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Psychological sweetening: Multisensory interactions shaping sweet taste perception

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PhD in Psychology

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Acknowledgments

Carl Jung believed that psychological theories were personal confessions. The science of his time was surely different from ours, yet there is still something confessional about the questions to which we willingly dedicate years of our lives trying to answer. As Eça de Queiroz put it, curiosity may lead one to "listen at doors or to discover America", but regardless of the merit or dignity of either venture, these impulses still say much about what we care for.

I've always felt fascinated by the world of food, which is an important part of why this thesis exists. I was lucky enough to be granted the necessary intellectual and material support to follow the path of curiosity, and for that, I am sincerely grateful. In this regard, my first words of gratitude must go to my advisors.

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Resumo

A investigação tem demonstrado que a audição pode modificar a perceção de alimentos/bebidas. Neste contexto, o conceito de *sonic seasoning* define a escolha deliberada de sons de modo a serem congruentes com determinados gostos/sabores e, consequentemente, modificarem a sua saliência na matriz sensorial de alimentos/bebidas. Neste trabalho, focamo-nos na possibilidade de modular a perceção do gosto doce através da música. Para esse fim, apresentamos um conjunto de seis artigos incluindo (a) uma revisão sistemática sobre as interações entre sons e gostos básicos e suas implicações para a perceção gustativa (Estudo 1) e (b) um estudo normativo que explorou a associação de músicas a gostos e a dimensões afetivas/emocionais (Estudo 2); um conjunto de estudos experimentais que indicaram (c) que a música influencia a sensibilidade para o gosto doce (Estudo 3); (d) a bidirecionalidade da relação audição-gosto (Estudo 4), nomeadamente que a música enfatiza o gosto doce numa amostra sensorialmente ambígua (Experiências 1a e 1b) e que a sua avaliação é influenciada pela estimulação gustativa (Experiência 2); (e) a preponderância de estímulos musicais associados ao gosto doce (correspondências intermodais) sobre estímulos musicais de valência positiva (afeto) na avaliação sensorial e hedónica de alimentos (Estudo 5); (f) o potencial da música para melhorar a perceção e aceitação de produtos com diferentes teores de açúcar (Estudo 6). Este projeto contribui para uma melhor compreensão de aspetos teóricos e metodológicos subjacentes ao *sonic seasoning* e reforça o potencial da música na melhoria da perceção e aceitação de alimentos com reduzido teor de açúcar.

Palavras-chave: correspondências intermodais, sonic seasoning, audição, perceção gustativa, consumo de açúcar

Categorias e códigos de classificação PsycINFO:

2320 Sensory Perception

3920 Consumer Attitudes & Behavior

Abstract

Recent research has demonstrated that audition can shape the perception of foods/drinks. In this context, the concept of sonic seasoning has been put forward as the way by which sounds may be deliberately selected to be congruent with specific taste/flavor sensations and, consequently, modify their salience in the sensory matrix of foods/drinks. In this work, we focus particularly on the possibility of modulating sweet taste perception through music. To this end, we present a collection of six articles, including (a) a systematic review on sound-taste interactions and their implications for taste perception (Study 1); a norming study exploring the associations between music and taste and emotional/affective dimensions (Study 2); a collection of experimental studies showing (c) that music can impact sweet taste sensitivity (Study 3); (d) the bidirectionality of sound-taste interactions (Study 4), namely that music emphasizes the sweet taste in food with an ambiguous flavor profile (Experiments 1a and 1b) and its evaluation is influenced by gustatory stimulation (Experiment 2); (e) the prominence of sweet taste associations (cross-modality) over positive valence (affect) in how music shapes the sensory and hedonic evaluation of foods (Study 5); (f) the potential of music to improve the sensory and hedonic evaluation of products with varying sugar content (Study 6). This project contributes to a better understanding of theoretical and methodological questions underlying sonic seasoning and reinforces the potential of music in improving the sensory evaluation and acceptance of products with low-sugar content.

Keywords: crossmodal correspondences, sonic seasoning, audition, taste perception, sugar consumption

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CHAPTER 1

Introduction

The history of taste perception begins early in development. The first taste sensations arise in utero as early as 14 weeks (Bradley & Stern, 1967; Hersch & Ganchrow, 1980; Witt & Reutter, 1998), and in the later stages of gestation, human fetuses show reactivity to the flavor sensations originating from maternal diets (Ustun et al., 2022).

In the first years of life, sensory cues, such as taste, smell, and texture, determine much of children's food preferences and choices and guide their learning of what is safe, desirable, and rewarding (Boesveldt et al., 2018). Throughout the lifespan, however, food preferences and choices become increasingly complex (Köster, 2009). Food acceptance becomes less determined by innate sensory preferences (e.g., rejecting bitter tastes) but instead reflects a vast array of expectations and predilections regarding how food should taste, smell, feel, look, and sound.

In the globalized world, food offer is as diverse as ever before, with food brands often striving to surprise the senses. From blue wine (Bacalhôa, n.d.) to pyramid-shaped watermelon (Tsui, 2019) or cappuccino-flavored chips (Lutz, 2014), the food market has seen the oddest sensory concoctions emerge in recent years. Gastronomists and chefs have also embarked on the quest to find novel and engaging multisensory eating experiences, from lighter-than-air cloud desserts (Passera, 2022) to metamorphic light plates that animate foods (King, 2014) or seafood dishes accompanied by sounds of crashing waves and seagulls (Spence & Piqueras-Fiszman, 2013).

These examples seem at odds with the simple and most fundamental function of food: providing nutrition and ensuring survival. Yet, they highlight one important aspect of our relationship with foods, which is that the senses (and, crucially, their interplay) are essential for the hedonic experience. The rise of ASMR-inspired[1] food commercials (Graakjær, 2021; Kim, 2020) and the surge of "food porn" contents on social media (ones that are characterized by bold and suggestive visual elements; Taylor & Keating, 2018) further attests to this primacy of the senses and the apparent realization that the eating experience is more than just taste.

[1] Autonomous Sensory Meridian Response (ASMR) typically refers to the experience of pleasant/relaxing affective and/or physiological sensations in response to audiovisual triggers (e.g., whispering, scratching). Despite the recent scientific literature around ASMR, the concept has gained prominence mainly on social media and through anecdotal reports (McGeoch & Rouw, 2020; Poerio et al., 2018).

In the scientific realm, eating has been depicted as one of the most multisensory human activities (Auvray & Spence, 2008; Small, 2012; Spence, 2015; Wang et al., 2019, 2021). Along with the interweaving of taste, olfaction, and the trigeminal modality in the oral cavity, auditory, tactile, and visual sensations seamlessly concur in the act of eating. These extrinsic sensory influences are not limited to the properties of the foods and drinks themselves but also include aspects like room temperature, ambient sounds, or the features of plateware and packaging (Wang et al., 2019).

During the act of eating, different sensory inputs are integrated into a perceptive whole that is more than the sum of its parts (Small, 2012). This multisensory integration occurs as a neural process whereby unisensory signals coalesce into a new product that differs from its basic components (Stein et al., 2010). Perhaps a proper metaphor for the phenomenology of multisensory perception would be that of an orchestration of the senses. Subjectively, the five senses of taste, smell, touch, hearing, and sight are perceived in combination akin to a symphony whose beauty and meaning depend on the harmonious conjugation of its instrumental groups and may not be reduced to their individual contributions.

A second and distinct phenomenon emerging from the interdependence among sensory modalities is cross-modality. Broadly speaking, this term refers to situations where stimuli arising from one sensory modality influence the perception or the ability to respond to stimuli presented in another sensory modality (Spence et al., 2009). It is at this intersection that we focus our attention throughout this work. We investigated the often-neglected contribution of audition on taste perception (Spence, 2016) from two perspectives. First, we were interested in the interactions between the two sensory modalities from the perspective of their mutual associations (i.e., crossmodal correspondences). Second, we set out to investigate the effects of sound on taste perception. We were particularly interested in understanding the potential contribution of music to improving the taste experience and testing its implications for better eating (namely, by testing the sweetening effect of music with low-sugar products).

This introductory chapter commences with an overview of the concept of multisensory food perception, from the neuropsychological bases of the flavor experience (1.1. Multisensory food perception) to the modulatory role of the extrinsic sensory cues (1.2. Multisensory food perception: More than meets the mouth). The interplay of audition and taste perception is then introduced from the perspective of the crossmodal associations between the two senses (1.3. A tale of sound and taste). A primer on the conceptual underpinnings of these associations is provided. The following section is devoted to the role of audition in shaping taste perception (1.4. Sonic sweetening: Its causes and consequences). This section covers the theoretical bases of sonic seasoning and examines its implications for eating behavior. We devote particular attention to sweet taste perception and the potential role of sound in reducing sugar consumption. The aims of this work and its research methodology are presented in the final section (1.5. Aims and overview of the research).

1.1. Multisensory food perception

1.1.1. Experiencing flavor

Our perception of foods and drinks results from the integration of at least three sources of sensory information, namely, taste, smell, and trigeminal sensations (International Organization for Standardization, 2008). Yet, the binding of these sensory modalities is so seamless that most people struggle to disentangle taste (i.e., the basic sensations of sweetness, saltiness, bitterness, sourness, and umami) from smell (Stevenson, 1999, 2014). The experience of flavor as a unitary sensory experience is thought to be facilitated by the concurrence of these sensory signals in time and space (Small, 2012; Stein, 1998). Indeed, taste receptors are located in the mouth, and retronasal smell receptors behind the nose bridge also receive volatile chemicals originating from events in the oral cavity (Small & Green, 2012; Stevenson, 2016). While this spatiotemporal coincidence may help understand how perceptual synthesis unfolds, it is also relevant to ask why this binding occurs.

From an evolutionary perspective, the integration of taste and smell sensations may be advantageous due to the complementarity of these sensory modalities in identifying suitable foods (Prescott, 2015). While basic tastes are useful cues for guiding broadly adaptive nutritional choices (e.g., sweetness for carbohydrates, umami for protein), olfactory inputs are paramount for learning to differentiate foods and diversifying dietary choices (Bartoshuk, 1991).

The consistent co-occurrence of taste and smell sensations during eating allows for the learning of contextual regularities. The fact that strawberry odors are consistently paired with the sweet taste may help explain why individuals describe the smell of strawberries as sweet, a phenomenon that has been described as a form of synesthesia (Stevenson et al., 1998; Stevenson & Boakes, 2004). The term synesthesia, in this sense, is meant to express a common subjective experience when a stimulus in one sensory modality evokes an experience associated with another sensory modality (i.e., phenomenal synesthesia) rather than the neurodevelopmental condition whereby individuals consistently experience these extraordinary perceptual phenomena (Stevenson & Tomiczek, 2007). Still, Auvray and Spence (2008) argued that multisensory perception of flavor does not necessarily represent a synesthetic experience but instead a unification of taste and smell into a single percept. Although anatomically independent, taste and smell (and the trigeminal modality) may be cognitively integrated similarly to how the separate vision systems (the "where" system related to motion, depth, and position, and the "what" system related to shape and color) are fused so that the attributes of both systems are perceived as indissociable (Abdi, 2002).

1.2. Multisensory food perception: More than meets the mouth

Beyond flavor, there are other examples of how sensory integration impacts how we perceive the world. Crossmodal influences, for instance, are circumstances where stimuli presented in one sensory modality influence the perception of stimuli in another modality (Spence et al., 2009). One classic example is the McGurk effect, where conflicting visual and auditory cues lead to a form of perceptual illusion. Specifically, when individuals listen to a given utterance [e.g., ba] over the image of someone mouthing another syllable [e.g., ga], they tend to perceive a different sound [e.g., da] which resembles a blend of the other two (McGurk & MacDonald, 1976). The Bouba/Kiki effect is also a popular example, in this case, of a crossmodal association between shapes and sounds. The effect refers to the significant consensus that a round shape is a better match for the word "Bouba", whereas a spiky shape is better suited to the word "Kiki" (Köhler, 1929; Ramachandran & Hubbard, 2001).

In the case of food perception, the range of possible multisensory influences lies beyond what happens in the oral cavity. Notably, visual and auditory cues also contribute largely to the multisensory experience with foods. In the former case, there is a seemingly intuitive understanding of how visual information may be relevant to the enjoyment of foods. Just as the famous adage about eating first with our eyes goes, the mere sight of foods initiates a series of anticipatory brain responses to prepare the organism for ingestion (Killgore et al., 2003; Wang et al., 2004). Indeed, the sight of foods is commonly considered part of the cephalic phase when hormonal and neural signals are elicited to prepare the gastrointestinal tract for digestion (Liddle, 2012; Smeets et al., 2010).

The visual aspect of foods is an important source of information regarding the sensory properties of foods, such as taste. For instance, individuals may expect fruits with colors closer to the red end of the spectrum to taste sweeter than those closer to the green end of the spectrum since this is a natural correlation in the environment (Foroni et al., 2016; Maga, 1974). It is possible – and likely – that these associations are further reinforced by the consistent use of congruent colors for food packaging, such as a red package for sweet popcorn versus blue for salty (Wang & Chang, 2022). These repeated pairings might help explain why individuals come to develop a seemingly shared understanding of the appropriateness of certain color-taste matchings, such as pink-sweet, green-sour, or white-salty (Wan et al., 2014; see also Spence & Levitan, 2021).

While natural co-occurrences of certain visual (e.g., color, shape) and gustatory attributes (e.g., taste, flavor) in foods may help shed light on the crossmodal mappings exhibited by some individuals, it is less clear why certain sounds become reliably associated with tastes as well. In effect, most foods and drinks do not have distinctive sounds. For instance, Vickers (1980) found that individuals have a less-than-perfect ability to distinguish foods based solely on their crushing sounds. The study also noticed that some foods (e.g., water chestnut) may produce more easily recognizable sounds than others (e.g., unripe pear). Unsurprisingly, current studies with food sounds seem to rely on a small range of sounds that are more easily identifiable, such as those associated with crispiness/crunchiness (Zampini & Spence, 2004) or fizziness/carbonation (Zampini & Spence, 2005). Otherwise, many other food sounds may be quite unspecific, such that without context, it might be difficult to distinguish the sound of a sizzling pan from that of a rainy night[2].

In the case of foods, the fact that sonic cues seem less determinant for object identification (compared to the sight or smell of foods) may help explain why audition is often seen as a less relevant sense for the eating experience (Spence, 2016). For instance, Schifferstein (2006) asked participants to rate the relative importance of the five sensory modalities for the enjoyment of different products. For foods, the auditory modality was rated as the less important sense, regardless of the product type. Put differently, the sound of foods was always seen as less important than their taste, smell, texture, or look, regardless of the product being an apple, a cheese, or even a cookie. Unsurprisingly, sensory lexicons (i.e., standardized vocabularies for the sensory analysis of foods) often overlook auditory attributes in product evaluation. In a recent review of sensory lexicons for a variety of food categories, Suwonsichon (2019) identified descriptors for taste, visual, olfactory, and textural attributes but not of auditory characteristics (for an exception, see, for instance, Dijksterhuis et al., 2007). Against this backdrop, one could be tempted to disregard audition altogether as a relevant sensory modality

[2] This ambiguity is, in fact, the trick for many radio or tv productions where so-called Foley artists artificially craft sounds that mimic something else, such as waves crashing or a heavy storm, without actually manipulating these elements (de Gotzen et al., 2013).

for food perception. However, a growing body of empirical evidence is now suggesting otherwise.

1.3. A tale of sound and taste

It has been mentioned before that many nonarbitrary associations exist between stimuli attributes in different sensory modalities. For audition and taste, there is now a growing body of literature showing that basic taste sensations may be crossmodally associated with a great diversity of sounds, from more simple stimuli, such as musical notes or words, to more complex sounds, such as musical pieces (Spence et al., 2019a).

1.3.1. Crossmodal correspondences between audition and taste

The interest in the associations between audition and taste is thought to have its roots in the seminal studies by Danish experimental psychologist Kristian Holt-Hansen. In one experiment, Holt-Hansen (1968) set out to find what he described as taste-pitch harmony. The experimenter manipulated the frequency of a sound and instructed participants to indicate when they felt the pitch was in harmony with the taste of a beer. This exercise was done for two different beer varieties, and interestingly, participants seemed to match different sound frequencies to the two beers. More intriguing, perhaps, was how participants described their experience of harmony. One participant is quoted as saying that the Carlsberg Elephant Beer, which is “not tasty”, “too dark”, “bitter”, and “scratching”, actually became “really quite a pleasant drink” when in harmony with the right pitch (p. 66). In a later experiment, Holt-Hansen (1976) again narrated participants’ extraordinary experiences in response to the sound-taste harmony, which included “tickling, prickly, or quivering” sensations or “heat in the head, the ears and the body” (p. 1025).

Such colorful observations intrigued other researchers and led to a later replication by Rudmin and Cappelli (1983) where the same procedure was repeated with different foods (i.e., hard candy, dill pickle) and drinks (i.e., alcoholic and non-alcoholic beer, and grapefruit juice). The authors found no trace of the exotic experiences described in the previous studies. However, participants still matched different sound frequencies to the products under analysis (e.g., higher frequency for hard candy, lower for non-alcoholic beer).

Rudmin and Cappelli’s paper could have been the last word on sound-taste interactions. However, by the turn of the millennium, researchers were becoming less interested in the isolated study of the senses in an Aristotelian fashion[3]. Instead, they were turning their attention to how the combination of sensory modalities may open new possibilities in our understanding of perception (Spence et al., 2009). It was a matter of time until the integration of audition and gustation was again a matter of scientific interest. Crisinel and Spence (2009) revisited the taste-pitch problem, this time looking for associations between pitch and basic taste sensations. In this study, participants completed an Implicit Association Test with names of bitter (e.g., coffee, dark chocolate) and sour foods (e.g., vinegar, pickles) alongside musical notes with higher and lower pitch levels. The results suggested that the two taste sensations were matched to pitch differently, one finding that was shortly after extended to other basic tastes and using different experimental approaches. Notably, the sour but also sweet taste was associated with a higher pitch, whereas bitterness, on the other hand, was more strongly linked to a low pitch (Crisinel & Spence, 2010a, 2010b).

In the years that followed, several other studies examined pitch-taste correspondences, turning it into what is possibly the most thoroughly studied acoustic parameter in terms of basic taste associations (Crisinel & Spence, 2011, 2012; Knöferle et al., 2015; Qi et al., 2020; Reinoso-Carvalho et al., 2016; Velasco et al., 2014; Wang et al., 2016; Watson & Gunther, 2017). Still, to some extent, pitch was just the tip of the iceberg regarding sound-taste correspondences. Some of these studies showed that when participants were asked to match tastes with musical notes, their responses were not solely based on the sounds' frequencies but also on the musical instrument playing those notes (Crisinel & Spence, 2010b; Watson & Gunther, 2017).

