolate was the object of Experiments 1a and 1b. Experiment 1a tested the influence of music on taste perception in a between-participants design, and Experiment 1b directly contrasted the soundtrack conditions within participants. We hypothesized that the chocolate would be perceived as sweeter when paired with the sweet (vs. bitter) soundtrack (H1) and more bitter when accompanied by the bitter (vs. sweet) soundtrack (H2). We also hypothesized the chocolate to be liked more when the tasting occurred while listening to the sweet (more pleasant) versus the bitter soundtrack (H3).

To test the hypothesis that sound-taste interactions also have implications for auditory perception, participants in Experiment 2 tasted a sweet (vs. bitter) chocolate while evaluating a "bittersweet" soundtrack. We hypothesized that the taste stimulus would shift the evaluation of the soundtrack in a congruent manner. In other words, tasting sweet chocolate should contribute to the bittersweet soundtrack being evaluated as sweeter (H4), whereas tasting bitter chocolate should lead to the soundtrack being evaluated as more bitter (H5). Considering the link between sweetness and pleasantness (Guedes, Prada, Garrido, et al., 2023; Wang et al., 2015), we also hypothesized that sweeter (vs. bitter) chocolate would lead to higher valence ratings of the soundtrack (H6).

2. Experiment 1a: Shaping taste perception through sound

This experiment examined how sound affects taste perception by presenting contrasting musical stimuli during a taste evaluation task. Participants tasted one piece of semi-dark chocolate while listening to one of two soundtracks previously evaluated as highly associated with sweetness or bitterness (Guedes, Prada, Garrido, et al., 2023). Semi-dark chocolate was chosen as an ambivalent gustatory stimulus, where sweet and bitter sensations are concurrently salient, contrary to milk or dark chocolates, where a single taste sensation is predominant. In this situation, we expected the underlying music-taste correspondences to highlight the congruent taste sensations in the chocolate evaluation task (Crisinel et al., 2012; Höchenberger & Ohla, 2019).

2.1. Materials and method

2.1.1. Participants and design

One hundred and nineteen university students (M_{age} = 21.1, SD = 4.9) volunteered to participate in this experiment. The sample included 99 participants who identified as women, 19 as men, and one as non-binary. Based on self-reported weight and height data, most participants (67%) were classified as normoponderal (18.5 kg/m^2 < BMI < 25 kg/m^2), 15% as underweight, and 18% as overweight or obese. Course credits were attributed as an incentive for participating in the study. Participants were randomly assigned to the sweet (n = 61) or bitter (n = 58) soundtrack conditions. The full sample characterization is provided in Supplementary Table 1.

2.1.2. Experimental materials

2.1.2.1. Gustatory stimuli. One piece of semi-dark chocolate (50% cocoa) was presented on a disposable white plate. The chocolate had a sugar content of 47%.

2.1.2.2. Auditory stimuli. The two instrumental soundtracks were selected from the Taste & Affect Music Database (Guedes, Prada, Garrido, et al., 2023). The sweet soundtrack ("Tranquility Lane" by Dawn, Dawn, Dawn) was associated with the sweet taste by 80.8% of the norming sample. The bitter soundtrack ("Intentional Evil" by Kikoru) was associated with the bitter taste by 64.4% of the norming sample. Both soundtracks corresponded to 30 s excerpts played in a loop throughout the tasting task. The excerpts are available in the original validation study materials, identified as stimuli #68 (sweet) and #26 (bitter). These soundtracks were not marketed directly to the public, thus being generally unknown to participants.

2.2. Procedure

All experiments were approved by the ethical review board of Iscte – Instituto Universitário de Lisboa (Approval #117/2020).

Participants were pre-screened for food allergies and/or intolerances. Before taking part in the experiment, they were instructed to refrain from eating, drinking coffee, brushing their teeth, or smoking for one hour before the experiment. Data were collected at the university lab, in a room with individual sound-proof booths equipped with computers and headphones. All data were collected via a web-based survey programmed in Qualtrics. All devices were kept at the same comfortable volume level. The study sessions were scheduled at fixed times during the day, with no sessions taking place 1 h before or after conventional main-meal times.