It has since been shown that sound-taste correspondences are not limited to simple stimuli, such as musical notes, but also to more complex musical compositions. Professional musicians, on the one hand, seem to have an intuitive understanding of how to express taste-related sensations through music. Except for the word "sweet" (*dolce*), there is no musical vocabulary to inform musicians on how a basic taste should sound like. Yet, the sample of professional musicians in Mesz's (2011) study seemed consistent in how they manipulated certain acoustic parameters, such as loudness, articulation, or dissonance, to create sweet, sour, salty, or bitter music pieces. Although one could be tempted to assume this as a sign of high emotional sophistication, it has been shown that laypeople are also capable of telling apart a sweet from a bitter music piece with above-chance accuracy (e.g., Mesz et al., 2011, 2012; Wang et al.,

[3] That is to say that much of our understanding of the senses - their identity and demarcation - is rooted in notions from classical philosophy and very prominently in the writings of Aristotle, notably the treatises *De anima* and *De sensu* (Ierodiakonou, 2022; Sorabji, 1971).

2015). Thus, it becomes increasingly intriguing to question what makes these crossmodal correspondences occur in the human mind.

1.3.2. Psychological mechanisms underlying sound-taste correspondences

Some of the earliest findings regarding crossmodal correspondences involve the auditory modality. The aforementioned Bouba/Kiki effect had its roots in Köhler’s (1929) seminal studies, and these sound-shape preferences have since been shown to hold even across different cultures and writing systems (Ćwiek et al., 2022). In the same year Köhler was experimenting with shapes, Edward Sapir (1929) found that meaningless words using the vowel [a] (e.g., ‘mal’) were more frequently associated with large objects. In contrast, those using the vowel [i] (e.g., ‘mil’) tended to be associated with smaller objects. Later research suggested that vowels such as [i] and [e] tend to have higher frequencies compared to low back vowels such as [o] and [a], while coincidently, smaller objects and animals also tend to produce higher-pitched sounds (Ozturk et al., 2013; Shayan et al., 2011).

As these historical examples illustrate, crossmodal correspondences appear to emerge as an “adaptation of sensory systems to natural scene statistics” (Parise, 2016, p.1). In some cases, these natural correlations may seem more obvious. The pitch-size association is one example of a relatively straightforward statistical inference based on the inverse relation between resonance frequency and the size of the resonator (keeping other factors constant, such as density or tension, Parise & Spence, 2013). As mentioned before, in the case of sound-taste correspondences, the criterion of statistical co-occurrence may be more challenging to grasp. While there is yet no definitive answer to how and why the brain generates such consistent mappings among auditory and gustatory cues, it is worth mentioning some of the current hypotheses to explain sound-taste correspondences.

To date, four mechanisms (statistical, semantic, hedonic, intensity matching) have gathered particular prominence in the literature referring to correspondences involving audition, in general, or more specifically referring to those associations between audition and tastes/flavors (Knöferle & Spence, 2012; Spence, 2020b).

1.3.2.1. Statistical co-occurrences

One of these hypotheses actually derives from a statistical regularity mechanism. Knöferle and Spence (2012) propose that the innate orofacial gestures displayed by infants in response to pleasant and unpleasant tastes (Ganchrow et al., 1983; Steiner et al., 2001) have associated speech sounds (e.g., protruding the tongue outward and upward in response to a pleasant taste could result in higher frequency sounds when exhaling) that may become associated with taste sensations with different hedonic values. Certain speech sounds (e.g., [i] and [o]) have also been linked with contrasting affective expressions (Garrido & Godinho, 2021; Rummer et al., 2014), which may allow them to become associated with different (pleasant and unpleasant) taste sensations (Motoki et al., 2020). As Ernst (2007) demonstrated, new correspondences between previously unrelated stimuli (i.e., luminance and stiffness) may be learned *ad hoc*. Similarly, it seems reasonable to expect that exposure to incidental correlations (i.e., not found in the natural world) may also allow the internalization of novel associations. For example, the consistent use of specific sounds in food brands, such as fricative (e.g., [f], [s]) and voiceless consonants (e.g., [p], [k]) for sweet products or stop (e.g., [t], [g]) and voiced consonants (e.g., [b], [d]) for salty, could contribute to developing expectations regarding how food brand names should sound based on their taste and vice-versa (Motoki et al., 2020).

1.3.2.2. Intensity matching

A second putative mechanism alludes to the structural organization of the perceptual system to explain, for instance, why participants match louder sounds to higher concentrations of tastants (e.g., sugar; Wang et al., 2016). The "intensity matching" hypothesis (Knöferle & Spence, 2012) is rooted in the notion that magnitude (regardless of the dimension to which it refers) is represented in similar terms in the brain (Bueti & Walsh, 2009; Walsh, 2003). As in the above-mentioned loudness-taste association, higher intensities in one (e.g., gustatory) dimension are expected to be mapped onto the intensity of the other dimension (e.g., auditory). However, this rule does not necessarily hold for every acoustic dimension, as Wang et al. (2016) also report that pitch-taste associations do not show a similar correlation across all taste categories.

1.3.2.3. Semantic matching

The fact that people describe different dimensions (volume, pitch, height) under the same terms (high and low) may give rise to a third type of crossmodal association (semantic). Several studies now show that sound pitch influences the speed at which people discriminate the position of a visual target, such that detection of an upper (vs. lower) visual stimulus is facilitated by the concurrent presentation of a higher- (vs. lower) pitched sound (Ben-Artzi & Marks, 1995; Evans & Treisman, 2010). The use of high/low terms to refer to intensity magnitudes in taste could then help extend to sound-taste mappings. Moreover, in various languages, the word "sweet" is involved in metaphors for sweet, tender musical sounds or manners of speaking (Mesz et al., 2012). Coincidentally, sweetness tends to be more readily decoded in sounds than any other taste sensation (Wang et al., 2015), which may suggest that semantic congruence among sensory modalities may help explain the associations between audition and taste.

1.3.2.4. Emotion mediation or hedonic matching

Finally, it appears that most auditory stimuli are not affectively neutral (Yang et al., 2018). Music, for example, is defined as a vehicle for emotions, and most people listen to music for its expressive and inducive effects (Juslin & Laukka, 2004; Juslin & Västfjäll, 2008; Zentner et al., 2008). According to an emotion mediation account, individuals tend to match liked or pleasant music to taste sensations to which they attribute similar preference or hedonic value (Spence, 2020a). This hypothesis is consistent, for instance, with the findings of Wang et al. (2015), where music-taste associations were partly mediated by pleasantness for the sweet and bitter tastes and partly by arousal for sourness.

The literature suggests that this hypothesis is not exclusive of complex auditory stimuli like music. Other studies found evidence for a hedonic matching account with more elementary stimuli, such as musical notes (Crisinel & Spence, 2010b, 2012). These studies revealed, for example, that notes played by more pleasant musical instruments, such as piano, were preferentially matched to the more pleasant taste sensations. Nevertheless, it seems reasonable to expect simple (e.g., musical notes) and complex (e.g., music) auditory stimuli to give rise to a significantly different latitude of emotional reactions. Moreover, the literature is often unclear regarding the dimensions that could mediate crossmodal correspondences of both types. Indeed, emotional variables may refer to basic emotion categories (e.g., sadness, fear, surprise; Ekman & Cordaro, 2011; Mohn et al., 2011; Tracy & Randles, 2011) or broader affective dimensions (e.g., valence, arousal; Barrett & Russell, 1999; Bradley & Lang, 2000; Russell, 1980). Similarly, it is not entirely clear whether crossmodal mappings depend on the emotions/affective dimensions conceptually associated with auditory stimuli or rather with respondents' affective states in response to these sounds (Spence, 2020a).

Currently, various sound-taste correspondences are described in the literature, and the conceptual hypotheses put forth so far seem to illustrate that diversity. As the above discussion suggests, some hypotheses might seem more suitable for a given class of correspondences than for others (e.g., intensity matching for loudness but not pitch-based associations). Therefore, more research will be needed to better understand the causal mechanisms underlying sound-taste correspondences.

1.4. Sonic sweetening: Its causes and consequences

As mentioned before, a convincing body of literature suggests reliable connections between the senses of audition and gustation. Under certain circumstances, sound-taste correspondences may lead to perceptual consequences, namely in how the tastes of foods and drinks are perceived (Spence et al., 2019b). This has led to the emergence of a body of literature around sonic seasoning, that is, the circumstances when "music/soundscapes are specially chosen, or else designed/composed, in order to correspond to, and hence hopefully to modify the associated taste/aroma/mouthfeel/flavor in food and beverages" (Spence, Reinoso-Carvalho, et al., 2019, p. 7). In this section, we focus particularly on the influence of sound on the perception of basic tastes, given their key relevance for food choice and acceptance (Boesveldt & de Graaf, 2017; Negri et al., 2012; Spetter et al., 2014). The implications for promoting better eating habits are discussed.

1.4.1. Food sounds and their impact on perception

Despite the initial neglect of audition as part of the eating experience (e.g., Spence, 2015a, 2016), there is now a growing recognition that the sounds produced by foods or those resulting from our interaction with them have important consequences for food perception and enjoyment (Spence et al., 2019b). One seminal paper in this regard showed that listening to augmented mastication sounds increased the perceived freshness and crispness of potato chips (Zampini & Spence, 2004). Participants in this experiment were instructed to bite potato chips while their own mastication sounds were fed back through headphones, unaltered or manipulated for loudness and sound frequency. The study found that chips were rated as crisper and fresher when the overall sound level was amplified or when only the high-frequency sound components were increased. Similar results were later obtained with apples, where mastication sounds influenced the perceived hardness and crispness of the samples (Demattè et al., 2014).

Carbonated beverages provide another striking example of when sounds take center stage in setting the right sensory expectations and experience. Anecdotal evidence seems to confirm that for sparkly wines, as the saying suggests, "the smaller the bubbles, the better the wine" (Spratt et al., 2018). One illustrative example from experimental psychology showed that participants judged sparkly water in a cup as significantly more carbonated when listening to its amplified sound or when they held the drinks closer (vs. far) to their ears (Zampini & Spence, 2005). Intriguingly, the influence of auditory feedback did not extend to actual oral perception, with no differences in carbonation being reported when participants tasted the samples instead of merely holding the cups in their hand.

These examples seek to highlight just how important food sounds may be to our experience with foods. However, extrinsic auditory cues, such as the sounds of packaging (e.g., opening a bottle of wine), cooking (e.g., popping popcorn), or the sounds of the surrounding environment (e.g., a noisy cafeteria vs. eating outdoors in a park) may also have significant consequences to food choice, intake, and perception (Zampini & Spence, 2010). Specifically, we center our attention on musical sounds as one of the most pervasive sonic stimuli in modern-day environments. With increasing digitalization and the democratization of artistic fruition, music is now readily available in most public and private eating environments (e.g., restaurants, cafeterias, homes). A vast body of earlier and more recent literature shows that music can affect important affective, cognitive, and behavioral processes associated with the consumption of foods and drinks, including drinking and eating speed (McElrea & Standing, 1992; Milliman, 1986; Roballey et al., 1985), food and beverage intake (Cui et al., 2021; Guéguen et al., 2008; McCarron & Tierney, 1989; Stroebele & de Castro, 2006), meal pleasantness and enjoyment (Fiegel et al., 2014; Kantono, Hamid, Shepherd, Yoo, Carr, et al., 2016; Kantono, Hamid, Shepherd, Yoo, Grazioli, et al., 2016; Mathiesen et al., 2021, 2022; Woods et al., 2011), or the duration of consumption episodes (Caldwell & Hibbert, 2002; Mathiesen et al., 2020, 2021, 2022; Stroebele & de Castro, 2006).

Beyond the musical influences on food-related behaviors, it seems increasingly evident that sounds may participate in shaping the sensory evaluation of foods and drinks. There is now compelling evidence that the perception of basic taste sensations may be influenced by the surrounding sonic atmosphere (Spence et al., 2019b). The crossmodal correspondences between audition and taste seem to hold particular significance to this effect, with sonic seasoning appearing to emerge from some form of congruence between the food's gustatory matrix and the crossmodal attributes of the sound being delivered concurrently. The seminal experiment of Crisinel et al. (2012) is one example of such an effect. In this study, participants tasted a bittersweet toffee while listening to a sweet or a bitter soundtrack. As hypothesized, the authors found that music enhanced the corresponding taste attribute in the food sample, such that the toffee was perceived as sweeter when accompanied by the sweet soundtrack and more bitter when paired with the bitter music. Other examples abound in the literature with selective manipulation of the most conventional taste sensations (sweetness, bitterness, saltiness, sourness, and umami). Sweetness has been the focus of particular attention in this regard, presumably because it seems, to date, the most easily recognizable taste attribute in music

(Wang et al., 2015). As Mesz et al. (2011) note, sweetness is the only taste sensation with translation into musical terminology. In musical scores, the Italian term “dolce” requests musicians to play in an emotionally tender manner (Juslin, 2013), perhaps mimicking the pleasurable feeling states experienced when tasting sweets (Booth et al., 2010).

Although not usually articulated in the literature, there is a second reason for the interest in enhancing sweet taste perception. Sugar intake levels are on the rise at the global scale (OECD & FAO, 2023). The excessive intake of free sugars[4] has raised particular concern due to its associations with poor dietary quality, namely by the higher energy intake from nutrient-poor foods (Louie & Tapsell, 2015; for a review, see Mela & Woolner, 2018). Although associations with health outcomes remain controversial (Stanhope, 2016), several studies point to a potential contribution of excessive sugar intake in the development of many non-communicable diseases, including cardiovascular disease (Richelsen, 2013; Vos et al., 2017; Yang et al., 2014), type 2 diabetes (Basu et al., 2013; de Koning et al., 2011; Malik et al., 2010; Malik & Hu, 2012), and oral health problems (Moynihan, 2016; Moynihan & Kelly, 2014; Sheiham & James, 2015). As such, enhancing sweet taste perception via crossmodal strategies could contribute to promoting healthier dietary shifts by encouraging the acceptance of products with reduced sugar content. Promising applications of crossmodal strategies for sugar reduction have already been described for taste-olfactory (e.g., adding vanilla aroma, Alcaire et al., 2017; Velázquez et al., 2020), or taste-texture correspondences (e.g., changing texturing agents in dairy desserts, Lethuaut et al., 2003). The possibility of implementing similar sensory-based interventions relying on extrinsic sensory cues (i.e., attributes that do not pertain to the foods themselves), such as customizing eating environments’ soundscapes (e.g., Wang et al., 2017), is so far only speculative. Notably, the evidence is virtually omissive in what concerns the sonic modulation of the taste of sugar-reduced or naturally low-sweetness products (see Section 1.4.4).

1.4.2. Sonic influences on the perception of sweet taste

Improving the auditory landscape of current eating environments requires us to look into the different sounds we may find in these environments. The current literature on sonic seasoning seems to suggest three different classes of sound stimuli with implications for sweet taste perception. Most commonly, these include music, noise, and environmental sounds. Table 1.1. presents an overview of the current literature regarding the sonic influences on sweet taste

[4] The World Health Organization (2015) defines free sugars as “monosaccharides and disaccharides added to foods and beverages by the manufacturer, cook or consumer, and sugars naturally present in honey, syrups, fruit juices, and fruit juice concentrates” (p. 1).

perception. As the table suggests, there is a predominance of studies based on musical stimuli (n = 29), with a lower number of papers investigating the influence of noise (n = 4) and environmental sounds (n = 3).

Table 1. 1. *Summary of Papers Examining the Influence of Sound on Sweet Taste Perception*

Study	Sound type	Auditory stimuli	Gustatory stimuli	Results
Crisinel, Cosser, et al. (2012)	Music	BT (trombone) and SW (piano) soundtracks	Cinder toffee	Samples rated significantly sweeter when listening to the SW (vs. BT) soundtrack.
De Luca et al. (2018)	Music	Peppy and lively vs. Fine music	White and red wine	White wine perceived as more delicate and sweeter if accompanied by a classical (vs. pop) music background. No differences in taste ratings for red wine.
Hauck & Hecht (2019) – Main study	Music	2 classical music pieces selected in a pilot study	Red wine, white wine, sugar water, citric acid solution	Samples not rated significantly different in the SW dimension.
Höchenberger & Ohla (2019) – Study 1	Music	BT (low-pitch trombone) and SW (high-pitch piano) soundtracks	Cinder toffee	Samples rated sweeter with a SW (vs. BT) sound, but this effect disappeared when a "no-sound" control was included in the statistical model.
Höchenberger & Ohla (2019) - Study 2	Music	Same as in Study 1	Same as in Study 1	Sweetness intensity was not influenced by sound.
Kantono et al. (2016)	Music	Music samples representing 14 musical genres	Three (dark/BT, bittersweet, milk/SW) chocolate gelati	TDS difference curves showed significant differences between gelati samples and music conditions. SW perceived as more dominant when neutral and liked music were played.
Kantono et al. (2019)	Music	14 sound segments in different music genres (with the least liked, more liked, and closest to the mid-range liking score selected for each individual)	Bittersweet gelato samples	Electrophysiological measures covaried with sensory changes while listening to music. Ratings of positive emotions were associated with SW perception.
Lin et al. (2022a)	Music	14 segments of music of different genres, 14 sounds, mixtures of liked music and pleasant sound (LMPS), and mixtures of disliked music and unpleasant sound (DMUS) unique to each panelist	Bittersweet chocolate ice cream	Consuming ice cream during the liked music condition resulted in the longest duration of perceived SW. Positive emotions correlated with SW in the positively valenced auditory conditions.
Reinoso-Carvalho et al. (2017)	Music	2 soundtracks corresponding to smoothness/creaminess and roughness	4 chocolates with 2 shapes (angular vs. round) and two formulas (71% vs. 81% cocoa content)	Chocolates rated sweeter while listening to the creamy (vs. rough) soundtrack.
Reinoso-Carvalho et al. (2019) - Study 1	Music	Positive and negative music	Beer (BT-dry pale lager)	No differences between SW ratings of the beer in positive (vs. negative) or sound (vs. silence) conditions.
Reinoso-Carvalho et al. (2019) - Study 2	Music	2 positive and 1 negative music track	Beer (pale lager)	Beer rated sweeter while listening to the positive (vs. negative) music.