Participants were told they would be evaluating a food sample while listening to music (using headphones). After providing informed consent, they were asked to provide sociodemographic information (e.g., age, gender) along with self-report measures of anthropometric (height, weight) and homeostatic variables (thirst, hunger). Participants were then randomly allocated to one of the two music conditions (bitter or sweet) and evaluated the chocolate in taste (sweetness and bitterness) and affective (valence and intensity) attributes. The survey was programmed to play the soundtracks automatically, and the sound player controls remained hidden from participants.

Finally, as a manipulation check, the two soundtracks that were used in the experiment were presented (in random order) to be evaluated in taste (sweetness) and affective (valence, intensity) dimensions. After completing the survey, participants were thanked and debriefed.

2.2.1. Measures

The chocolate sample was evaluated in sensory and affective attributes using 9-point scales. The sensory attributes were sweetness (1 = *not sweet at all* to 9 = *very sweet*) and bitterness (1 = *not bitter at all* to 9 =

very bitter), whereas the affective items referred to valence (1 = *very negative* to 9 = *very positive*) and intensity (1 = *not intense at all* to 9 = *very intense*).

In the soundtrack evaluation task, participants rated each excerpt on sweetness (1 = *not sweet at all* to 9 = *very sweet*), valence (1 = *very negative* to 9 = *very positive*), and intensity (1 = *not intense at all* to 9 = *very intense*) using 9-point scales. All scales were presented in randomized order.

2.3. Data analytic plan

All analyses were conducted with IBM SPSS Statistics v28. To examine the influence of music on the chocolate's taste, we computed a mixed ANOVA with the soundtrack (sweet, bitter) as the between-participants variable and the type of attribute (sweet, bitter) as the within-participants variable. Affective (valence, intensity) ratings were compared with independent samples *t*-tests. The ratings of the musical excerpts (manipulation check) in the attributes of sweetness, valence, and intensity were compared using paired-samples *t*-tests.

2.4. Results

The ANOVA results showed that the soundtrack condition did not significantly affect the overall taste experience, $F(1, 117) = 0.841$, $p = .361$, $\eta_p^2 = 0.01$. Moreover, no significant interaction was observed between the soundtrack condition and the type of taste attributes ($p = .571$). The results of the *t*-tests also showed no significant differences in the affective (valence, intensity) variables (all $p > .181$). The mean ratings of the chocolate in the two soundtrack conditions are presented in Fig. 1.

The manipulation check confirmed that the soundtracks were perceived as intended. The sweet soundtrack was perceived as sweeter ($M = 7.52$; $SD = 1.58$) than the bitter soundtrack ($M = 2.34$; $SD = 1.48$), $t(118) = 24.78$, $p < .001$, $d = 2.27$. The sweet soundtrack was also perceived as significantly more positive ($M = 7.17$; $SD = 1.77$) than the bitter soundtrack ($M = 3.01$; $SD = 1.54$), $t(118) = 20.98$, $p < .001$, $d = 1.92$; whereas the bitter soundtrack was perceived as more intense ($M = 7.67$; $SD = 1.54$) than the sweet soundtrack ($M = 3.73$; $SD = 2.38$), $t(118) = 14.59$, $p < .001$, $d = 1.34$.

3. Experiment 1b: Shaping taste perception through sound in a within-participants design

The results of Experiment 1a did not show the expected effect of music on the perceived taste of chocolate. However, it has been previously argued that crossmodal associations are relative in nature (Spence, 2011, 2019). If so, some form of contrast between the auditory stimuli could be needed for a sonic seasoning effect to become evident. To further test this possibility, we replicated the procedures of Experiment 1a, but this time manipulating sound within participants.

3.1. Methods

3.1.1. Participants and design

Sixty-eight university students ($M_{age} = 22.5$, $SD = 5.7$) participated in this experiment. The sample included 52 participants who identified as women and 16 as men. Based on self-reported weight and height data, most participants (76%) were classified as normoponderal (18.5 kg/m^2 < BMI < 25 kg/m^2), 3% as underweight, and 21% as overweight or obese. Course credits were attributed as an incentive for participating in the study. Participants completed the chocolate evaluation task with both soundtracks (in counterbalanced order). The full sample characterization is provided in Supplementary Table 1.