Study	Sound type	Auditory stimuli	Gustatory stimuli	Results
Reinoso-Carvalho et al. (2019) - Study 3	Music	2 positive and 1 negative music	Beer (strong dark ale)	Beer rated sweeter while listening to the positive (vs. negative) music.
Reinoso-Carvalho, Gunn, Molina et al. (2020)	Music	2 soft/hard songs and 2 (positive/negative) songs	2 types of chocolates (milk and dark)	Chocolate rated sweeter with positive music (regardless of chocolate and culture). No differences were significant with soft/hard music.
Reinoso-Carvalho, Gunn, ter Horst, & Spence (2020)	Music	2 soft/hard songs and 2 (positive/negative) songs	2 types of chocolates (milk and dark)	No evidence of the chocolate's SW being rated differently while listening to soft (vs. hard) songs. Chocolate rated as tasting sweeter when evaluated with positive (vs. negative) music.
Reinoso-Carvalho, van Ee, Rychtarikova, Touhafi, Steenhaut, Persoone, Spence, & Leman (2015)	Music	3 soundtracks congruent with SW, BT, and bittersweet chocolates	BT, medium, and SW chocolates	BT chocolate rated sweeter when listening to the subject SW soundtrack (vs. silence). Differences found only for the BT chocolate and more strongly for the subject-matched soundtracks (i.e., participants' individual music-chocolate matches).
Reinoso-Carvalho, Velasco, et al. (2016)	Music	A fragment of the song "Oceans of Light" by The Editors	Dark ale beer	No significant differences found with the presence of the song.
Reinoso-Carvalho, Wang, van Ee et al. (2016) - Control Study	Music	NA	Same as in Studies 1-3	No significant differences found for SW ratings when comparing the SW soundtracks of Studies 1 and 2 and silence.
Reinoso-Carvalho, Wang, van Ee et al. (2016) - Study 2	Music	SW and SO soundtracks	Beer	Beer rated significantly sweeter when listening to the SW (vs. SO) soundtrack.
Reinoso-Carvalho, Wang, van Ee, et al. (2016) - Study 1	Music	SW and BT soundtracks	Beer	Beer rated significantly sweeter when listening to the SW (vs. BT) soundtrack.
Spence et al. (2013) - Study 2	Music	4 classical music pieces	4 wines with distinctive sensory characteristics (e.g., acidity, SW)	Participants perceived the wine as tasting sweeter and enjoyed the experience more while listening to the matching music (vs. tasting in silence).
Stafford et al. (2012)	Music	A piece of music and news articles recorded by a male voice	5 freshly prepared drinks of cranberry juice and vodka in different proportions	Samples rated sweeter in the music than in control and other distracting conditions.
Wang and Spence (2016) - Study 1	Music	Consonant and dissonant versions of two short piano melodies	Juice mixtures	Fruit juice rated sweeter while listening to the consonant (vs. dissonant) music. Correlations between music pleasantness ratings and SO-SW ratings were significant.
Wang and Spence (2016) - Study 2	Music	Consonant and dissonant versions of one melody with piano and trumpet sounds	2 blends of fruit juice	Juice rated significantly sweeter while listening to consonant (vs. dissonant) music. Correlation between ratings of music pleasantness and ratings on the SO-SW scale was significant.
Wang and Spence (2018)	Music	Consonant and dissonant versions of a short melody	Juice mixture	Juice rated sweeter with the more positive (vs. negative) visual and musical stimuli.

Study	Sound type	Auditory stimuli	Gustatory stimuli	Results
Wang et al. (2017) - Study 2	Music	Spicy and SW soundtracks and white noise	A dish with SW and spicy components	Soundtracks modified people's evaluation of the expected and actual spiciness of foods but not of expected or actual ratings of SW taste.
Wang et al. (2019)	Music	2 pieces of music that varied in tempo, mode, and instrumentation	Red wine	No significant differences observed in dominance durations of SW.
Wang et al. (2020) - Study 1	Music	A SW and BT soundtrack	70% cocoa chocolate	Chocolates rated sweeter with the SW (vs. BT) soundtrack. The taste-congruent soundtracks had no such effect on taste ratings for those participants who heard the soundtrack only after tasting.
Wang et al. (2020) - Study 2	Music	Same as in Study 1	Same as in Study 1	Chocolates rated sweeter with the SW (vs. BT) soundtrack –before or during tasting.
Reinoso-Carvalho, van Ee, Rychtarikova, Touhafi, Steenhaut, Persoone, and Spence (2015)	Music, Soundscape	A fragment of “Vem morena, vem” by Jorge Bem	Chocolate sample	Customers reported a better tasting experience when the sounds were presented as part of the food’s identity and were willing to pay significantly more for the experience. No significant differences in taste ratings were observed.
Bravo-Moncayo et al. (2020)	Noise	3 versions of a food court noise (baseline unfiltered noise; passive-controlled noise, and active-controlled noise)	Coffee	No significant differences in SW were observed.
Lorentzen et al. (2021)	Noise	1 “quiet” sound setting and 1 recording of fMRI noise	5 concentrations of 4 basic tastants (SW, SA, SO, and BT) from the Taste-Drop-Test	Loud acoustic fMRI noise did not affect the tastants' gustatory perception.
Woods et al. (2011)	Noise	White noise (Quiet, loud) or no noise (Baseline)	Savory/crunchy (salted crisps), savory/soft (mini cheese), SW/ crunchy (Biscuits), and SW/soft (flapjack) stimuli	Background noise reduced the reported intensity of SW, regardless of hardness (crunchy or soft).
Yan & Dando (2015)	Noise	Cabin noise	Aqueous solutions for the five basic tastes at 3 concentration levels	Loud noise suppressed SW taste perception across all concentrations.
Lin et al. (2019)	Soundscape	Environmental sounds: café, fast food restaurant, bar, food court, and park	Chocolate gelato	SW was cited more in the early mastication period when listening to park and café sounds. The valence evoked by the pleasant park sound was positively correlated with SW.
Xu et al. (2019)	Soundscape	Café soundscape presented alone (control) or overlaid with bird (café-bird), forest (café-forest), and machine sounds (café-machine)	Chocolate ice cream	SW and creaminess were dominant at the start of the consumption episode while listening to the café-forest soundscape. When listening to the café-forest soundscape, ice cream was associated with SW and positive emotions.

Note. SW = Sweet, BT = Bitter, SA = Salty, SO = Sour; NA = Not applicable.

1.4.3. Conceptual hypotheses for understanding sonic seasoning

So far, we have emphasized the importance of sound-taste correspondences in modulating taste perception. However, it has been argued that the mere existence of a crossmodal correspondence does not necessarily lead to changes in perception (Knöferle & Spence, 2012). The psychological processes altering flavor perception or evaluation were the focus of Wang's (2017) doctoral thesis, where five main mechanisms were outlined: response bias, sensory expectations, attention capture, physiological response, and emotion mediation.

1.4.3.1. Response bias

Researchers in the sonic seasoning field are often careful in describing their findings in terms of an effect on food evaluation rather than on actual perception. One reason for this is that there is a valid possibility that participants are not perceiving stronger taste sensations (such as a food/drink being perceived as sweeter) but instead are being nudged by the crossmodal attributes of sounds to make different use of the evaluation scales (such as providing higher sweetness ratings). To put this hypothesis to the test, Wang et al. (2020) had participants taste chocolate while a soundtrack was delivered before, during, or after the tasting. The authors found that taste ratings were affected when the soundtracks were delivered during but not after tasting (Experiment 1), suggesting that sonic seasoning corresponds to an actual perceptual effect rather than a mere response bias. Interestingly, no differences were observed when the soundtrack was played before (vs. during) tasting (Experiment 2), which seems consistent with the idea that auditory stimuli may alter taste expectations.

1.4.3.2. Expectations and attention capture

Sensory expectations are remarkably relevant for food consumption because they can improve or worsen food perception even before ingestion (Deliza & Macfie, 1996). Expectations can shape not only how objects are perceived but even how they are identified, for instance, when stimuli are ambiguous (De Lange et al., 2018). Hence, one explanation that has been put forth for sonic seasoning is the creation of sensory expectations based on the crossmodal attributes of sounds. Indeed, as the findings reported by Wang et al. (2020) seem to suggest, being exposed to a crossmodal soundtrack before tasting may effectively modulate how tastes are perceived.

An alternative hypothesis is that music may direct attentional resources toward the congruent gustatory attributes of foods and drinks. Currently, numerous studies follow dynamic sensory methods (such as the Temporal Dominance of Sensations, TDS; Di Monaco et al., 2014; Pineau et al., 2003). These methods are particularly interesting for sonic seasoning research, where the perception of both auditory and gustatory stimuli unfolds and changes over time (Krumhansl, 2002). To date, this research has shown that sound may lead to significant changes in the patterns of dominance of taste sensations through time (Kantono et al., 2019; Kantono, Hamid, Shepherd, Yoo, Grazioli et al., 2016; Lin et al., 2019, 2022a; Wang, Mesz, et al., 2019; Xu et al., 2019), consistent with the view that sounds can direct attention to specific sensory attributes, thus making them appear dominant in the flavor matrix (Wang, Mesz, et al., 2019).

1.4.3.3. Physiological response

Alternatively, evidence emerging from TDS studies shows that physiological responses may have an important role in modulating taste perception. Listening to music and soundscapes has been shown to elicit electrophysiological changes (e.g., skin conductance, heart rate, or respiratory rate), which seem to correlate with changes in flavor perception (Kantono et al., 2019; Xu et al., 2019). The physiological response hypothesis further suggests that changes in taste perception occur through a low-level route (rather than a higher-level cognitive mechanism involving priming or response bias) where music would induce changes in physiological response akin to those elicited by the act of eating (Wang, 2017). For example, Wang et al. (2017) hypothesized that listening to sour music would prompt changes in salivary flow, mimicking the physiological response to sour foods. While the findings disconfirmed this hypothesis, other studies point to differences in saliva composition (e.g., cortisol) in response to music (Khalfa et al., 2003; Ooishi et al., 2017; Wuttke-Linnemann et al., 2019), some of which with potential involvement with parameters of taste perception (Burmester et al., 2019; Dsamou et al., 2012).

1.4.3.4. Emotion mediation and sensation transference

It should be noted that many of the aforementioned changes in physiological response are intimately linked with emotional states (Kantono et al., 2019). Music, in particular, can not only communicate emotions but also change listeners’ subjective feelings (Hunter & Schellenberg, 2010). This is particularly relevant considering that the way individuals perceive tastes is strongly influenced by their emotional states (Al’absi et al., 2012; Platte et al., 2013). For example, one study assessed individuals’ perception of ice cream after attending a hockey game. The study found that participants’ satisfaction with the game's outcome was significantly associated with the perceived intensity of the sweet taste, whereas sour taste perception was significantly diminished (Noel & Dando, 2015). Several studies to date have found similar effects of music varying in affective/emotional attributes and subsequent perception of tastes and flavors (Kantono, Hamid, Shepherd, Yoo, Grazioli et al., 2016; Reinoso-Carvalho et al., 2019; Reinoso-Carvalho, Gunn, Horst, et al., 2020; Reinoso-Carvalho, Gunn, Molina, et al., 2020). Wang and Spence (2018) further showed that the influence of stimuli valence is comparable among different modalities. In this study, listening to a positive (vs. negative) soundtrack or looking at a picture of a smiling (vs. crying) child had a comparable impact in enhancing sweetness perception while decreasing perceived sourness intensity.

In a similar vein, the feelings evoked by auditory stimuli may also be transposed to the hedonic evaluation of foods and drinks. This process, coined as sensation transference, may help explain why liked music affects not only how participants evaluate the taste of foods but also how much they enjoy them (Kantono, Hamid, Shepherd, Yoo, Carr, et al., 2016; Reinoso-Carvalho et al., 2016). Sensation transference has also been proposed as a potential mechanism to explain differences in taste ratings, as the pleasantness of a song may also be transferred to the evaluation of attributes such as sweetness or bitterness, which are positively and negatively associated with pleasantness, respectively (Reinoso-Carvalho, Touhafi, et al., 2017).

1.4.4. Implications for healthier eating and sugar reduction

While sonic seasoning may have interesting and intriguing implications for the quality of the eating experience, its potential role in promoting healthier eating remains poorly understood. If music can indeed shape taste/flavor perception and the hedonic evaluation of foods, one could speculate that audition has the potential to improve the acceptance of healthier food/drink alternatives. Recently, Campinho et al. (2023) showed that listening to music associated with the salty taste enhanced the perceived saltiness of bread samples and led to a more favorable hedonic evaluation. Interestingly, the soundtrack was effective in improving the perception of bread with lower salt content, suggesting that sonic cues may aid in promoting the acceptance of healthier products.

Given the current public health demands for reducing sugar intake (World Health Organization, 2015), sonic seasoning could become a promising tool for supporting this dietary shift as well. However, this possibility seems insufficiently supported by the evidence accumulated thus far. One relevant limitation is the lack of research on healthier (e.g., low-sugar) foods and drinks. Currently, there seems to be a predominance of studies with highly enjoyable products like chocolate (Reinoso-Carvalho et al., 2017; Reinoso-Carvalho, Gunn, Horst, et al., 2020; Reinoso-Carvalho, Gunn, Molina, 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), ice cream/gelati (Kantono, Hamid, Shepherd, Yoo, Grazioli, et al., 2016; Kantono et al., 2019; Lin et al., 2019, 2022a; Xu et al., 2019), beer (Reinoso-Carvalho et al., 2019; Reinoso-Carvalho, Velasco, et al., 2016; Reinoso-Carvalho, Wang, et al., 2016), or wine (Burzynska et al., 2019; Spence et al., 2013; Wang, Mesz, et al., 2019; Wang & Spence, 2015). In addition, the generalizability of these findings to less appealing food categories has been questioned (Fiegel et al., 2014; Hauck & Hecht, 2019).

Against this backdrop, it is relevant to ask whether music can work as a sonic "sweetener" for products with lower sugar contents, such as in products formulated with a reduction (low or reduced sugar) or no addition of sugar (zero sugar or sugar-free), as well as in products that are naturally low in sugar (e.g., vegetables like cucumbers). If that is indeed the case, music might aid in compensating for sugar reduction in sensory terms. What is more, the notion of sensation transference suggests that the benefits of finding the right musical accompaniment may be more far-reaching, as they also include enhancing the hedonic evaluation of food products (Reinoso-Carvalho, Wang, et al., 2016). In sum, two main issues seem to arise from this debate, namely, regarding i) the generalizability of current findings in terms of sonic seasoning to products with a broader range of sensory characteristics as well as acceptance levels, including those with lower sugar content, and ii) understanding what attributes to look for in music to promote the desired outcomes, namely, regarding crossmodal attributes (e.g., music-taste associations) or affective dimensions (e.g., valence or pleasantness).

1.5. Aims and overview of the research

A lot has changed since sound was considered a "forgotten flavor sense" (Spence, 2016). The past decade has witnessed an increasing interest in the contributions of audition to taste and flavor perception, with a growth in scientific prolificity to match (Spence et al., 2019b). A vast body of literature now reveals intriguing connections between tastes/flavors and sounds, from the simplest (e.g., pure tones) to the most complex (e.g., music; Knöferle & Spence, 2012; Spence, 2020). Likewise, we are now gaining a broader understanding of how audition contributes to the taste experience and how it can affect eating behaviors and choices for the better (Spence et al., 2019b). The fruitfulness of research on sound-taste interactions also has its pitfalls when it comes to cohesiveness. As different research programs worldwide accumulate new – sometimes conflicting – findings, it becomes increasingly challenging to ascertain what we know and in what direction the field should progress.

Figure 1. 1. *Overview of the Chapters Comprising the Empirical Studies*

Figure 1.1. presents an overview of the chapters comprising the empirical studies. In Chapter 2 - "Toward the Integration of the Sound-Taste Literature", we present two distinct papers with a common ambition. First, the paper *Crossmodal Interactions Between Audition and Taste: A Systematic Review and Narrative Synthesis* (Guedes, Garrido, Lamy, Cavalheiro, et al., 2023) provides an overview of the literature on sound-taste interactions. This article focuses mainly on the five most commonly accepted basic taste categories (i.e., sweetness, bitterness, saltiness, sourness, and umami) and synthesizes the evidence on (a) the crossmodal associations between these tastes and different categories of sound stimuli and (b) the effects of exposure to different sounds on the perception of these tastes. One important challenge in integrating the evidence accumulated thus far is the methodological heterogeneity that often hinders comparability among studies. Therefore, the second article *The Taste & Affect Music Database: Subjective Rating Norms for a New Set of Musical Stimuli* (Guedes, Prada, Garrido, & Lamy, 2023), presents the first extensive study of musical stimuli for multisensory research and beyond. The paper provides subjective rating norms for 100 musical stimuli, including basic taste correspondences, as well as emotional and affective dimensions.

One of the main ambitions of this chapter was to contribute to identifying empirical, theoretical, and methodological gaps in the literature and anticipate the future directions in the field. Chapter 3 – "Shaping Taste Perception Through Music: Empirical, Theoretical, and Methodological Issues" – builds on the lessons learned in Chapter 2 to explore the possibility of modulating sweet taste perception with music. Relevant to this empirical purpose, this section also addresses issues of methodological (e.g., measures of taste perception and study design) and theoretical nature (e.g., the role of affect in sonic seasoning).

In the first paper, *Sensitive to Music? Examining the Crossmodal Effect of Audition on Sweet Taste Sensitivity* (Guedes, Prada, Garrido, Caeiro, et al., 2023), we explored the modulatory power of music beyond the most common measures of taste function. Traditionally, sonic seasoning refers to the selective employment of sounds (such as music or soundscapes) with the intention of matching or modifying taste or flavor attributes of foods (Spence et al., 2019b). While this definition is broad enough regarding the parameters of taste perception that may be liable to the influence of audition, most research to date has focused on measures of the intensity of different taste sensations. In this experiment, we examined whether the perceptual effects of music could extend to taste sensitivity. To that end, we examined the influence of exposure to high (vs. low) sweetness music on participants' ability to detect gustatory sensations and identify sweet taste in sucrose solutions.

The second paper, *Bidirectionality in Multisensory Perception: Examining the Mutual Influences Between Audition and Taste* (Guedes, Prada, Lamy, & Garrido, 2023a) further examined the perceptual implications of taste-sound correspondences, but this time involving the two sensory modalities. In the first two experiments, we examined how music may assist in making sweet or bitter sensations salient when both gustatory attributes are accessible (i.e., in bittersweet chocolate). Considering that crossmodal correspondences are thought to be relative (rather than absolute), we further investigated the hypothesis that contrast between the two soundtracks would be necessary for the "sweetening" effect to emerge. As such, the two experiments followed a similar procedure, except that the first followed a between-participants design, and the second manipulated the auditory condition within-participants. In a third experiment, we sought to investigate the symmetrical influence of gustation in shaping taste and affective associations in response to music. For that purpose, participants who tasted sweet or bitter chocolate evaluated a soundtrack previously tested as evoking sweet and bitter taste correspondences in an equal measure (i.e., "bittersweet" music). This paper introduced two novel contributions, first, by (a) addressing, for the first time, the perceptual implications of sound-taste correspondences on the evaluative processes in auditory in gustatory modalities and (b) rigorously testing the hypothesis that contrast between auditory stimuli is necessary to sonic seasoning.