3.1.2. Procedure

The same procedures of Experiment 1a were followed, but this time participants tasted two identical pieces of the same chocolate paired with the two (sweet and bitter) soundtracks in counterbalanced order. The chocolate samples were identified with different three-digit codes (unrelated to the samples' identity), such that participants were unaware that they were tasting the same chocolate. A cup of water was available throughout the experiment, and participants were instructed to drink after each sample to cleanse the palate.

As a manipulation check, after completing the tasting task, the two soundtracks were presented again (in random order) to be evaluated in taste (sweetness, bitterness) and affective (valence, intensity) dimensions. After completing the survey, participants were thanked and debriefed.

3.2. Data analytic plan

All analyses were conducted with IBM SPSS Statistics v28. We

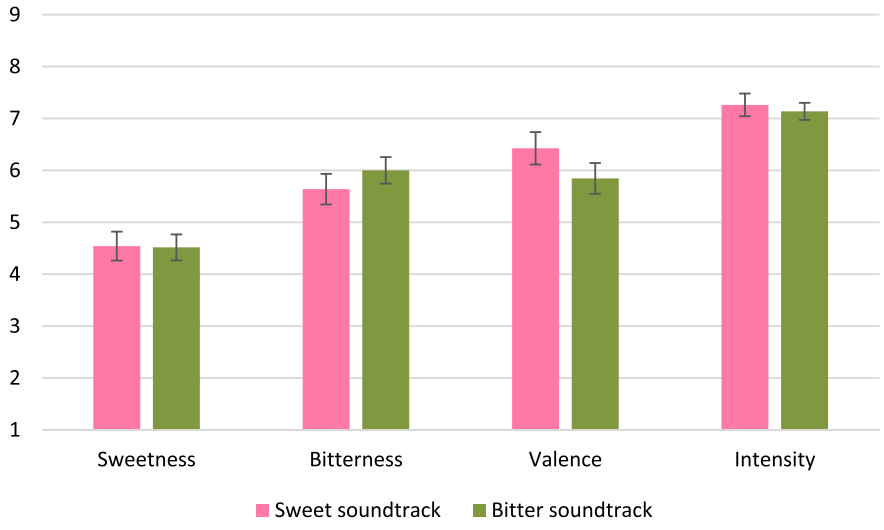

Fig. 1. Mean ratings of the chocolate sample in the sweet soundtrack and bitter soundtrack conditions. *Note.* Error bars represent standard errors.

computed a repeated measures ANOVA with soundtrack (sweet, bitter) and the type of attribute (sweet, bitter) as the independent variables. The chocolate's affective ratings (valence, intensity) were compared with paired-samples *t*-tests.

3.3. Results

The ANOVA results showed that the soundtrack condition did not significantly influence the overall taste experience, $F(1, 67) = 0.66$, $p = .420$, $\eta_p^2 = 0.01$. However, a significant interaction indicated that music impacted the sweet and bitter ratings differently, $F(1, 67) = 5.67$, $p = .020$, $\eta_p^2 = 0.08$. Pairwise comparisons with Bonferroni correction showed that although the bitterness ratings varied in the expected direction, the differences did not reach statistical significance ($p = .157$). Conversely, participants provided significantly higher sweetness ratings while listening to the sweet ($M = 5.12$, $SE = 0.28$) than the bitter soundtrack ($M = 4.50$, $SE = 0.27$), $p = .004$.

Results of the *t*-tests showed that valence ratings were also higher while listening to the sweet ($M = 6.13$, $SD = 2.50$) than the bitter soundtrack ($M = 5.59$, $SD = 2.26$), $t(67) = 2.52$, $p = .014$, $d = 0.31$. Intensity ratings did not differ significantly between conditions ($p = .117$). The mean ratings of the chocolate in both soundtrack conditions are presented in Fig. 2.

Once again, the manipulation check confirmed that the soundtracks evoked the intended taste and affective associations. The sweet soundtrack was perceived as sweeter ($M = 7.46$; $SD = 1.83$) than the bitter soundtrack ($M = 2.37$; $SD = 1.38$), $t(67) = 17.27$, $p < .001$, $d = 2.09$. In contrast, the latter music excerpt was evaluated as significantly more bitter ($M = 6.34$; $SD = 2.11$) than the former ($M = 1.78$; $SD = 1.34$), $t(67) = 15.26$, $p < .001$, $d = 1.85$. Likewise, the sweet soundtrack was perceived as significantly more positive ($M = 7.47$; $SD = 1.73$) than the bitter soundtrack ($M = 3.04$; $SD = 1.52$), $t(67) = 17.23$, $p < .001$, $d = 2.09$; whereas the bitter soundtrack was perceived as more intense ($M = 7.85$; $SD = 1.34$) than the sweet soundtrack ($M = 3.13$; $SD = 2.12$), $t(67) = 13.9$, $p < .001$, $d = 1.69$.