While the two previous papers sought to expand our understanding of the ways in which music influences sweet taste perception, it is relevant to question why these changes occur. When it comes to sweet taste perception, the literature consistently shows a strong interdependence between cross-modality and affect. First, it has been suggested that emotion and affect may help explain how sound-taste correspondences occur in the human mind (Knöferle & Spence, 2012). Generally, taste sensations hold different hedonic values (e.g., sweet is pleasant; Ventura & Mennella, 2011), and sounds carry emotional information (Weninger et al., 2013). Affective commonalities, such as variations in a pleasantness range, seem to account for why some exemplars of sound stimuli (or more specific acoustic parameters) are reliably associated with tastes (Crisinel & Spence, 2010a, 2012). Similarly, some authors posit that the feelings evoked by sounds can help explain why taste perception is modulated by auditory cues (Lin et al., 2019; Reinoso-Carvalho et al., 2019), and it has been questioned whether manipulating the affective properties of music may result in more robust seasoning effects than cross-modality alone (Reinoso-Carvalho, Gunn, Horst, et al., 2020; Reinoso-Carvalho, Gunn, Molina, et al., 2020).

Thus, the third paper in this chapter (*Disentangling Cross-Modality and Affect in "Sonic Seasoning": The Effect of Music Associated with Different Degrees of Sweetness and Valence on Food Perception;* Guedes, Garrido, Lamy, & Prada, 2023) examines the contribution of cross-modality and affect to the multisensory tasting experience. Based on two complementary experiments, the study investigated how music chosen to reflect contrasting crossmodal attributes (higher sweetness vs. lower sweetness) and affect (more positive vs. less positive valence) influenced the perceived sweetness as well as the hedonic evaluation (e.g., liking) of foods. Following previous discussions suggesting that these effects might be exclusive of highly preferred foods and drinks (Fiegel et al., 2014; Lin et al., 2022b), this study hoped to extend the evidence to foods with varying sweetness and healthiness levels.

To further address the possibility of employing music to promote better eating, Chapter 4 ("Sonic 'Sweetening' as a Path for Sugar Reduction") presents the paper *Sweet Music Influences Sensory and Hedonic Perception of Food Products with Varying Sugar Levels* (Guedes, Prada, Lamy, & Garrido, 2023b). This study was designed to answer the current scarcity of literature on healthy foods and explore the potential use of music to improve the acceptance of low-sugar alternatives. As such, this experimental study examined the effects of exposing participants to music with different crossmodal profiles (high vs. low sweetness) in the sensory and hedonic evaluation of products with varying sugar contents. This included alternative versions of processed products (regular and 0% cookies) as well as vegetables with different levels of naturally present sugars (carrots and cucumbers). This chapter aims to contribute to a better understanding of the applied potential of sonic seasoning, for example, in mitigating the effects of sugar reduction.

The last section of the thesis (Chapter 5 – General Discussion) summarizes the main contributions of this research project and reflects on its significance for this field of inquiry. The discussion is centered around theoretical, methodological, and practical questions. From a theoretical standpoint, we begin by addressing the issue of fragmentation and the need for integration in the field. Relevant to this point, we highlight the contributions of the systematic review to a more cohesive body of literature and to a clearer definition of the conceptual and methodological issues in the field. From a conceptual standpoint, we devote particular attention to the role of emotion in sonic seasoning, particularly in the case of sweetness perception. From a methodological perspective, we highlight the contributions of the systematic review and norming study to identify trends and limitations within current research. We also reflect on how the set of experimental studies may contribute to inform future methodological decisions, for example, in what concerns measures of taste perception (e.g., taste sensitivity) and experimental designs (e.g., within vs. between participants). Finally, we discuss the practical applications of this research. Particular emphasis is given to sugar consumption and the potential applications of sound as a "sweetening" strategy with implications not only for perception but also for acceptance of low-sugar products.

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CHAPTER 2

Toward the Integration of the Sound-Taste Literature

The study of sound-taste interactions has made significant advances in the past decade. Along with a steady increase in scientific production, there have been substantial efforts to make sense of the current knowledge and envision the future of the field (Spence, 2016; Spence et al., 2019b, 2019a). As research around sound-taste correspondences and their implications for taste perception proliferates, it becomes increasingly important to provide an up-to-date outlook on the current literature and reflect on existing knowledge gaps and future research priorities.

The current climate of scientific uncertainty, fueled by discussions around replication, transparency, and quality, advises that we maximize the informative value of existing research so that a global picture of a given phenomenon emerges as accurate and informative as possible (Ledgerwood, 2014). Against this background, a systematic examination of the literature on sound-taste interactions seemed timely (Guedes, Garrido, Lamy, Cavalheiro, et al., 2023). This review aimed at identifying and describing the crossmodal mappings between the two sensory modalities (e.g., pitch-taste correspondences) and the implications of exposure to different auditory conditions on the perception of basic tastes (e.g., the effect of music in modulating sweet taste perception).

One issue that emerged from this review was the rapid proliferation of empirical studies, often with the development of novel auditory stimuli for the purpose of each experiment. The rapid advances in the empirical domain appear not to be met by theoretical construction in equal measure. The field still lacks further clarification of underlying psychological mechanisms and a more consistent examination of the existing hypotheses. Additionally, studies differ in terms of settings as well as in their choice of rating scales, making comparability extremely difficult. This challenge was first addressed in Wang et al.'s (2015) study, where the taste-related soundtracks composed to that point were compiled and tested together. While this study focused on soundtracks that were originally developed to evoke taste-related associations, subsequent research suggested that everyday music, such as Jazz, Folk, or Pop songs, can influence taste perception as well, particularly when evoking specific affective and emotional states (Kantono et al., 2019; Kantono, Hamid, Shepherd, Yoo, Grazioli, et al., 2016). These findings raise intriguing questions concerning how the modulatory effects of everyday music may be impacting eating behaviors in meal settings with background music, such as restaurants, cafés, or food courts.

To address this question, we conducted the first norming study in the field, which was based on a compilation of 100 music excerpts (Guedes, Prada, Garrido, & Lamy, 2023). This study aimed to obtain rating norms for a comprehensive stimulus set whose diversity in musical genres and emotional features sought to meet the needs of experimental research as well as real-world interventions. The soundtracks were evaluated in terms of crossmodal correspondences, as well as affective and emotional associations, thus responding to the current call for the integration of crossmodal and emotional attributes in sonic seasoning (Reinoso-Carvalho, Gunn, Horst, et al., 2020; Reinoso-Carvalho, Gunn, Molina, et al., 2020).

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Crossmodal Interactions Between Audition and Taste: A Systematic Review and Narrative Synthesis

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Abstract

Taste perception results from integrating all the senses. In the case of audition, research shows that people can associate certain auditory parameters (e.g., pitch) with basic tastes. Likewise, the surrounding sonic environment (e.g., noise, music) may influence individuals' evaluation of the taste attributes of foods and drinks. This paper presents the first pre-registered systematic examination of the literature on the crossmodal interactions between audition and taste. For that purpose, four indexing services (EBSCOhost, SCOPUS, Web of Science, and PubMed) were searched using three sets of keywords on the crossmodal interactions between audition and basic tastes. Empirical, quantitative studies with healthy subjects in field, lab, or online settings were considered for inclusion. A total of 2484 records (*n* = 1481 after removing duplicates) were subject to abstract and title screening, followed by a full-text screening (*n* = 79). Sixty articles, reporting 94 eligible studies, were reviewed. Results suggest that taste may be crossmodally associated with a) pitch and musical instruments; b) words, nonwords, and speech sounds; and c) music and soundtracks. Moreover, the reviewed evidence supports the employment of auditory stimuli in the context of taste modulation, specifically in the case of a) familiar music; b) custom soundtracks, and c) noise, tones, and soundscapes. Overall, this review provides a comprehensive outlook on the multisensory interactions between audition and taste. The results show that audition has a relevant contribution to taste perception with important implications for how foods and drinks are perceived. The theoretical and practical implications of these findings are discussed.

Keywords: audition, taste, multisensory perception, crossmodal correspondences, sonic seasoning, systematic review

1. Introduction

Taste perception plays a central role in determining food preference and choice. Since early in ontogeny, infants show a preference for foods with sweet tastes, while bitterness is a common reason for rejection (Mennella & Bobowski, 2015). Later in life, basic taste sensations (sweetness, bitterness, saltiness, sourness, and umami) are still relevant determinants of preference. For instance, salt and sugar are currently consumed in excessive amounts on a global scale, despite the negative health consequences (World Health Organization, 2012, 2015). Likewise, sensitivity to basic tastes has been previously associated with food preference and choice in adults (Chamoun et al., 2019; Proserpio et al., 2016).

Despite its major contribution to eating enjoyment, a great deal of what people think of when they refer to taste is actually flavor, that is, the combination of gustatory and olfactory sensations. An illustrative example is the common reporting of taste loss when olfactory perception is compromised (namely due to COVID-19 infections), even when taste function is intact (Le Bon et al., 2021). The classic confusion between taste and olfaction may be explained by the fact that these senses (and, to a lesser extent, also the trigeminal modality) are combined to form a unitary perception of flavor (Auvray & Spence, 2008; Stevenson, 2014). This binding process is associated with why some people may refer to certain odors, such as vanilla, as "sweet" and why, in turn, some of these odors may lead to increased perceived taste intensities (Stevenson et al., 1999). Indeed, sweetness enhancement by the addition of aromas is a well-established sensory trick for improving the acceptance of low-sugar products (Bertelsen et al., 2020, 2021).

To a certain degree, all the senses contribute to flavor perception. However, an important distinction should be made between the senses that are constitutive and those that are merely modulatory of flavor perception. While this distinction is still a matter of debate, there seems to be some agreement that taste and olfaction are intuitive examples of the constitutive senses, whereas vision and audition are generally reserved a role as modulatory senses (Skrzypulec, 2021; Spence, 2015a). In the visual modality, the colors of foods and drinks (e.g., Calvo et al., 2001) or of the plateware/glassware (Piqueras-Fiszman et al., 2012) in which they are served may account for different tasting experiences (for a review, see Spence, 2019). As far as audition is concerned, there are several ways by which hearing may influence how people perceive food (Spence et al., 2019). Yet, the role of this sensory modality is not always acknowledged in the context of eating. It has been previously argued that audition has been neglected in the context of multisensory research and that sound may have a much more significant impact on eating than what it has been given credit for (Spence, 2016). In this review, we systematically examine the existing evidence on the crossmodal links between audition and taste.

1.1. Audition and taste perception

Some foods produce singular sounds, such as the crunch of biting an apple or the crackling sound of a spoon on a *crème brûlée*. To understand how sonic cues may impact the sensory experience, one seminal experiment had participants taste potato chips while listening to their own mastication sounds through headphones, either unaltered or manipulated for volume and frequency (Zampini & Spence, 2004). The results suggested that chips were perceived as fresher and crisper when listening to the sound with amplified frequency and/or volume compared to when the sound was unaltered.

Apart from the sounds of foods themselves, environmental sounds (e.g., the soundscape of a busy cafeteria vs. that of a Michelin-star dining room) may also affect eating behavior differently. For instance, listening to music during eating is associated with longer meals and higher food intake (Stroebele & de Castro, 2006). Loud background music, in particular, may lead to increased consumption of soft and alcoholic drinks (Guéguen et al., 2008; McCarron & Tierney, 1989). Listening to fast-tempo music can make participants drink faster (McElrea & Standing, 1992) and eat more quickly, accounting either for shorter eating times (Mathiesen et al., 2020) or a larger number of bites per minute (Roballey et al., 1985).

This bulk of research highlights that audition is implicated in eating and influences how we behave towards food. Another line of inquiry has shown that audition may also play a role in how the taste experience unfolds (Spence, 2012, 2015b, 2016; Yan & Dando, 2015). One of the first pieces of evidence of associations between audition and taste came from Holt-Hansen's (1968,1976) seminal experiments, in which distinct beer varieties were matched to different sound pitches. More recently, other examples of systematic crossmodal associations have been documented that link taste with various sounds (e.g., music, speech sounds) or sonic attributes (e.g., frequency, tempo). Just as individuals seem able to describe vanilla or caramel odors as “sweet”, it appears that a similar ability may also exist for auditory stimuli, such as music pieces (e.g., Guedes, Prada, Garrido, & Lamy, 2023). These consistent mappings between attributes of stimuli pertaining to different sensory modalities (such as audition and gustation) are known as “crossmodal correspondences” (Knöferle & Spence, 2012).

One important implication of such links between the auditory and gustatory modalities is the potential use of sound to modulate how people subjectively perceive the taste of foods and beverages in real-world contexts. Sounds may contribute to creating taste expectations, directing attention toward specific sensory attributes, or influencing thinking and feeling processes that change how individuals experience (or report experiencing) the taste of foods and drinks (Wang, 2017). While research in these topics is becoming increasingly prolific, no systematic effort has been attempted to map all the possible connections between taste and audition and integrate the existing evidence under one overarching review. Thus, the current work aims at i) providing an updated outlook on a rapidly growing body of literature; ii) addressing the issue of bias of traditional reviews by following a pre-registered systematic protocol; iii) mapping the diverse crossmodal interactions between audition and taste; and iv) identifying research gaps and future directions in the field.

This paper examines the crossmodal role of audition in taste perception from two perspectives. First, we review the evidence regarding the crossmodal correspondences between audition and taste, that is, studies examining the subjective associations people make between specific auditory stimuli (e.g., music) or sonic parameters (e.g., pitch) and basic tastes (sweetness, bitterness, sourness, saltiness, umami). Second, we examine how hearing may actually impact taste perception by reviewing experimental evidence testing the effects of exposure to different sound conditions on the perception of taste in foods and beverages.

2. Method

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

2.1. Literature search

The study was pre-registered in PROSPERO and can be accessed here. A systematic search was conducted based on four indexing services (EBSCOhost, SCOPUS, Web of Science, and PubMed) in April 2020 and updated in July 2022. The search strategy was developed using the PICOS and SPIDER tools and included three sets of keywords regarding crossmodal or multimodal interactions (cross-modal* OR crossmodal* OR multi-sensor* OR multisensor* OR multimodal* OR multi-modal*) between audition (audition OR auditory OR sound* OR music* OR nois* OR sonic* OR hearing) and basic tastes (sweet* OR sugar* OR bitter* OR sour OR sourness OR salt* OR umami OR tast* OR flavor* OR flavour* OR gustat* OR acid*

OR in-mouth). The search spanned titles, abstracts, and keywords in the four databases, and results were limited to peer-reviewed publications in four languages (English, French, Spanish, and Portuguese).

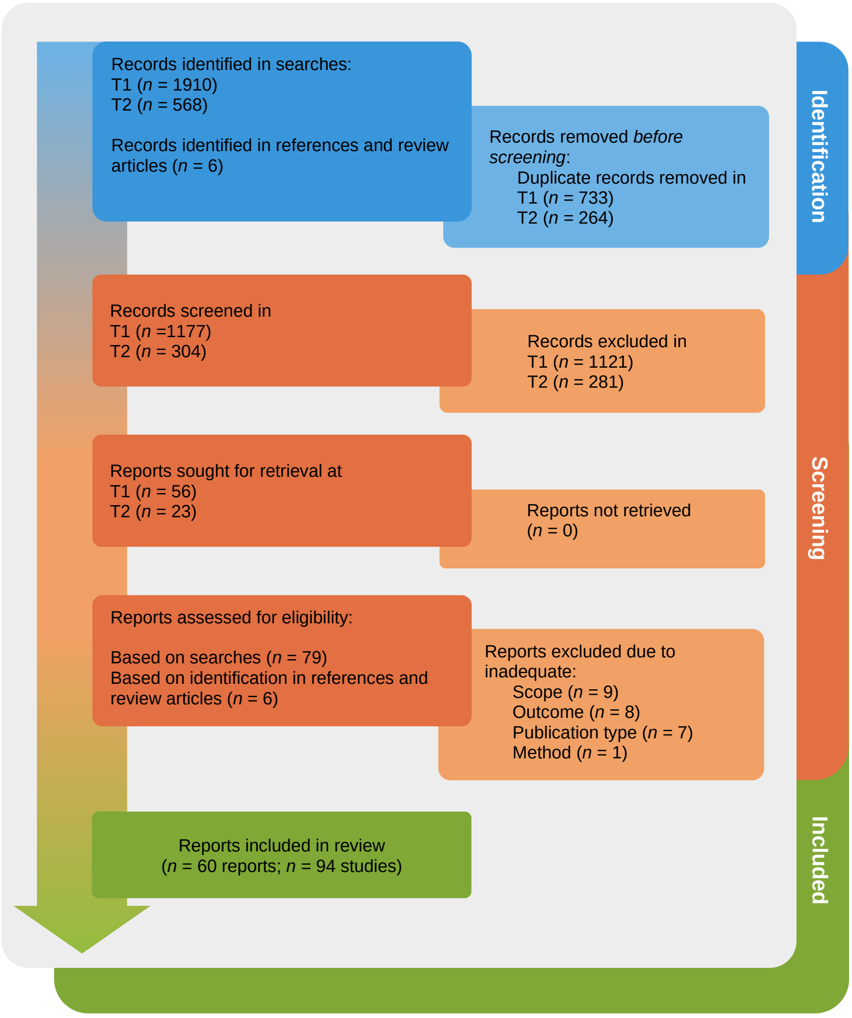
2.2. Inclusion and exclusion criteria

Empirical, quantitative studies in field, lab, or online settings were considered for inclusion. Given the phenomena of interest, studies selected for inclusion had to clearly relate audition and taste. For the sake of parsimony, only the five basic tastes were targeted (sweetness, saltiness, bitterness, sourness or acidity, and umami). Although some scholars make a case for a sixth taste of fat, the ongoing nature of the debate cautioned against its inclusion in this review (Besnard et al., 2015; Keast & Costanzo, 2015). The search did not include flavor variables (e.g., aromas) and oral-somatosensory attributes (e.g., texture, pungency). For the auditory domain, no *a priori* exclusion criteria were defined. Opinion/commentary, conference papers, and clinical studies (e.g., synesthesia) were excluded. Review papers were not considered for data extraction but were scanned to identify additional references. There were no further exclusion criteria regarding participants' characteristics (e.g., age, sex, body mass).