4. Experiment 2: The influence of taste on auditory perception

In the first set of experiments, we examined the effect of music on the taste attributes and affective evaluation of bittersweet chocolate. This second experiment aimed to explore whether different taste stimuli may influence the evaluation of the crossmodal attributes of music.

It is common practice to formulate sound-taste correspondences tasks in a forced-choice format. This strategy could be seen as implying that correspondences between the two sensory modalities are unambiguous and absolute (i.e., a sound is either sweet OR bitter) rather than ambiguous and relative (i.e., a sound may be concurrently sweet AND bitter to a certain extent). Yet, even when correspondences are treated as nominal data, there might still be evidence of ambiguity at the interindividual level, for example, when two or more taste categories are selected in equivalent proportions (Guedes, Prada, Garrido, et al., 2023).

In this experiment, we took "bittersweetness" as an example of ambiguity in crossmodal correspondences. Participants were exposed to contrasting gustatory stimuli (i.e., bitter or sweet chocolate) while evaluating a soundtrack previously associated with sweetness and bitterness in even proportions.

4.1. Method

4.1.1. Participants and design

One hundred and six university students ($M_{age} = 26.2$, $SD = 10.3$) volunteered for this experiment. The sample included 69 participants who identified as women, 34 as men, and three as non-binary. Based on self-reported weight and height data, most participants (66%) were classified as normoponderal (18.5 kg/m^2 < BMI < 25 kg/m^2), 11% as underweight, and 23% as overweight or obese. Course credits were attributed as an incentive for participating in the study. Participants were randomly assigned to the conditions of sweet ($n = 54$) or bitter chocolate ($n = 52$).

4.1.2. Experimental materials

4.1.2.1. Gustatory stimuli. The sweet (milk) chocolate had an approximate cocoa percentage of 30% and 52% sugar. The bitter (dark) chocolate had 85% cocoa percentage and 14% of sugar. The chocolate samples were served in individual pieces on disposable white plates.

4.1.2.2. Auditory stimuli. The auditory stimulus for this experiment was again selected from the Taste & Affect Music Database (Guedes, Prada, Garrido, et al., 2023). The chosen music excerpt ("Not Ready to Go" by Christophe Gorman) was rated as sweet by 41.2% and as bitter by 43.5% of the norming sample. The validated music excerpt has a 30 s duration and is freely available in the validation study materials (Stimulus #5; Guedes, Prada, Garrido, et al., 2023).

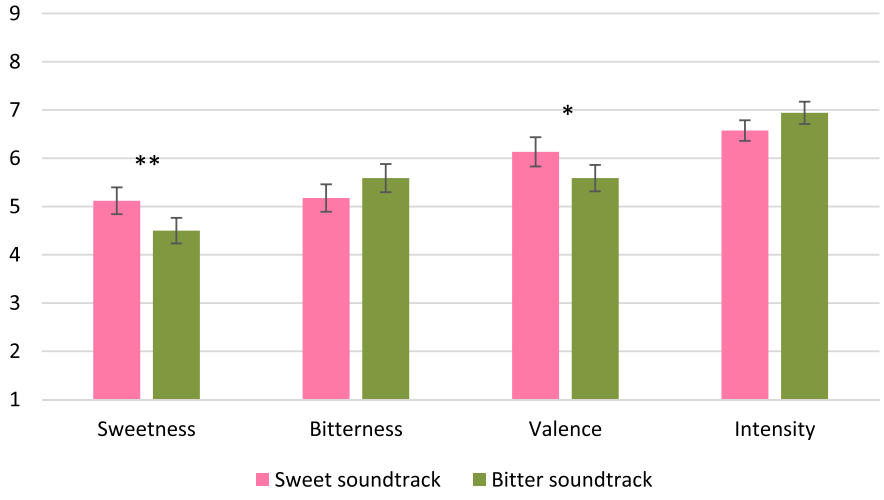

Fig. 2. Mean ratings of the chocolate sample in the sweet soundtrack and bitter soundtrack conditions. *Note.* Error bars represent standard errors. * $p < .050$; ** $p < .010$.