2.3. Selection of studies

The first search resulted in 1910 records managed in Endnote version X7. Two rounds of (automatic and manual) removal of duplicates resulted in 1193 records (see Figure 2.1.). The remaining results were exported to the online reference management platform Rayyan (Ouzzani et al., 2016) for the title and abstract screening stage. This platform identified and excluded 16 additional duplicate records, and the remaining (n = 1177) were screened by two independent reviewers. Inter-rater agreement was 99%, which resulted in Cohen's $\kappa = 0.88$ ($p < .001$), 95% CI [.823, .945]. Disagreements were resolved by discussion between the two reviewers. The final number of records selected in the title and abstract screening round was 56.

Following the method outlined above, an additional search took place in July 2022. This search resulted in 304 articles for title and abstract screening, of which 23 were subject to full-text screening. Across the two searches, 79 articles were subject to full-text screening, and 57 were retained for data extraction. Three additional records were included by scanning through the references of review papers, totaling 60 articles for review. An overview of the stages of selection and extraction of records is presented in Figure 2.1.



Note. T1 = Time 1 (April 2020); T2 = Time 2 (July 2022).

Figure 2. 1. *PRISMA Flow Diagram Representing the Stages of Record Identification, Screening, and Inclusion*

2.4. Data extraction

One author led the data extraction process, and a second author reviewed the coded data. The extracted characteristics were:

1. Article information: Authors, title, year, journal, and country of authors' affiliations.
2. Sample: Type of sample (e.g., college students, restaurant patrons), sample size, number or percentage of women, age (mean, standard deviation, and/or range), and sample selection criteria.
3. Method: Scope of the study, setting (e.g., field, lab, online), general procedures, stimuli type and origin (auditory and gustatory), measures.

4. Design: Conditions, design, randomization, baseline or control conditions, follow-up, independent and dependent variables.

5. Analysis and results: Data analysis, number of participants per group, means, standard deviations or standard errors, inferential statistics (e.g., Student's *t*, *F*-statistic, Pearson's *r*), and summary of results.

3. Results

The full data regarding studies' characteristics (article information, sample, method, design, and results) is available at osf.io/t4r76.

3.1. General characterization

The total number of manuscripts selected for extraction was 60, which reported 94 eligible studies. Most of these studies followed a within-subjects design ($n = 72$), whereas 14 were mixed and eight were between-subjects. In terms of scope, 56 studies examined the crossmodal correspondences between audition and taste, and 38 tested the modulatory role of audition in taste perception.

Correspondence studies focused on the associations between basic tastes and (a) music and soundtracks[5] ($n = 22$), (b) words, nonwords, and speech sounds ($n = 20$), (c) tones, musical notes, and musical instruments ($n = 14$). The most systematically examined taste category was sweetness ($n = 54$), followed by bitterness ($n = 38$), sourness ($n = 36$), saltiness ($n = 36$), and umami ($n = 7$). The distribution of taste variables across categories of studies is presented in Figure 2.2.

Studies testing the modulatory effects of audition in taste perception focused mainly on (a) music ($n = 12$), (b) soundtracks ($n = 16$), and (c) noise, tones, and soundscapes ($n = 7$). Three studies simultaneously included stimuli from two categories, namely noise with soundtracks and music with soundscapes. Most studies examined the influence of sound on sweetness perception ($n = 35$), followed by bitterness ($n = 28$), sourness ($n = 23$), saltiness ($n = 7$), and umami ($n = 2$). The number of studies testing the effects of different sounds on each of the basic tastes is presented in Figure 2.3.

[5] Here, music refers to known pieces, usually in familiar genres (e.g., jazz, classical). Soundtracks are bespoke stimuli, commonly produced to match taste or flavor attributes.

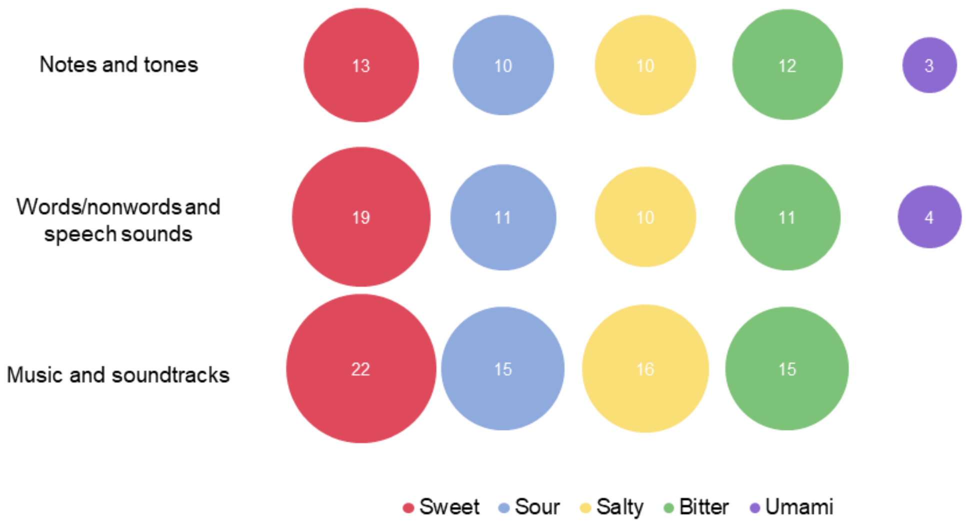


Figure 2. 2. *Number of Studies Examining the Correspondence Between Each Basic Taste and Various Categories of Sounds*

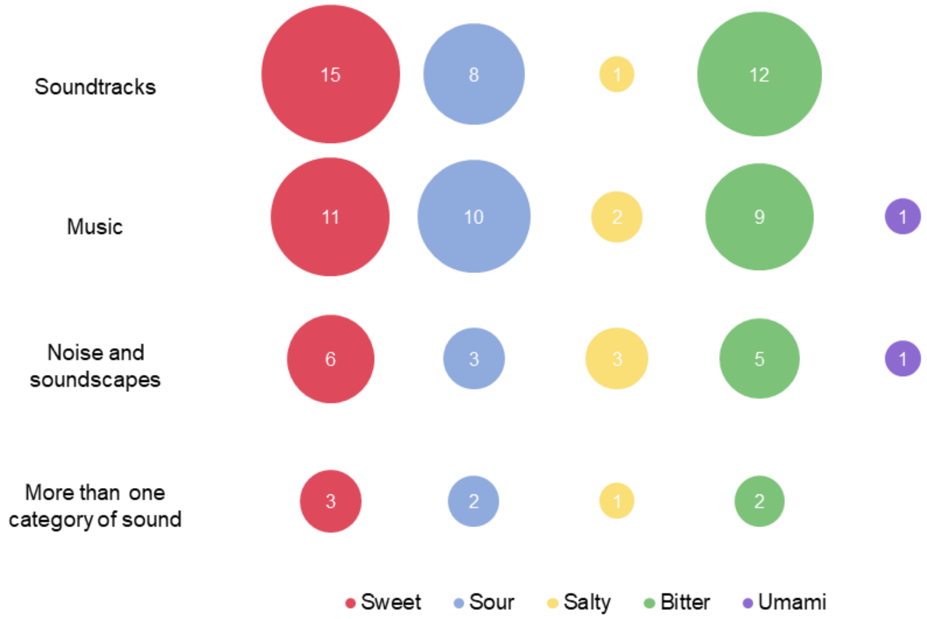


Figure 2. 3. *Number of Studies Examining the Influence of Different Sounds on the Perception of Each Basic Taste*

All the included articles were published after 2009, with about half (51.7%) released after 2017. International collaborations originated about 55% of the selected papers, with a majority of contributions from researchers affiliated with European institutions at the time of publication (in 66% of all papers).

Table 2. 1. *Total Number of Studies Selected for Inclusion and Number of Studies per Category*

	Number of Studies (*N* = 94)	%
Sound-taste correspondences studies	56	60%
a. Music and soundtracks	22	23%
b. Words, nonwords, and speech sounds	20	21%
c. Tones, musical notes, and musical instruments	14	15%
Taste modulation studies	38	40%
a. Music	12	13%
b. Soundtracks	16	17%
c. Noise, tones, and soundscapes	7	7%
d. More than one category	3	3%

3.2. Crossmodal correspondences between audition and taste

3.2.1. Tones, musical notes, and musical instruments

The reviewed studies described several crossmodal correspondences, linking basic tastes with auditory attributes (for an overview, see Table 2.2.). One of the most common psychoacoustical parameters associated with taste is sound frequency (or pitch). One of the earliest examples is Crisinel and Spence's (2009) study using the Implicit Association Test (IAT) to measure the association between tastes and sound frequency. Results indicated an association between higher-pitched sounds and sour-tasting foods and between lower-pitched sounds and bitter-tasting foods. Crisinel and Spence (2010a) presented further support in favor of the sour-high pitch association, as well as for a sweet taste-high pitch correspondence. Bitter and salty tastes, however, were not associated with lower-pitched sounds.

Since these studies relied on food names to represent taste categories (e.g., “dark chocolate” for bitter, “lemon juice” for sour), the same authors aimed to replicate these findings, using real tastants (e.g., sucrose) and flavors (e.g., vanilla; Crisinel & Spence, 2010b). Here, participants had to select one musical note (played by different musical instruments) to match each gustatory stimulus. The results also pointed toward an association between sweet and sour tastes and high-pitched sounds, with participants choosing higher-pitched musical notes for the sucrose (sweet) and citric acid (sour) solutions, while caffeine (bitter) and monosodium glutamate (umami) led to the choice of lower-pitched sounds. Besides the association with musical notes, there were also differences in the choice of musical instruments (e.g., preference for piano sounds to match sucrose, while brass was preferred for caffeine).

A replication of Crisinel and Spence's (2009, 2010a, 2010b) studies presented further support for the association between bitter taste and low pitch and between sweet taste and high pitch (Watson & Gunther, 2017). However, the results differed according to the type of instrument (i.e., significant differences in the choice of pitch according to tastes were found for trombone tones but not for clarinet). Knöferle et al. (2015) also found support for the bitter-low pitch correspondence, as well as an association between high pitch and both sweetness and sourness. This experiment also found evidence for crossmodal mappings between basic taste words and other auditory parameters, such as roughness, discontinuity, tempo, and sharpness.

Wang et al. (2016) reported an effect of taste on pitch choice, with sweetness and sourness again leading to the choice of higher-pitched notes. In this study, three concentration levels were used for each taste solution to test the effect of taste intensity on pitch and volume choice. While the type of tastant was influential for pitch choice, taste intensity significantly impacted the choice of sound volume. A recent study with Chinese students also found a main effect of taste on pitch choice, with bitterness and saltiness being significantly associated with low-pitched sounds (Qi et al., 2020). An association between taste and choice of instruments was also observed, as participants showed a preference for specific instrument-taste pairings over others with significantly above-chance probability.

Three other studies reported pitch-taste correspondences in real foods and beverages. Reinoso-Carvalho, Wang, de Causmaecker, et al. (2016) found that individuals tended to match bitter beers to lower-pitched sounds and sweeter beers to higher-pitched sounds. In another study, chocolates that were rated as sweeter were matched to a higher pitch, whereas the bitter were matched to a lower pitch (Crisinel & Spence, 2012). Crisinel and Spence (2011) found that participants matched the taste of flavored milk solutions to different musical instruments. This study also reported an effect of the flavor (e.g., vanilla, lemon) of milk solutions on pitch choice, although no results were reported specifically for basic taste ratings.

One indirect source of evidence for taste-pitch correspondence comes from an experiment where participants saw images of different packages after a high- or low-pitched sound (Velasco et al., 2014). When asked if the package was more appropriate for a sweet or sour product, high-pitched sounds were more frequently associated with sourness, whereas low-pitched sounds were more associated with sweetness. These results align with previous findings observed for sourness but not sweetness, which is usually associated with a higher pitch.

Overall, across nine studies that specify the direction of association between sound pitch and sweet taste, six reported a link with higher-pitched sounds, one reported an association with a lower pitch, and two reported no association. In contrast, bitterness was associated with a lower pitch in five studies, whereas three reported no association. For sourness, five studies reported a link with a higher pitch, while two reported no association. The findings regarding saltiness are mixed, with five studies reporting null results, one reporting an association with a higher pitch and one with a lower pitch. Umami was associated with a lower pitch across two studies, and one reported no association. In the remaining studies where pitch-sound associations were reported (*n* = 3), only information regarding relative (pairwise) differences was available.

Table 2. 2. *Synthesis of Studies Testing the Association of Tones, Notes, and Musical Instruments with Basic Tastes*

Study	Auditory stimuli	Gustatory stimuli	Basic taste					Results
			SW	SO	SA	BT	UM	
Crisinel and Spence (2009)	High-pitched and low-pitched sounds	BT-tasting and SO-tasting food names		x		x		Stronger association between lower-pitched sounds and visually presented BT-tasting foodstuffs and between higher-pitched sounds and SO-tasting foodstuffs.
Crisinel and Spence (2010a) – Study 1	High-pitched and low-pitched sounds	SW and SA food words	x		x			The association between SW tastes and high-pitched sounds and between SA tastes and low-pitched sounds was stronger than the association between SW tastes and low-pitched sounds and between SA tastes and high-pitched sounds.
Crisinel and Spence (2010a) – Study 2	Same as in Study 1	SA, SW, BT, and SO food words and neutral words	x	x	x	x		SW and SO tastes were associated with high-pitched sounds. No pitch-taste associations for BT and SA.
Crisinel and Spence (2010b)	Musical notes	Gustatory stimuli representing the five basic tastes	x	x	x	x	x	The association of SW and SO tastes to high-pitched notes was confirmed. By contrast, UM and BT tastes were preferentially matched to low-pitched notes. All tastes gave rise to significant preferences in the choice of instrument (medium effect sizes for SW and BT, small effect sizes for SA and SO).
Crisinel and Spence (2011)	Musical notes	Milk with different flavors and fat contents	x	x	x	x		Basic taste ratings were not independent of the choice of instrument (small effect sizes for SA, medium for SW and SO, and large for BT). Flavor significantly affected pitch choice, but no data was available for basic taste ratings.
Crisinel and Spence (2012) - Study 1	Musical notes	Chocolate with different cocoa content	x	x	x	x		SW ratings were positively correlated with pitch, whereas BT ratings were negatively correlated with pitch. Taste ratings were not associated with the choice of instrument. While there was an overall correlation between pleasantness ratings and the chosen pitch, it disappeared when a single stimulus was considered in isolation.
Crisinel and Spence (2012) - Study 2	NA	NA	x	x	x	x		The proportion of participants choosing a taste-related adjective was not significantly higher than chance for either of the two pairs (SO-BT or SW-SA).

Study	Auditory stimuli	Gustatory stimuli	Basic taste					Results
			SW	SO	SA	BT	UM	
Knöferle et al. (2015)	Short chord progression	NA	x	x	x	x		SW was associated with a higher pitch, low roughness, and low discontinuity. BT was associated with a lower pitch, high roughness, high discontinuity, and low tempo. SO was associated with high pitch, high roughness, and high tempo. A main effect was found for sharpness, although most pairwise comparisons were nonsignificant. The attack/onset time of the sounds was not reliably linked to any of the basic tastes.
Qi et al. (2020)	Musical notes	Chinese words to describe SO, SW, BT, SA, and UM tastes	x	x	x	x	x	Lower pitch was more preferentially matched to a BT or SA taste than SO, SW, or UM. Certain types of Chinese instruments were preferentially matched to taste terms, except for SO (yunluo and guzheng for SW, dizi and erhu for BT, dizi for SA, yunluo for UM).
Reinoso-Carvalho, Wang, de Causmaecker, et al. (2016)	Sounds with different pitch levels	Beers	x			x		People tended to match beers with BT-range profiles at significantly lower pitch ranges when compared to the average pitch of a much sweeter beer.
Velasco et al. (2014)	High-pitched sound and low-pitched sound	NA	x	x				SW tastes were better expressed through rounded shapes, typefaces, and names (soft, rounded), while SO tastes were better conveyed through more angular shapes, typefaces, and names (sharp, angular). In addition, sounds having a low pitch enhanced the perception of SW whereas high-pitched sounds enhanced the perception of SO.
Wang et al. (2016) - Study 1	Musical notes	Samples of BT, SW, SO, SA, and UM solutions	x	x	x	x	x	Taste quality significantly affected participants' choice of pitch and volume ratings. SW and SO solutions were matched to a significantly higher pitch than the BT, SA, and UM solutions. The SO solution was matched to a significantly higher volume than the SA, SW, and UM solutions. Lower concentration solutions were matched to lower volume and higher concentration solutions were matched with higher volume. The perceived intensity of the samples was correlated with pitch choice, except for SO and UM.
Wang et al. (2016) - Study 2	Same as in Study 1	Same as in Study 1	x	x	x	x	x	Taste quality significantly affected participants' choice of pitch and volume ratings. SW and SO solutions were matched to a significantly higher pitch than the BT, SA, and UM solutions. Pitch was positively correlated with SO taste intensity and negatively with UM intensity.
Watson and Gunther (2017)	Musical notes	SW, SA, and BT samples	x		x	x		This study replicated previous findings of low-pitch/BT and high-pitch/SW crossmodal correspondences. Results differed according to instrument type (trombone or clarinet).

Note. NA = Non-applicable; SW = Sweet; SO = Sour; SA = Salty; BT = Bitter; UM = Umami.

3.2.2. Words, nonwords, and speech sounds

The Bouba-Kiki effect is a popular example of sound symbolism, that is, the ability to associate a speech sound with no semantic meaning (e.g., "Bouba") to a certain attribute in another sensory modality (e.g., rounded shapes) (Ramachandran & Hubbard, 2001). In the case of taste, Gallace et al. (2011) found evidence of regularity in the association between different foods and different nonwords. For instance, salty potato crisps were significantly more “Takete” than brie cheese, which is more “Maluma”. However, the taste ratings of these foods (e.g., salty/sweet) were not significantly correlated with the choice of nonwords. Crisinel, Jones, and Spence (2012), on the other hand, found evidence of systematic preferences for certain nonwords in response to basic taste solutions. In this experiment, participants were instructed to rate each aqueous solution using scales anchored by nonword pairs, such as “Lula-Ruki”, “Maluma-Takete”, “Bobolo-Decter”, and “Bouba-Kiki”. Saltiness led to significant differences from the midpoint of all nonword scales (i.e., more “Ruki”, “Takete”, “Decter”, and “Kiki”), while sweetness was more strongly associated with “Maluma” and “Lula” than “Takete” and “Ruki”, respectively. The “Bobolo-Decter” scale was the only one to detect significant preferences in response to both the citric acid solution (i.e., sourness) and the caffeine solution (i.e., bitterness). Ngo et al. (2013) followed a similar approach in two experiments with British and Colombian participants. The authors concluded that more “rounded” nonwords (such as “Bouba”) and low-pitched sounds share some form of crossmodal correspondence with exotic juices that are rated as being sweet and low in sourness. However, there were also some differences between samples, such as an association between passion fruit and sharp sounds for the British but not for Colombian participants. Overall, research with nonwords suggests a tendency to associate sweetness with rounder sounds (e.g., “Maluma”) and sourness and saltiness with sharper sounds, although results seem to depend on the nonword being tested.

The effects of sound symbolism are particularly evident in cultures where certain words reflect underlying associations between speech sounds and sensory attributes. For instance, instead of employing adjectives, Japanese speakers may opt for a sound symbolic expression like “mofu-mofu” to describe the sensory experience of a warm, soft blanket (Sakamoto & Watanabe, 2013). Sakamoto and Watanabe (2016) tested the crossmodal correspondence between speech sounds and tastes by examining the spontaneous sound symbolic words (SSW) produced by native Japanese speakers when tasting drinks such as tea and coffee. The authors analyzed the phonemes in the first syllable of each SSW and found several correlations with taste ratings. For instance, participants resorted to phonemes like /sh/ and /zy/ in response to sweet tastes, /g/, /d/, /z/, and /e/ in response to salty and /d/, /z/, and /e/ in response to sour. Interestingly, these phonemes are unrelated to the Japanese adjectives for those tastes, except in the case of bitterness, in which SSW shared similar sounds with the word “nigai” (i.e., bitter), namely /n/, /z/, and /i/. In another set of studies with Japanese participants (Motoki et al., 2020), fictitious brand names were created by systematically manipulating the type of vowels (front/back) and consonants (fricative/stop and voiced/voiceless). The four experiments suggested regular patterns of association between the brand names and expectations towards the products' taste. In the case of sweetness, three main effects were found, indicating that front (vs. back) vowels, fricative (vs. stop) consonants, and voiceless (vs. voiced) consonants increased the expected sweetness. In contrast, stop (vs. fricative) and voiced (vs. voiceless) consonants were more associated with bitterness. Saltiness was associated with voiced (vs. voiceless) and stop (vs. fricative) consonants in two studies, whereas sourness presented a less clear pattern of association. Pathak et al. (2020) and Pathak and Calvert (2021) later extended these findings to vowel length, showing that people expect words containing long vowels to be associated with sweetness. These findings were consistent across studies, either in evaluation tasks (e.g., asking participants to rate the "sweetness" of a hypothetical brand name) or in free-choice tasks (e.g., having participants invent their own brand names for a sweet product).

Simner et al. (2010) asked participants to match four tastants (sweet, sour, bitter, salty) with sounds varying in several speech-related attributes and spectral balance. Increasing concentration of tastants corresponded to higher levels of all sound attributes (vowel height, vowel front/backness, voice discontinuity, and spectral balance). Significant main effects were also observed for taste type. For instance, sweet tastes were associated with lower vowel height compared with the bitter, salty, and sour tastes. The sweet taste was also associated with more continuous vowels than the bitter and sour tastes and lower spectral balance compared with the sour taste. Finally, three experiments have shown that basic tastes may also be associated with voice qualities (Motoki, Pathak, & Spence, 2022). For instance, falsetto voices were matched more strongly with sweetness, whereas creaky voices were more associated with bitterness.

In terms of the associations between speech sounds and tastes, results were particularly consistent for the sweet taste. This taste category seems to be well characterized by long vowels (eight out of eight studies), voiceless consonants (four out of four studies), fricative and front vowels (three out of four studies), and falsetto voices (three out of three studies). The other tastes presented less consistent patterns of association across studies, although some tendencies may also be observed, such as voiced consonants for bitterness or modal voices for umami. These findings are summarized in Table 2.3.

Table 2. 3. *Synthesis of Studies Testing the Association of Words, Nonwords, and Speech Sounds with Basic Tastes*

Study	Auditory stimuli	Gustatory stimuli	Basic taste					Results
			SW	SO	SA	BT	UM	
Crisinel, Jones, et al. (2012)	Soft-sounding nonwords (Maluma, Lula, Bouba, Bobolo) and hard-sounding nonwords (Kiki, Ruki, Takete, Decter) presented as scale anchors	12 gustatory stimuli to represent the five basic tastes and more complex flavors	x	x	x	x	x	Salt was consistently associated with sharper sounds (Ruki, Takete, Decter, Kiki). Sugar was significantly more associated with the soft-sounding words Lula (vs. Ruki) and Maluma (vs. Takete), but not Bobolo or Bouba. SO and BT were more associated with Decter (vs. Bobolo), but no differences were observed in the other scales. UM did not give rise to any significant preference in any of the scales.
Gallace et al. (2011)	Nonwords (Kiki–Bouba, Maluma–Takete, Lula–Ruki, Decter–Bobolo)	12 different foods	x		x	x		There were crossmodal associations between complex foods/flavors and words, but no significant correlations were found between basic taste ratings (e.g., SA-SW) and word scales (e.g., Bouba-Kiki).
Motoki et al. (2020) - Study 1	Fictitious brand names manipulated for vowel (front/back) and consonant sounds (fricative/stop, voiced/voiceless)	Taste words	x	x	x	x		Front (vs. back) vowels, fricative (vs. stop) consonants, and voiceless (vs. voiced) consonants respectively increased the expected SW. Fricative (vs. stop) consonants and voiceless (vs. voiced) consonants respectively increased the expected SO. Back (vs. front) vowels and voiced (vs. voiceless) consonants respectively increased expected SA. Stop (vs. fricative) consonants and voiced (vs. voiceless) consonants respectively increased the expected BT.
Motoki et al. (2020) - Study 2	Fictitious brand names manipulated for vowel and consonant sounds (different sets of words)	Taste words	x	x	x	x		The main effects indicated that front (vs. back) vowels, fricative (vs. stop) consonants, and voiceless (vs. voiced) consonants respectively increased the expected SW. Stop (vs. fricative) consonants increased the expected SO. Stop consonants increased the expected SA more than fricative consonants. Stop (vs. fricative) vowels and voiced (vs. voiceless) consonants respectively increased expected BT.
Motoki et al. (2020) - Study 3a, 3b	Fictitious brand names manipulated for vowel and consonant sounds (different sets of words)	Taste words	x	x	x	x		Experiment 3a found that fricative (vs. stop) consonants and voiceless (vs. voiced) consonants respectively increased the expected SW. Stop consonants and voiced consonants respectively increased the expected SA more than fricative or voiceless consonants. Voiced (vs. voiceless) consonants increased the expected BT. No main effects were observed for expected SO. Experiment 3b found that front (vs. back) vowels and voiceless (vs. voiced) consonants respectively increased expected SW. Front (vs. back) vowels increased the expected SO. Voiced (vs. voiceless) consonants increased expected SA and BT.
Motoki, Pathak, and Spence (2022) - Study 1	24 vocal stimuli differing in the types of phonation (modal, whispery, creaky, and falsetto)	NA	x	x	x	x	x	Falsetto voices were matched more strongly with SW than the other voices; creaky voices were matched more strongly with SA and BT than the other voices; creaky and falsetto voices were matched more strongly with SO than were the modal voices; modal voices were matched more strongly with UM than were the falsetto and creaky voices.
Motoki, Pathak, and Spence (2022) - Study 2	Eight vocal stimuli (modal, whispery, creaky, and falsetto) selected from Study 1	NA	x	x	x	x	x	Falsetto voices were matched more with SW than the other voice types; creaky sounds were matched more with SO than the modal and whispery voices; modal and creaky voices were matched more with SA than the falsetto voices; creaky voices were matched more with BT than the other voices; modal, falsetto and whispery voices were matched more with UM than creaky voices.
Motoki, Pathak, and Spence (2022) - Study 3	Same as in study 2	Pictures of SW, SO, SA, BT, and UM foods	x	x	x	x	x	Falsetto voices were matched more with SW and SO foods than the other voice types; modal

Study	Auditory stimuli	Gustatory stimuli	Basic taste					Results
			SW	SO	SA	BT	UM	
								voices were matched more with SA, BT, and UM foods than the other voice types.
Ngo et al. (2013) - Study 1	Line scales corresponding to speech sounds (e.g., Bouba-Kiki) and pitch (e.g., low pitch vs. high pitch)	Six sweetened juices	x	x				For Colombian participants, words containing more ‘rounded’ speech sounds (e.g., Bouba and Maluma) and low-pitched sounds all share some form of crossmodal correspondence with tastes/flavors that are rated as being low in SO. Words containing more ‘sharp’ speech sounds (Kiki and Takete) and high-pitched sounds share some form of crossmodal correspondences with SO tastes/flavors instead.
Ngo et al. (2013) - Study 2	Same as in Study 1	Same as in Study 1	x	x				For the participants tested in Oxford, words containing more ‘rounded’ speech sounds (e.g., Bouba and Maluma) and low-pitched sounds all share some form of crossmodal correspondence with tastes/flavors that are rated as being SW and low in SO. Words containing more ‘sharp’ speech sounds (Kiki and Takete) and high-pitched sounds share some form of crossmodal correspondences with SO tastes/flavors instead.
Pathak and Calvert (2021) - Study 1	Ten hypothetical brand name (HBN) pairs differing in vowel type (short vs. long)	NA	x					Participants rated HBNs with long (vs. short) vowels as more appropriate for a very (vs. less) SW chocolate
Pathak and Calvert (2021) - Study 2	NA	NA	x					Participants chose a significantly higher number of long (vs. short) vowels for creating BNs of very SW chocolates and used a significantly higher number of long vowels for creating BNs for very (vs. less) SW chocolates.
Pathak and Calvert (2021) - Study 3	20 hypothetical brand names (HBN) used in Study 1	Chocolate images (floral/very SW and circular/SW shapes)	x					Participants associated HBNs with long vowels with the floral (very SW) shape significantly more than with the circular (SW) shape and associated the floral shape more with HBNs with long vowels than with the HBNs with short vowels.
Pathak and Calvert (2021) - Study 4	10 HBN with long vowels	SW vs. non-SW products	x					D values significantly different from zero suggested a stronger association of HBN with long vowels with SW products than with non-SW products. Participants were faster in associating SW products with the HBN with long vowels (than with the non-SW products). Differences in error rates were not significantly different.
Pathak et al. (2020) - Study 1	Ten bi-syllabic word pairs differing in vowel type (short vs. long)	SW and non-SW products	x					The study found a stronger association of long vowels with expectations of SW compared to short vowels.
Pathak et al. (2020) - Study 2	NA	Images of six SW food items (natural and man-made) and six non-SW items (natural and man-made)	x					Participants used a significantly higher number of long vowels to create novel words for SW (vs. non-SW) food products.
Pathak et al. (2020) - Study 3a	Nine bi-syllabic word pairs from Study 1	SW and very SW products	x					Long (vs. short) had a stronger association with very SW (vs. SW) products.
Pathak et al. (2020) - Study 3b	Nine bi-syllabic word pairs from Study 1	BT and very BT products				x		Vowel length was not significantly associated with BT (vs. very BT) products.
Sakamoto and Watanabe (2016)	NA	Six drinks presented in their original form or with the addition of soy sauce, water, or	x	x	x	x		This study explored the perceptual structure of gustation categories by analyzing a variety of phonemes of Japanese sound symbolic words spontaneously produced to express taste/textures. The results showed that each sound was associated with a few specific taste evaluation scales. Most phonemes were

Study	Auditory stimuli	Gustatory stimuli	Basic taste					Results
			SW	SO	SA	BT	UM	
		carbonated water						associated with taste scales as well as texture scales.
Simner et al. (2019)	Four different sound continua selected to examine different acoustic qualities: F1, F2, voice discontinuity, and spectral balance	Four tastants (SW, SA, BT, SO) in two concentrations (medium, high)	x	x	x	x		Increasing concentrations of taste corresponded to increasing values in F1, F2, and spectral balance, and more staccato vowel sounds. SW tastes were judged to be low in frequency in F1, F2, and spectral balance. In the latter two sliders, they were judged lower than SO tastes, and in the first slider, they were judged lower than BT, SA, and SO tastes. An additional tendency in F2 was for BT to be rated lower than SO. In other words, these sliders revealed a sequence from SW to BT to SO (with SA numerically between BT and SO). Finally, the SW taste was judged to match smoother, more continuous vowel sounds than the BT and SO tastes, which were judged to match more staccato sounds.

Note. NA = Non-applicable; SW = Sweet; SO = Sour; SA = Salty; BT = Bitter; UM = Umami.

3.2.3. Music and soundtracks

The use of musical expressions like the Italian term “dolce” (i.e., to play in a slow, gentle manner) suggests that certain music attributes may be intuitively associated with taste. To test if such vocabulary is conceptually meaningful rather than accidental, Mesz et al. (2011) asked trained musicians to improvise in accordance with taste words (sweet, salty, sour, and bitter). The resulting improvisations revealed consistent patterns of articulation, duration, loudness, gradus, and dissonance. When these improvisations were later presented to non-musical experts, the underlying taste was guessed with significantly above change accuracy. Based on the patterns of association between taste and certain attributes of music composition, Mesz et al. (2012) developed a composition algorithm and found that participants were able to decode the taste associated with each algorithmically generated music with above-chance accuracy. More recently, Wang et al. (2021) contributed to understanding the auditory attributes of salty soundtracks. In this study, the authors found that emotional (negative valence, high arousal, minor mode) and other sonic attributes (long decay, high roughness, and regular rhythm) were systematically associated with the perception of “saltiness” in music.

While several taste-inspired musical compositions have been created in the past, they were usually tested independently. In an effort to compare soundtracks produced by different researchers and designers, Wang et al. (2015) compiled 24 soundtracks used in previous studies. The results showed that the different soundtracks elicited different taste associations. Of the 24 soundtracks, 21 led to a significant association with one particular taste, and in 14 of them, the most chosen taste word was the one intended by the composer. Sweet soundtracks were the most easily decoded by participants (56.9% “correct” associations), followed by salty (44.4%), sour (41.7%), and bitter soundtracks (31.4%). Following a different approach, the Taste and Affect Music Database (Guedes, Prada, Garrido, & Lamy, 2023) provides subjective ratings and basic taste correspondences for a set of 100 music excerpts of different moods and genres. Overall, all four basic taste categories achieved basic taste correspondences above the chance level (25%), suggesting that music may communicate gustatory attributes even when not composed with that purpose in mind. Similar to Wang et al. (2015), sweetness was the most commonly identified taste, followed by bitterness, saltiness, and sourness.

To further explore the influence of sound attributes on taste-sound associations, Guetta and Loui (2017) tested the same violin melody, played in different styles, inspired by four basic tastes (sweet, sour, salty, bitter). Participants were able to match the sound clips to taste words with above-chance accuracy. In another experiment described in this same paper, participants correctly matched each melody style with a corresponding chocolate sample (e.g., matching the sweet melody with the sweeter chocolate). When separately comparing match rates for each taste group, only the sweet category resulted in significantly above-chance performance. In a field study, visitors of a science fair who were challenged to freely associate taste words with several musical pieces revealed a significant preference for words like “chocolate” and “tasty” when exposed to putatively sweet music, while sour music elicited associations with words like “fruits” or “sour” (Kontukoski et al., 2015). Moreover, when these participants were asked to mix different ingredients to create a drink to match the music, differences in the drinks' sugar and acid content were found between the “sour” and “sweet” music conditions.

The associations between soundtracks and taste may also have the potential to influence choice behavior. Individuals exposed to a salty soundtrack were more likely to select pictures of salty (vs. sweet) foods when asked to indicate what food they would rather eat. The opposite pattern was found for sweet soundtracks (Padulo et al., 2020). Sweet and salty soundtracks also led to higher visual fixation times in congruent compared to incongruent foods (i.e., fixation on sweet foods was longer when listening to sweet soundtracks; Peng-Li et al., 2020). Music genre may also contribute to shaping food choices, as evidenced in two experiments where jazz and classical music (vs. hip hop and rock/metal) were associated with a higher preference for healthy savory foods. Classical music also led to a higher preference for sweet foods (healthy or indulgent) compared to all other genres (Motoki, Takahashi, et al., 2022).

Among the articles included in the current review that empirically tested the effect of sound in shaping taste perception, six reported results of pilot studies validating the associations between music or soundtracks and basic tastes. For instance, Reinoso-Carvalho, van Ee, Rychtarikova, Touhafi, Steenhaut, Persoone, Spence, et al. (2015) reported the process of composing three soundtracks to match chocolates with different bitter-to-sweet profiles. Wang et al. (2017) explored the concepts of sweetness and spiciness in two soundtracks composed to enhance both gustatory qualities in a new restaurant dish. In another pilot study with two pairs of contrasting (soft/hard and positive/negative mood) soundtracks, Reinoso-Carvalho, Gunn, ter Horst, et al. (2020) found that the positive soundtrack elicited the sweetest ratings and the negative soundtrack was more strongly associated with bitterness.

Wang and Spence (2016) created consonant and dissonant[6] versions of two short melodies and, as expected, observed that they were associated with sweetness and with sourness, respectively. Another experiment aimed at developing and testing soundtracks to elicit smoothness/creaminess and roughness, respectively (Reinoso-Carvalho, Wang, et al., 2017). Besides being rated as creamier, the smooth/creamy (vs. rough) soundtrack was also rated as sweeter. Finally, Hauck and Hecht (2019) tested how classical music pieces evoked taste and other sensory associations. This pilot test resulted in the selection of two pieces (Alban Berg's "Three pieces for orchestra" and Tchaikovsky's "Waltz of the Flowers") that differed significantly in sensory associations, including sweetness, sourness, and bitterness.

Table 2.4. summarizes the current studies of music-taste correspondences. Notwithstanding the diversity of approaches, the reviewed studies seem consistent in showing that sounds and tastes were matched by participants in a nonarbitrary fashion. The evidence seems stronger for the sweet taste, not only in terms of the studies reporting easier recognition of this sensation in comparison with others (e.g., Guedes, Prada, Garrido, & Lamy, 2023; Knöferle et al., 2015; Wang et al., 2015) but also in terms of the relative predominance of studies targeting this taste (*n* = 21), compared to saltiness (*n* = 15), sourness (*n* = 14), bitterness (*n* = 14) and umami (*n* = 0).

Table 2. 4. *Synthesis of Studies Testing the Association of Soundtracks, Music, and Sound Clips with Basic Tastes*

Study	Auditory stimuli	Gustatory stimuli	Basic taste				Results
			SW	SO	SA	BT	
Guedes, Prada, Garrido and Lamy (2023)	100 instrumental musical excerpts	NA	x	x	x	x	All four tastes presented choice rates above what would be expected by chance (i.e., 25%). Significant correlations were observed between taste correspondences and emotional/affective dimensions (e.g., between SW ratings and pleasant emotions). Sweet soundtracks were more easily identified, followed by BT, SA, and SO.
Guetta and Loui (2017) - Study 1	8 violin music clips for SW, SA, BT, and SO tastes	NA	x	x	x	x	Participants were able to match the clips to taste words with above-chance accuracy.