4.1.3. Procedure

Pre-screening (e.g., allergies) and preparation procedures (e.g., avoiding eating one hour before the experiment) and experimental setting and apparatus were the same as in Experiments 1a and 1b.

Participants were told that a chocolate brand was testing a new soundtrack to promote one of their products. Their task consisted in tasting the chocolate and evaluating the soundtrack. At this phase, participants were randomly given a piece of bitter or sweet chocolate and evaluated the soundtrack using the provided scales. After completing the survey, participants were thanked and debriefed.

4.1.4. Measures

The soundtrack was evaluated in several affective and taste-related attributes using 9-point scales. The taste-related attributes of interest were sweetness (1 = *not sweet at all* to 9 = *very sweet*) and bitterness (1 = *not bitter at all* to 9 = *very bitter*). The affective attributes included two dependent variables, pleasantness (1 = *not pleasant at all* to 9 = *very pleasant*) and intensity (1 = *not intense at all* to 9 = *very intense*), in addition to two filler items (joy and sadness) to support the cover story. All scales were presented in randomized order.

4.2. Data analytic plan

All analyses were conducted with IBM SPSS Statistics v28. To examine whether the taste of chocolate influenced the taste associations in response to the bittersweet soundtrack, we computed a mixed ANOVA with chocolate type (milk/sweet, dark/bitter) as the between-participants variable and the type of crossmodal associations in response to the soundtrack ("sweet", "bitter") as within-participants variable. The affective evaluation of the music excerpt (valence, intensity) was compared with independent samples *t*-tests.

4.3. Results

The mixed ANOVA results showed that the chocolate type did not change the overall music evaluation, $F(1, 104) = 1.03$, $p = .312$, $\eta_p^2 = 0.01$. However, a significant interaction effect indicated that results differed between sweetness and bitterness evaluation, $F(1, 104) = 22.41$, $p < .001$, $\eta_p^2 = 0.18$. Pairwise comparisons with Bonferroni correction showed that participants evaluated the bittersweet music as sweeter when tasting the sweeter chocolate ($M = 6.11$, $SE = 0.31$) than when tasting the bitter chocolate ($M = 4.52$, $SE = 0.31$), $p < .001$. Likewise, the bittersweet soundtrack was perceived as more bitter when tasting the bitter chocolate ($M = 5.10$, $SE = 0.33$) than when tasting the sweet chocolate ($M = 3.04$, $SE = 0.32$), $p < .001$.

The results of the *t*-tests revealed that the soundtrack was also perceived as more pleasant when tasting the sweeter chocolate ($M = 6.83$, $SD = 1.77$) than the bitter chocolate ($M = 5.88$, $SD = 2.28$), $t(104) = 2.4$, $p = .018$, $d = 0.47$. The intensity ratings did not differ significantly between groups ($p = .963$).

Fig. 3 presents the mean ratings for the taste (sweetness, bitterness) and affective (pleasantness, intensity) ratings of the soundtrack as a function of the chocolate being tasted.

5. General discussion

Across three experiments, we examined the bidirectional relationship between audition and taste. First, these findings reinforced that music can shape taste perception. We found that the sweet and bitter soundtracks influenced the evaluation of chocolate but only when both (sweet and bitter) soundtracks were presented to participants (within-participants design, Experiment 1b) rather than when participants were exposed to either one or the other (between-participants design, Experiment 1a). When the same chocolate was tasted twice, participants were more prone to provide higher sweetness and valence ratings when the chocolate was paired with sweet (vs. bitter) music. Second, we showed for the first time that gustatory stimuli may influence the crossmodal associations in response to music. Experiment 2 found that the sweet (vs. bitter) taste of chocolate influenced participants' associative process in response to a soundtrack previously evaluated as bittersweet (Experiment 2). The sweeter stimulus appears to have shifted the crossmodal associations in the congruent direction, such that the bittersweet soundtrack was evaluated as sweeter, less bitter, and more pleasant when tasting chocolate with higher (vs. lower) sugar content. Contrary to the previous experiments, the effect was notorious in a between-participants design, suggesting that contrast between gustatory stimuli may not be necessary.

Crossmodal correspondences are thought to be bidirectional in nature (Deroy & Spence, 2013), which in the sound-taste case implies that sounds give rise to different taste correspondences just as tastes can be differentially matched to different sounds. A critical implication of crossmodal correspondences has been the possibility of using sound to shape taste perception (i.e., sonic seasoning; Spence et al., 2019). A growing body of literature now suggests that delivering auditory stimuli purposely chosen to match taste/flavor attributes can influence the multisensory eating experience (Guedes, Garrido, Lamy, et al., 2023).

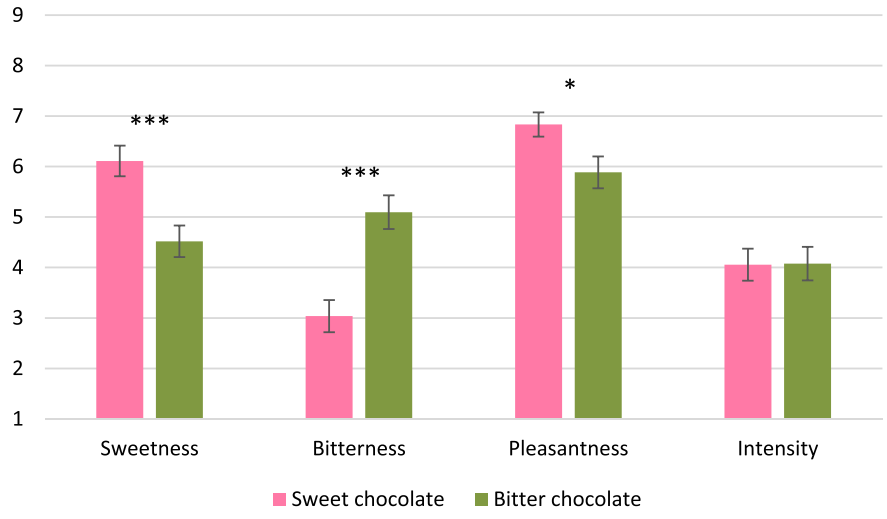

Fig. 3. Mean ratings of the musical stimuli in the sweet chocolate and bitter chocolate conditions. *Note*. Error bars represent standard errors. * $p < .050$; *** $p < .001$.

The attributes of sounds can transfer to the evaluation of foods and drinks, influencing not only their gustatory attributes but also their hedonic perception (Guedes, Prada, Lamy, et al., 2023; Kantono et al., 2016; Reinoso-Carvalho et al., 2016).

The current findings partially support this hypothesis. Indeed, music that differs in taste correspondences and affective dimensions resulted in different evaluations of the same chocolate. However, this difference became apparent only when participants were exposed to both soundtracks subsequently (Experiment 1b). In Experiment 1a, in which music was manipulated between participants, the chocolate's taste ratings did not differ significantly. Interestingly, the manipulation check results confirmed that participants associated the two soundtracks with different levels of sweetness and bitterness when both excerpts were presented.

Previously, it has been suggested that contrast between sounds could be a necessary condition for sonic seasoning to emerge since crossmodal associations are thought to be relative (Spence, 2011, 2019). In effect, literature reviews on the topic show a predominance of studies following repeated measures designs (Guedes, Garrido, Lamy, et al., 2023; Spence et al., 2019), although it is unknown whether studies with between-participants designs are less commonly conducted or simply not reported due to null results (Franco et al., 2014). Direct comparisons between study designs also seem to be lacking in the literature, hindering researchers' ability to make empirically based decisions.

Recently, the contrast assumption has been challenged in a large-sample study where music pieces with different emotional profiles triggered changes in the multisensory perception of chocolates, notwithstanding the between-participants methodology adopted in the study (Reinoso-Carvalho, Gunn, ter Horst, et al., 2020). The same study also tested music with different crossmodal profiles (a "soft" soundtrack more associated with sweetness and a "hard" soundtrack associated with bitterness) but found that their impact on the chocolate evaluation was less pronounced than with the emotional music. One possibility is that music selected based on crossmodal correspondences may need some form of contrast to provoke changes in taste perception, but the same principle does not necessarily apply to emotional music to the same extent.