[6] Consonance is typically associated with stability and pleasantness, while dissonance communicates uneasiness and a need of resolution (Lahdelma & Eerola, 2020)

Study	Auditory stimuli	Gustatory stimuli	Basic taste				Results
			SW	SO	SA	BT	
Guetta and Loui (2017) - Study 2	Same as in Study 1	NA	x	x	x	x	Participants represented complex auditory stimuli consistent with taste dimensions. The style of musical playing (articulation, nuances, accents, richness) contributed to distinguishing the stimuli from one another.
Guetta and Loui (2017) - Study 3	Same as in Study 1	4 types of (SW, SO, SA, BT) chocolate ganache	x	x	x	x	Participants matched chocolates with sounds with above-chance accuracy. Match rates were significantly above-chance for the SW category only.
Hauck and Hecht (2019) - Pilot study	5 classical music pieces	NA	x	x	x	x	Two soundtracks differed significantly in 14 out of 16 dimensions, including SW, SO, and BT.
Knöferle et al. (2015) - Study 2	4 soundtracks varying the low-level properties of a 30-second piece of music	NA	x	x	x	x	The participants decoded the correct taste word for each piece of music at a level that was significantly above chance. The observed matching performance was most accurate for the SW taste, slightly less accurate for the SA taste, and least accurate for the BT and SO tastes.
Knöferle et al. (2015) - Study 3	Same as in Study 2	NA	x	x	x	x	Both the U.S. and the Indian sample exceeded chance level in the number of correct mappings. US participants, controlling for music experience, were significantly better at matching the sounds to the correct taste words. Compared to BT sounds, SW sounds were significantly easier to match, while SO and SA sounds were significantly harder to match.
Kontukoski et al. (2015)	4 musical pieces (2 SW and 2 SO)	SW and SO liquid ingredients	x	x			Exposure to the SW or SO musical pieces elicited some congruent taste associations in the free association task (e.g., chocolate for SW music) and in the food-pairs task (e.g., stronger choice preference for lemon for SO music). SW or SO elements in the music were reflected in sugar content and acid content of foods developed in association with music.
Mesz et al. (2012)	Four musical pieces produced by an algorithm (SO, BT, SW, SA)	NA	x	x	x	x	Results showed that participants could decode well above chance the taste word of the composition.
Mesz et al. (2011) - Study 1	Trained musicians improvised on a MIDI keyboard with piano timbre	NA	x	x	x	x	In free improvisation, taste words elicited consistent musical patterns: BT improvisations were low-pitched and legato (without interruption between notes), SA were staccato, SO were high-pitched and dissonant, and SW were consonant, slow, and soft.
Mesz et al. (2011) - Study 2	3 melody improvisations corresponding to each taste word (SO, BT, SW, SA)	NA	x	x	x	x	Non-musical expert listeners classified with high performance the taste word which had elicited the improvisation.
Motoki, Takahashi et al. (2022) - Study 1	20 soundtracks of four genres (Jazz, Classical, Hip-hop, and Rock/Metal)	16 (healthy savory, indulgent savory, healthy SW, and indulgent SW foods) food names	x				Listening to Classical music increased people's preferences for both healthier and indulgent SW foods as compared with the other musical genres. Positive valence mediated the relationship between music genre and indulgent and healthy SW foods.
Motoki, Takahashi et al. (2022) - Study 2	Same as Study 1	Same as Study 1	x				Listening to Classical music increased people's preferences for both healthier and indulgent SW foods compared to the other musical genres. Positive valence mediated the relationship between music genre and indulgent and healthy SW foods.
Padulo et al. (2020)	4 SA, 4 SW, 4 neutral (environmental soundtracks), and 4 silent soundtracks	128 (SW/high-calorie, SW/low-calorie, SA/high-calorie, SA/low-calorie)	x		x		Results indicate that low- and high-calorie SA food selection was greater while listening to SA soundtracks, while low- and high-calorie SW food selection was greater while listening to SW soundtracks compared to neutral soundtracks.

Study	Auditory stimuli	Gustatory stimuli	Basic taste				Results
			SW	SO	SA	BT	
		food images					
Peng-Li et al. (2020)	A SW and a SA soundtrack	16 SW and SA food images	x		x		Across both cultures, participants spent more time fixating on SW food while listening to SW music and SA food when listening to SA music, while no differences were observed in the no music condition. Participants' choices in each sound condition were consistent with fixation time spent.
Reinoso-Carvalho, Gunn, ter Horst, and Spence (2020) - Pre-test	2 songs produced to correspond with softness and hardness and 2 songs to prompt positive and negative emotional effects	NA	x			x	A main effect of music was found for the cross-modal ratings. The positive song evoked the sweetest ratings, followed by the soft song. Negative and hard songs evoked the most BT ratings.
Reinoso-Carvalho, van Ee, Rychtarikova, Touhafi, Steenhaut, Persoone, Spence, and Leman (2015) - Control study	3 (SW, BT, and Medium) soundtracks	NA	x			x	Participants' evaluations of the musical selections differed significantly, with the SW soundtrack rated as the sweetest, the BT soundtrack as the most BT, and the medium soundtrack falling in between.
Reinoso-Carvalho et al. (2017) - Pilot study	2 soundtracks corresponding to smoothness/creaminess and roughness	NA	x			x	The creamy soundtrack was rated as significantly sweeter than the rough soundtrack.
Wang et al. (2017) - Pilot study	A SW and a spicy soundtrack	NA	x	x	x		The spicy and SW soundtracks were matched significantly more frequently to spicy and SW tastes, respectively, than all other options.
Wang et al. (2015)	5 BT, 5 SA, 7 SO, and 7 SW soundtracks previously produced by various researchers and designers	NA	x	x	x	x	Out of the 24 soundtracks, only three had nonsignificant preferences in the choice of taste matches. Overall, the SW soundtracks most effectively evoked the taste intended by the composer, whereas the BT soundtracks were the least effective.
Wang and Spence (2016) - Control experiment	Consonant and dissonant versions of two short melodies	NA	x	x			Participants reliably associated the consonant soundtracks with SW and the dissonant soundtracks with SO.
Wang et al. (2021)	36 short sound clips varying in 13 musical (e.g., articulation, tempo, consonance) and emotional (valence and arousal) attributes	NA			x		The results revealed that SA was associated most strongly with a long decay time, high auditory roughness, and a regular rhythm. Regarding emotional associations, SA was matched with negative valence, high arousal, and minor mode.

Note. NA = Non-applicable; SW = Sweet; SO = Sour; SA = Salty; BT = Bitter.

3.3. Modulating basic taste perception with auditory stimuli

3.3.1. Music

There were 14 studies in our sample testing the effect of music on the perceived taste of foods and beverages, either alone (*n* = 12) or in comparison with other sonic stimuli (*n* = 2). Most of these focused on beverages with alcoholic content (n = 10), and the remaining studies focused on sweet foods, such as ice cream and chocolate.

In the case of alcoholic beverages, two studies in wine-tasting settings described a main effect of classical music on the sweetness rating of wines compared to tasting in silence (Spence et al., 2013), as well as differences in perceived acidity profiles when listening to a classical music piece that was selected to match the sensory attributes of the wine, compared to tasting in silence (Wang & Spence, 2015). An exploratory study found that a white chardonnay wine was perceived as sweeter when a piece of classical music was played compared to silence, but no differences in taste perception were found when compared to when a pop song was played (De Luca et al., 2019). Using the Temporal Dominance of Sensations (TDS) method, Wang et al. (2019) found that the presence of music led to significantly different dominance profiles for sensory attributes of a red wine, particularly for the bitter taste. In Hauck and Hecht's (2019) study, music (Berg vs. Tchaikovsky) influenced the perceived saltiness and sourness of wines and aqueous solutions, but not sweetness and bitterness.

The valence of music affected the sweetness and bitterness (but not sourness) ratings of beers (Reinoso-Carvalho et al., 2019). Pleasant (vs. unpleasant) music enhanced sweetness perception and decreased bitterness ratings. In another study, the mere presence of music seemed to enhance sweetness ratings of alcoholic beverages compared to control and other distracting conditions (Stafford et al., 2012). Finally, Reinoso-Carvalho, Velasco, et al. (2016) found that tasting a beer with a specific musical accompaniment was considered more enjoyable and led to higher sourness ratings than in silence.

Three studies in our sample report the effects of emotionally laden music on the taste of chocolate gelati using the TDS method. Two of these studies suggest that listening to liked music is associated with longer dominance of sweetness, while disliked music elicits a longer dominance of the bitter taste (Kantono et al., 2016, 2019). As in real-world settings, background music is often intertwined with ambient sounds, Lin et al. (2022) tested the effects of combinations of liked and disliked music with pleasant and unpleasant sounds. Once again, preferred music led to higher dominance of sweetness, whereas bitterness was more evident in unpleasant sound conditions (i.e., disliked music, unpleasant sounds, and a combination of both). Another study examined the influence of sonic stimuli in a more ecologically valid setting (Reinoso-Carvalho, van Ee, Rychtarikova, Touhafi, Steenhaut, Persoone, & Spence, 2015). In this case, participants were customers of a chocolate shop who evaluated a chocolate praline while listening to a customized musical accompaniment or the shop's own soundscape. In this context, listening to music did not significantly impact taste ratings.

A summary of the findings is provided in Table 2.5. Given the large proportion of studies with alcoholic drinks (beer and wine), it is not surprising that there were more studies targeting sweet (*n* = 13), sour (*n* = 11), and bitter (*n* = 11) tastes compared to saltiness (*n* = 3), and umami (*n* = 1). Overall, differences in bitterness profiles were more consistent, with reported differences in seven studies, whereas changes in sweetness perception were also reported in seven studies (although with a higher number of null results). In contrast, only three studies reported significant differences in sourness.

Table 2. 5. *Synthesis of Studies Testing the Effect of Music on Basic Taste Perception*

Study	Auditory stimuli	Gustatory stimuli	Basic Taste					Results
			SW	SO	SA	BT	UM	
De Luca et al. (2018)	Peppy and lively vs. Fine music	White and red wine	x	x				The white wine was perceived to be more delicate and sweeter if accompanied by a classical (vs. pop) music background. The red was perceived as less alcoholic when pop music (vs. silence) was transmitted, but no differences in taste ratings were observed.
Hauck and Hecht (2019) - Main study	Two classical music pieces selected in a pilot study	Red wine, white wine, sugar water, and citric acid solution	x	x	x	x		There was a significant main effect of music on rating dimensions. The univariate effect of the factor 'music' was significant in SO and SA dimensions but not BT and SW. The two music pieces were previously shown to differ significantly in BT, SW, and SO but not SA.
Kantono et al. (2019)	14 sound segments in different music genres (with the least liked, more liked, and closest to the mid-range liking score selected for each individual)	Bittersweet gelato samples	x			x		Electrophysiological measures can covary sensory changes while listening to music. Ratings of positive emotions were associated with SW perception, while ratings of negative emotions were associated with BT perception.
Kantono et al. (2016)	Music samples representing 14 musical genres	Three (dark/BT, bittersweet, milk/SW) chocolate gelati	x	x	x	x	x	The TDS difference curves showed significant differences between gelati samples and music conditions. SW was perceived more dominant when neutral and liked music were played, while BT was more dominant for disliked music.
Lin et al. (2022)	14 segments of music of different genres, 14 sounds, mixtures of liked music and pleasant sound (LMPS), and mixtures of disliked music and unpleasant sound (DMUS) unique to the individual panelists	Bittersweet chocolate ice cream	x			x		Consuming ice cream during the liked music condition resulted in the longest duration of perceived SW, whereas BT was dominant under the disliked music and unpleasant sound (DMUS) and disliked music conditions, respectively. Positive emotions correlated with SW and cocoa in the positively valenced auditory conditions. Negative emotions were associated with BT and roasted tastes/flavors under the negatively valenced auditory conditions.
Reinoso-Carvalho, Velasco, et al. (2016)	A fragment of the song "Oceans of Light" by The Editors	Dark ale beer	x	x		x		The presence of the song seemed to have a modulatory effect on the perceived SO of the beer, but not SW and BT.

Study	Auditory stimuli	Gustatory stimuli	Basic Taste					Results
			SW	SO	SA	BT	UM	
Reinoso-Carvalho, van Ee, Rychtarikova, Touhafi, Steenhaut, Persoone, and Spence (2015)	A fragment of “Vem Morena, Vem” by Jorge Bem	Chocolate sample	x	x	x	x		Customers reported a better tasting experience when the sounds were presented as part of the food’s identity and were willing to pay significantly more for the experience. The participants who heard the kitchen soundscape (condition B) instead of the song (conditions A, C, and D) rated the chocolate as tasting less SW, although this comparison failed to reach statistical significance. The comparisons between the ratings on BT, SO, and SA levels among conditions were inconclusive.
Reinoso-Carvalho et al. (2019) - Study 1	Positive and negative music	Beer (BT-dry pale lager)	x	x		x		No differences were found between sensory ratings of the beer (SW, BT, and SO) when comparing positive versus negative or sound versus silence conditions.
Reinoso-Carvalho et al. (2019) - Study 2	Two positive and one negative music track	Beer (pale-lager)	x	x		x		Participants rated the beer as tasting sweeter while listening to the positive (vs. negative) music and more BT while listening to the negative (vs. positive) music. No differences were observed for SO ratings.
Reinoso-Carvalho et al. (2019) - Study 3	Two positive and one negative music	Beer (strong dark ale)	x	x		x		Participants rated the beer as tasting sweeter while listening to the positive (vs. negative) music and more BT while listening to the negative (vs. positive) music. No differences were observed for SO ratings.
Spence et al. (2013) - Study 2	Four classical music pieces	Four wines with distinctive sensory characteristics (e.g., acidity, SW)	x	x				Participants perceived the wine as tasting sweeter and enjoyed the experience more while listening to the matching music than while tasting the wine in silence. No significant difference in acidity.
Stafford et al. (2012)	A piece of music and news articles recorded by a male voice	Five freshly prepared drinks of cranberry juice and vodka in different proportions	x			x		SW perception was significantly higher in the music than in control and other distracting conditions. BT ratings were lower in the music group compared to the control.
Wang and Spence (2015)	Two pieces of classical music (chosen to match each wine)	White and red wine		x				The wine tasted while listening to Debussy was rated as significantly more acidic than while listening to Rachmaninoff, regardless of the type of wine.
Wang et al. (2019)	Two pieces of music that varied in tempo, mode, and instrumentation	Red wine	x	x		x		There was a higher dominance duration for BT in both music conditions (vs. silence) but no differences between the two soundtrack conditions. No significant differences were observed in dominance durations of SW and acidity.

Note. NA = Non-applicable; SW = Sweet; SO = Sour; SA = Salty; BT = Bitter.

3.3.2. Soundtracks

Sixteen studies in our sample tested the effect of soundtracks on sensory perception of foods and drinks. Generally, these auditory stimuli were produced by researchers and sound designers to match or enhance tastes or flavors. One of the first studies to empirically test this possibility showed that a bittersweet cinder toffee was perceived as tasting significantly more bitter when participants listened to a bitter soundtrack compared to a sweet soundtrack (Crisinel, Cosser, et al., 2012). Höchenberger and Ohla (2019) conducted two experiments to replicate these results. In the first experiment, the soundtracks influenced bitterness-sweetness ratings in the expected direction (i.e., the samples were perceived as sweeter under the sweet sound condition vs. the bitter sound condition). However, when a “no sound” condition was included in the statistical analysis, the effect of sound was no longer significant. Moreover, when independent taste rating scales were used in Experiment 2 (for sweet, bitter, salty, and sour) instead of a bipolar bittersweet scale (Experiment 1), the effect of sound was no longer significant.

Across three experiments, Reinoso-Carvalho, Wang, van Ee, et al. (2016) found that sensory (i.e., sweet, bitter, and sour) properties of soundtracks may transfer to the sensory perception of beers. Interestingly, the modulatory effects of sounds for two of the beers were significant when comparing pairs of soundtracks differing in taste correspondences but not when comparing soundtracks and silence conditions. Conversely, for the remaining beer, the soundtracks led to different taste ratings only when comparing soundtrack and silence conditions.

One study testing the effect of a “creamy” (vs. “rough”) soundtrack on the taste of chocolate showed that sound could modulate perceived creaminess, as well as the perceived sweetness of the samples (Reinoso-Carvalho, Wang, et al., 2017). Another study with “sweet” and “bitter” soundtracks found differences in taste ratings for bitter chocolate but not for sweet chocolate (Reinoso-Carvalho, van Ee, Rychtarikova, Touhafi, Steenhaut, Persoone, Spence, et al., 2015). Interestingly, the modulatory effects were more evident when comparisons were made using each participant’s individual correspondences between the soundtracks and tastes (i.e., pairing the sweet chocolate with the soundtrack that the participant selected as “sweet” in a pretest instead of the group average). Furthermore, the time of presentation of the soundtracks also leads to different modulatory effects. Specifically, while presenting the soundtracks before or during tasting significantly modulated taste ratings, this effect did not hold when a soundtrack was presented after tasting (Wang et al., 2020).

Although most soundtracks were created with taste associations in mind, two recent studies have highlighted the role of emotional associations in eliciting changes in taste perception. One study found stronger evidence for an effect of positive (vs. negative) soundtracks on the perceived sweetness of chocolates than for soft (vs. hard) soundtracks (Reinoso-Carvalho, Gunn, ter Horst, et al., 2020). Similar results were obtained when comparing different cultures, namely, between Japanese and Colombian participants (Reinoso-Carvalho, Gunn, Molina, et al., 2020).

Two additional studies in our sample tested the effect of consonant and dissonant soundtracks on the taste of juices (Wang & Spence, 2015; 2018). Both studies suggested that consonant soundtracks increased perceived sweetness, being also perceived as more pleasant than dissonant soundtracks. The study by Wang and Spence (2018) included both visual and auditory stimuli and found that valence (positive vs. negative) was more determinant than sensory modality (visual vs. auditory) in taste perception differences.

One study conducted in a naturalistic eating setting tested the effect of spicy (high pitch, fast tempo, and a distorted timbre) and sweet (high pitch, legato articulation, and consonant harmony) soundtracks on the perception of a restaurant dish (Wang et al., 2017). Here, although participants reported expecting the dish to be spicier when listening to a spicy soundtrack, actual taste (i.e., sweetness) ratings were unaffected by the soundtrack.