Another aspect that has remained elusive in previous within-participants experiments is whether the effects of music on sweet taste perception reflect an enhancing effect of a crossmodally congruent sound (i.e., sweet) or rather a dampening effect of the contrasting auditory stimulus (Guedes, Prada, Lamy, et al., 2023). Regrettably, the manipulation check of Experiment 1a did not include the bitterness dimension. However, the results of Experiment 1b could be seen as partially supporting the first hypothesis, considering that in a context where sweetness and bitterness were assessed as separate dimensions (rather than on a sweet-to-bitter continuum; e.g., Crisinel et al., 2012; Höchenberger & Ohla, 2019), sweet (vs. bitter) music significantly increased sweetness ratings, whereas bitter music not only attenuated sweet taste perception, as it also seemed to improve its corresponding taste sensation, although not to a significant extent. Nevertheless, this issue could not be fully clarified in this study, and further investigation is needed, namely, by including a baseline condition (e.g., tasting the sample in silence).

Interestingly, differences in bitterness ratings were more subtle than in sweetness (and failed to reach statistical significance) even though the manipulation check confirmed that the bitter soundtrack effectively communicated the taste attribute it intended to convey. One possible interpretation for this finding is that sweetness is generally a more tangible crossmodal attribute in music. The sweet soundtrack was selected based on a norming study where 80.8% agreed on this taste association, whereas the highest agreement rate for bitterness was 64.4% (Guedes, Prada, Garrido, et al., 2023). Similarly, in the manipulation check of Experiment 1b, the mean sweetness rating for the sweet soundtrack was slightly higher than the mean bitterness rating of the bitter soundtrack, suggesting that sweetness may be a more pronounced crossmodal attribute with a modulatory influence in proportion. Alternatively, this result could also reflect attributes of the chocolate itself. As such, it could be of interest to study whether similar results would be obtained with samples with different sweet-bitter profiles.

As the literature on sonic seasoning becomes growingly solid and well-established, there is still scarce evidence regarding the potential effects of gustation in auditory processing. A sensation transference mechanism similar to what has been described for sonic seasoning could help explain the results of Experiment 2, where the evaluation of a bittersweet soundtrack was significantly shifted congruently with gustatory sensations. From a crossmodal standpoint, this soundtrack could be considered an example of an ambiguous stimulus. Indeed, participants in the norming study were almost equally prone to associate it with the sweet or the bitter taste. The presence of a gustatory stimulus with a sweet (vs. bitter) profile may have helped solve this perceptual ambiguity based on the congruency between the two sensory modalities. These results could then be framed in light of previous literature describing crossmodal disambiguation effects, such as those of sound over vision (Plass et al., 2017; Zeljko et al., 2021), vision over taste (Liang et al., 2013) or touch over vision (Blake et al., 2004; Lunghi et al., 2010).

Interestingly, the gustatory manipulation influenced the soundtrack's evaluation without the need for a direct contrast between conditions. This may suggest that sweet and bitter gustatory sensations do not require direct comparison to activate the intended taste concept. Alternatively, evoking taste-related associations through sound is potentially more challenging, as these correspondences depend on a more complex web of associations. For instance, previous studies suggest that sweet and bitter taste associations in response to music may depend on affective cues, as well as a broad range of psychoacoustic parameters, such as pitch, loudness, articulation, and others (e.g., Mesz et al., 2011; Wang et al., 2015). Although we did not test this hypothesis, we would expect participants to be more likely to agree on the taste category (sweet or bitter) that is more salient in milk and dark chocolate than on the taste that best matches each soundtrack. As mentioned before, when music-taste correspondences are evaluated in a forced-choice format, there is an above-chance agreement around certain taste options, but agreement rates are frequently less than perfect (Guedes, Prada, Garrido, et al., 2023; Wang et al., 2015). Possibly, the complexity of sound-taste judgments also increases liability to individual differences, based on previous experience or cognitive tendencies, with likely consequences for the consistency of crossmodal mappings (for a review, see Spence, 2022).

5.1. Limitations and future directions

Some limitations should be considered when interpreting these studies' results. Previous sonic seasoning studies have relied mostly on highly palatable food and beverages, including chocolate (for a review, see Guedes, Garrido, et al., 2023). While research consistently shows that taste perception is liable to the influence of sound, it is uncertain whether these results are generalizable to different food products, particularly those differing in hedonic value. Previously, it has been suggested that music could impact foods differently depending on the products' hedonic value (Fiegel et al., 2019), although there is evidence suggesting that similar sonic seasoning effects may be found on foods with different palatability levels (Guedes, Prada, Lamy, et al., 2023). In this study, we focused solely on one product, which limits our ability to ascertain the generalizability of the sonic seasoning effects.

In both sonic seasoning experiments reported here, we examined the effects of two soundtracks previously evaluated as highly associated with sweet and bitter tastes. The manipulation check further confirmed this assumption but also reinforced that both music excerpts differed significantly in their affective value. Notably, the sweet soundtrack was evaluated as more pleasant than the bitter, whereas the latter was evaluated as more intense. Considering prior literature showing that

music pleasantness and/or liking may account for differences in taste perception (Kantono et al., 2016, 2019; Reinoso-Carvalho, Gunn, Molina, et al., 2020; Reinoso-Carvalho, Gunn, ter Horst, et al., 2020), we cannot rule out the possibility that the differences observed here were motivated by differences in participants' affective state, rather than crossmodal associations alone. Moreover, participants' familiarity with the auditory stimuli was not assessed as part of the manipulation check. Objective familiarity levels are expected to be negligible, considering that the soundtracks used in this study were not disseminated to the public (unlike pop hits or classical music). However, it could be of theoretical interest to contemplate familiarity as a subjective dimension, similar to the procedure of the original norming study (Guedes, Prada, Garrido, et al., 2023).

In Experiment 2, we tested the influence of the taste of chocolate in disambiguating the taste associations and affective responses to a musical stimulus. However, while in sonic seasoning studies, participants are usually unaware of the experimental manipulation (i.e., they are blind to the fact that music excerpts reflect different taste qualities), the same might not be said of this experiment. Indeed, it may seem more evident that the taste associations in response to a soundtrack should be influenced by a gustatory stimulus presented concurrently than the other way around. Thus, future studies looking to further examine bidirectionality in taste-sound interactions may look for influences of taste stimulation on the evaluation of specific acoustic attributes (e.g., volume, pitch) rather than taste and affective dimensions alone.

One additional limitation of this set of experiments concerns the sampling strategy. The studies reported here were based on samples of university students with relatively narrow age intervals and imbalanced gender proportions. Any considerations regarding the generalizability of these findings should thus be made with caution considering, for example, age and gender differences in taste function (e.g., Bertelsen et al., 2020; Hyde & Feller, 1981; Mojet et al., 2001; Yoshinaka et al., 2016). In future research, it could also be relevant to assess the practical applications of these laboratory findings to real-world settings, for example, by replicating these experiments in meal contexts (e.g., restaurants, cafeterias).

6. Conclusions

This paper presents two main contributions to understanding the crossmodal interactions between sound and taste. First, the results suggest that the perceptual effects of sound-taste correspondences may operate bidirectionally. Contrasting (sweet vs. bitter) gustatory stimuli seemed to contribute to disambiguating an auditory stimulus previously evaluated as bittersweet, whereas contrasting (sweet vs. bitter) soundtracks influenced the perception of the corresponding taste attributes in a bittersweet chocolate.

Second, these findings seem to support the hypothesis that the effects of music on taste may depend on the direct contrast between soundtracks with different "taste" profiles. Although this possibility has been discussed elsewhere (Reinoso-Carvalho, Gunn, ter Horst, et al., 2020; Spence, 2011, 2019), to our best knowledge, this is the first time this hypothesis has been tested directly by conducting two equivalent experiments, differing only in the sound manipulation (within vs. between participants). From a research perspective, this would mean that within-participants designs would be more suitable for observing sonic seasoning effects. From an applied perspective, this could imply that simply customizing soundscapes to match any of the basic tastes could be insufficient to improve the multisensory experience. While more research is needed to back this hypothesis, this potential limitation should alert us to the complexities of implementing multisensory strategies in real-world environments. One possible pathway to overcoming these limitations could be the study of multicomponent interventions integrating different sensory modalities. Creating smarter multisensory environments could contribute to creating not only more pleasant eating experiences but also potentially healthier consumption patterns, for instance, by compensating for sugar reduction (Guedes, Prada, Lamy, et al., 2023).

CRediT authorship contribution statement

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

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodqual.2023.104964.

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