Table 2.6. summarizes the evidence in this category of studies. Once again, sweet (*n* = 16) and bitter (*n* = 12) sensations were examined more frequently, followed by sourness (*n* = 8) and salty (*n* = 1). Most studies reported significant differences in sweet (*n* = 13) and bitter (*n* = 9) attributes, whereas differences in sourness were reported in five studies.

Table 2. 6. *Synthesis of Studies Testing the Effect of Soundtracks on Basic Taste Perception*

Study	Auditory stimuli	Gustatory stimuli	Basic taste				Results
			SW	SO	SA	BT	
Crisinel, Cosser, et al. (2012)	BT (trombone) and SW (piano) soundtracks	Cinder toffee	x			x	The samples were rated as significantly more BT when listening to the BT (vs. SW) soundtrack.
Höchenberger and Ohla (2019) - Study 1	BT (low-pitch trombone) and SW (high-pitch piano) soundtracks	Cinder toffee	x			x	Samples tasted sweeter with a SW sound and more BT with a BT sound, but this effect disappeared when a “no-sound” control was included in the statistical model.
Höchenberger and Ohla (2019) - Study 2	Same as in study 1	Same as in study 1	x	x	x	x	Taste quality-specific intensity was not influenced by sound.
Reinoso-Carvalho et al. (2017)	Two soundtracks corresponding to smoothness/creaminess and roughness	Four chocolates with 2 shapes (angular vs. round) and two formulas (71% vs. 81% cocoa content)	x			x	The participants reported that the chocolates tasted sweeter while listening to the creamy soundtrack and more BT while listening to the rough soundtrack.
Reinoso-Carvalho, Gunn, ter Horst and Spence (2020)	2 soft/hard songs and 2 (positive/negative) songs	Two types of chocolates (milk and dark)	x	x		x	The chocolates were rated as having a more intense flavor for those listening to softer (vs. harder) music. There was no evidence that participants rated the chocolate’s SW, BT, or SO differently while listening to soft (vs. hard) songs. The chocolate was rated as tasting sweeter when evaluated with positive (vs. negative) music, but no differences were observed for SO and BT.
Reinoso-Carvalho, Gunn, Molina et al. (2020)	2 soft/hard songs and 2 (positive/negative) songs	Two types of chocolates (milk and dark)	x			x	Chocolate was rated as sweeter with positive music (regardless of chocolate and culture) and more BT with the negative music (except for dark chocolate in the Japanese sample). No differences concerning the sensory evaluation of the chocolates were significant with soft/hard music.
Reinoso-Carvalho, van Ee, Rychtarikova, Touhafi, Steenhaut, Persoone, Spence, and Leman (2015)	3 soundtracks congruent with SW, BT, and medium chocolates	BT, medium, and SW chocolates	x			x	The BT chocolate was rated as sweeter when listening to the subject SW soundtrack [vs. silence] and as more BT with the BT song [vs. medium sound], with the subject BT song [vs. subject sweet sound], and with the subject medium sound [vs. subject SW sound]. Differences were found only for the BT chocolate and more strongly for the subject-matched soundtracks (i.e., participants' individual music-chocolate matches).

Study	Auditory stimuli	Gustatory stimuli	Basic taste				Results
			SW	SO	SA	BT	
Reinoso-Carvalho, Wang, van Ee, et al. (2016) - Study 1	SW and BT soundtracks	Beer	x			x	The participants rated the beer as significantly sweeter when listening to the SW soundtrack than when listening to the BT soundtrack.
Reinoso-Carvalho, Wang, van Ee et al. (2016) - Study 2	SW and SO soundtracks	Beer	x	x			The participants rated the beer as significantly sweeter when listening to the SW soundtrack than when listening to the SO soundtrack.
Reinoso-Carvalho, Wang, van Ee et al. (2016) - Study 3	SO and BT soundtracks	Beer		x		x	No significant differences were found in any of the taste ratings.
Reinoso-Carvalho, Wang, van Ee et al. (2016) - Control	NA	Same as in Studies 1-3	x	x		x	The ratings differed significantly only for the beers in experiment 3, compared to silence. The beer was rated as significantly more BT and SO in single taste scales while listening to the BT soundtrack, compared to silence. The beer was also rated as more SO on the BT-SO scale while listening to the BT soundtrack.
Wang and Spence (2018)	Consonant and dissonant versions of a short melody	Juice mixture	x	x			Participants rated the juice as sweeter and less SO while exposed to more positive (vs. negative) visual and musical stimuli.
Wang et al. (2017) - Study 2	Spicy and SW soundtracks and white noise	A dish with SW and spicy components	x				Soundtracks modified people's evaluation of the expected and actual spiciness of foods but not of expected or actual ratings of SW taste.
Wang and Spence (2016) - Study 1	Consonant and dissonant versions of two short piano melodies	Juice mixtures	x	x			Participants rated the fruit juice as tasting sourer while listening to the dissonant music than while listening to the consonant music. The correlations between music pleasantness ratings and SO-SW ratings were significant.
Wang and Spence (2016) - Study 2	Consonant and dissonant versions of one melody with piano and trumpet sounds	Two blends of fruit juice	x	x			Participants rated the juice as tasting significantly sweeter while listening to consonant (vs. dissonant) music. The correlation between ratings of music pleasantness and ratings on the SO-SW scale was significant.
Wang et al. (2020) - Study 1	A SW and BT soundtrack	70% chocolate	x			x	The chocolates experienced with the sweet soundtrack were rated as sweeter than the chocolates experienced with the BT soundtrack. The taste-congruent soundtracks had no such effect on taste ratings for those participants who heard the soundtrack only after tasting.
Wang et al. (2020) - Study 2	Same as in study 1	Same as in study 1	x			x	Participants rated the chocolates as tasting sweeter when they had listened to the SW soundtrack – either before or during tasting – compared to the BT soundtrack.

Note. NA = Non-applicable; SW = Sweet; SO = Sour; SA = Salty; BT = Bitter.

3.3.3. Noise, tones, and soundscapes

Participants in Burzynska's et al. (2019) study tasted two wines while in silence and while listening to a low (100 Hz) or high (1000 Hz) frequency sine wave tone. While the sound condition had a relative impact on some of the wine's attributes (e.g., higher aromatic intensity with the lower frequency tone), the only dependent measure related to basic tastes (acidity) was unaffected by the experimental manipulation.

Three studies examined the effect of noisy stimuli on taste perception. Woods et al. (2011) showed that food was rated significantly less sweet and salty under loud (vs. quiet) white noise.

Yan and Dando (2015) tried to reproduce the auditory experience of a noisy airline cabin and exposed participants to the simulated noise for 30 min before and during the tasting of five aqueous solutions. Although the noise condition did not impact ratings for salty, bitter, and sour tastes, sweet taste perception was significantly suppressed by noise, regardless of concentration levels. In contrast, umami was perceived as more pronounced under the loud noise condition. Since it is common to conduct research on gustatory function with fMRI, Lorentzen et al. (2021) tested whether the noise of an fMRI scanner could represent a confound in these studies by impacting taste identification, intensity, or hedonic ratings. According to these results, no significant impact of noise (compared to silence) was found for any taste variables, regardless of the taste in question (sweet, salty, sour, or bitter).

Regarding soundscapes, Bravo-Moncayo et al. (2020) found that the taste of coffee was evaluated as more bitter and with a more intense aroma when listening to a filtered (less loud) version of a noisy food court soundscape, compared to an unfiltered (louder) background noise. Two studies in our review tested the effect of soundscapes on continuous dynamic measures of sensations using two different methods. In the Temporal Dominance of Sensations (TDS) method, participants select the most dominant sensory attribute at a given moment in time, while in the Temporal Check-All-That-Apply (TCATA) method, participants may choose more than one attribute simultaneously. One study employed the former method to assess differences in perception of ice-cream flavor while listening to a café soundscape or the same soundscape overlaid with bird, forest, and machine sounds (Xu, Hamid, Shepherd, Kantono, Reay, et al., 2019). These soundscapes elicited different taste and flavor trajectories and emotional experiences. For instance, when listening to the café-forest soundscape, sweetness was more dominant and for a longer duration at the start of consumption than the café-bird and café-machine soundscapes. The bitter taste was perceived as more dominant at the end of the consumption period when listening to the café control and café-machine soundscapes as compared to the café-birds and café-forest soundscapes. Additionally, a correlation was observed between evoked emotions and taste and flavor ratings, specifically between unpleasant emotions and bitterness dominance and between pleasant emotions and sweetness dominance. A similar result was obtained in a study using the TCATA method in which participants identified sweetness more frequently in positive valence conditions, such as a park or a café soundscape (Lin et al., 2019). In contrast, bitterness was more pronounced in high arousal, low valence conditions, such as bar, fast food, and food court soundscapes.

A summary of findings may be found in Table 2.7. Overall, the results seem to indicate some inconsistency regarding the influence of noise on taste perception, which could be attributable to methodological differences (e.g., stimuli characteristics). As far as soundscapes are concerned, differences in sweetness and bitterness perception were reported in accordance with the emotional tone of the stimuli.

Table 2. 7. *Synthesis of Studies Testing the Effect of Notes, Noise, and Soundscapes on Basic Taste Perception*

Study	Category	Auditory stimuli	Gustatory stimuli	Basic Taste					Results
				SW	SO	SA	BT	UM	
Bravo-Moncayo et al. (2020)	Noise	Three versions of a food court noise (baseline unfiltered noise - UBN; passive-controlled noise - PBN, and active-controlled noise - ABN)	Coffee	x	x		x		Consumers rated the coffee as more BT while listening to the filtered (vs. unfiltered) noises. The differences in acidity and SW were not significant.
Burzynska et al. (2019)	Notes and tones	Sine waves with a bass frequency of 100 Hz and 1000 Hz	Two red wines		x				The acidity ratings of both wines did not differ significantly across sound conditions.
Lin et al. (2019)	Soundscape	Environmental sounds: café, fast food restaurant, bar, food court, and park	Chocolate gelato	x			x		BT, roasted, and cocoa notes were more evident when the bar, fast food, and food court sounds were played. SW was cited more in the early mastication period when listening to park and café sounds. The valence evoked by the pleasant park sound was positively correlated with SW, whereas the arousal associated with bar sounds was correlated with BT, roasted, and cocoa attributes.
Lorentzen et al. (2021)	Noise	One "quiet" sound setting and one recording of fMRI noise	Five concentrations of four basic tastants (SW, SA, SO, and BT) from the Taste-Drop-Test	x	x	x	x		Loud acoustic fMRI noise did not affect gustatory perception for any of the tastants.
Woods et al. (2011)	Noise	White noise (Quiet, loud) or no noise (Baseline)	Savory/crunchy (salted crisps), savory/soft (mini cheese), SW/crunchy (Biscuits), and SW/soft (flapjack) stimuli	x		x			Background noise reduced the reported intensity of SW and SA, regardless of hardness (crunchy or soft).
Xu et al. (2019)	Soundscape	Café soundscape presented alone (control) or overlaid with bird (café-bird), forest (café-forest), and machine sounds (café-machine)	Chocolate ice cream	x			x		SW and creaminess were dominant at the start of the consumption episode while listening to the café-forest soundscape. BT was perceived at the end of the consumption period in café/control and café-machine soundscapes. Listening to the café-machine soundscape evoked negative emotions associated with BT and creaminess, which were also associated with increased heart rate (HR) and respiration rate (RESP). When listening to the café-forest soundscape, ice cream was associated with SW and positive emotions.
Yan et al. (2015)	Noise	Cabin noise	Aqueous solutions for the five basic tastes at three concentration levels	x	x	x	x	x	Loud noise suppressed SW taste perception across all concentrations and enhanced UM in medium and high concentrations. SO, BT, and SA tastes were unaffected.

Note. NA = Non-applicable; SW = Sweet; SO = Sour; SA = Salty; BT = Bitter; UM = Umami.

4. Discussion

The present work provides an overview of the current evidence on the relationship between audition and taste. Although not always seen as such, audition has been growingly acknowledged as a relevant sensory modality for taste (and flavor) perception (Spence, 2016). According to these findings, there are at least two ways by which audition and taste interweave.

First, it seems that there are regularities in how people match sounds to basic tastes. The scope of sound-taste associations seems to range from more elementary auditory stimuli, such as musical notes or speech sounds, to more complex stimuli, such as music. One important consequence of the multimodal nature of human perception is that stimulating one sensory modality may contribute to modulating the perception of information in another modality (Evans & Treisman, 2010). That seems to be the case with taste perception as well. Thus, a second complementary line of inquiry is now shedding light on how the crossmodal correspondences between sounds and tastes may result in different sensory experiences with foods and drinks. According to the reviewed literature, there are several ways whereby sound may influence taste perception. The most common strategies involve musical stimuli, either something one could expect to hear in a restaurant, such as pop, jazz, or classical music (e.g., Hauck & Hecht, 2019) to less familiar, bespoke soundtracks that are intentionally composed to convey basic taste attributes (e.g., Wang et al., 2015).

In most eating settings, people are exposed to other auditory stimuli as well. Ambient noise in places like canteens or food courts is known to have a negative impact on customers' experience (Spence, 2014). However, it's still unclear how it may affect taste perception, as is evidenced by the mixed findings reviewed here. Indeed, the answer may depend on the type of noise as well as the basic taste in question. Research with soundscapes reinforces the need to pay attention to environmental sounds in eating settings, as these may shape how tastes are perceived. Notably, these studies (but also those with musical stimuli) seem to suggest that emotional/affective dimensions may be relevant to understanding the implications of sound for the taste experience. Particularly, pleasant emotions and affect may be significant factors for enhancing sweetness perception, whereas unpleasant emotions and affect seem to emphasize bitterness perception (Lin et al., 2019; Xu, Hamid, Shepherd, Kantono, Reay, et al., 2019).

4.1. Psychoacoustic attributes of taste-evoking stimuli

One quintessential challenge in crossmodal research is determining what attributes make up a sweet or a salty sound which can be approached by asking professional musicians to create musical compositions based on taste attributes (e.g., Mesz et al. 2011). Another – more common – method is based on laypeople's intuitive matching of sounds to tastes (i.e., how sounds varying in sonic attributes such as pitch or loudness are differently matched to tastes).

The most commonly studied acoustic attribute in this regard is pitch. Previous research has shown that high-pitched sounds are crossmodally associated with attributes like brightness (Marks & Pierce, 1989), higher spatial position (Rusconi et al., 2006), or a small size (Bien et al., 2012; Fernández-Prieto et al., 2015). Regarding sound-taste associations, there seems to be a fair degree of consistency in how individuals match the sound frequency to some of the basic tastes. The majority of the reviewed studies suggest an association between higher-pitched sounds and sweet and sour tastes, whereas lower-pitched sounds are more frequently associated with bitterness. It should be noted, however, that this pattern may depend, for instance, on the type of instrument under analysis (Watson & Gunther, 2017). On the other hand, the taste-pitch patterns seemed to hold regardless of whether taste stimuli were presented as food words (Crisinel & Spence, 2009; 2010; Qi et al., 2020) or actual gustatory stimuli (Crisinel & Spence, 2011; Reinoso-Carvalho, Wang, de Causmaecker, et al., 2016).

Besides pitch, other acoustic attributes may be manipulated to mimic basic tastes: For instance, Mesz et al. (2011) found that musicians systematically manipulate attributes like duration, dissonance, articulation, and loudness. Knöferle et al. (2015) later showed that individuals with no musical training are also able to match tastes to sounds with different roughness, discontinuity, tempo, and sharpness. Wang et al. (2015) provided an overview of the taste-evoking soundtracks released to date and systematized some of the main acoustic attributes (pitch, instruments, harmony, and articulation) of bitter, salty, sour, and sweet soundtracks. Although some attributes were consistently associated with tastes (for example, sweetness and consonance), others were less stable across taste categories (e.g., bitter soundtracks may be consonant or dissonant, low-pitched or medium-pitched). For that reason, defining the sonic attributes of taste-evoking stimuli remains a challenge.

4.2. Understanding taste-sound correspondences

Understanding the acoustic mechanics of a sweet or salty sound may help understand how taste-sound correspondences unfold. However, it is also important to question why gustation and audition interweave in predictable ways. Most studies reviewed here do not explicitly seek to test conceptual hypotheses for sound-taste associations or sonic seasoning effects. Nonetheless, we should briefly mention some likely conceptual explanations for the findings reviewed here.

At least four possible mechanisms underlying taste-sound correspondences have been put forward, namely, statistical, intensity-matching, semantic, and hedonic hypotheses (Knöferle & Spence, 2012). These mechanisms are summarized in Table 2.8., alongside illustrative examples taken from this review. The statistical co-occurrence hypothesis posits that individuals learn to match attributes that tend to coexist frequently together in natural environments. For instance, color-taste associations (e.g., between red-colored products and sweetness) are thought to depend on previous knowledge that fruits tend to transition from colors at the green end of the spectrum to colors at the red end of the spectrum as they ripen (Foroni et al., 2016; Maga, 1974). In the case of sound-taste associations, such associative learning may not be as straightforward since it is not easy to imagine the natural sound of bitter food. Still, it has been proposed that innate orofacial gestures in response to pleasant and unpleasant tastes may have associated speech sounds. For instance, protruding the tongue outward and upward in response to a pleasant taste could result in higher frequency sounds when exhaling (Knöferle & Spence, 2012). Motoki et al. (2020) provide another illustration of a statistical mechanism. In their study of brand names and taste expectations, the authors argue that people may learn to associate certain food brand names with tastes based on real-world patterns (for example, based on the common occurrence of brand names containing stop and voiced consonants for salty products).

The intensity matching hypothesis posits that crossmodal correspondences may stem from mappings based on magnitude judgments. The so-called "prothetic" (or magnitude-related) hypothesis is in line with Wang's et al. (2016) findings, where participants consistently matched higher sound loudness to higher concentrations of tastants. Although intensity-matching seemed to explain (or, at least, show consistency with) the results observed for sound volume, the same was not the case with pitch. While the expected pattern (higher tastants concentration to higher pitch) was observed for some of the tastants, the opposite pattern was observed for others. Moreover, the results also depended on the measure in question (i.e., objective concentration measures or subjective intensity ratings).

On a different note, the fact that pitch is verbally described as differing in height (i.e., "high or "low") serves as an example of a semantic commonality in which the same language terms are applied to describing different perceptual phenomena. According to this view, an association between spatial position and sound frequency could be attributed to this commonality (Knöferle & Spence, 2012). In different languages, the word "sweet" is a common synesthetic metaphor for describing acoustic qualities, such as a soft voice or a delicate way of playing an instrument (Mesz et al., 2012). This association has been hypothesized to be involved in why some studies report a seemingly easier recognition of sweet taste attributes in music pieces compared with other taste categories (e.g., Guedes, Prada, Garrido, & Lamy, 2023; Knöferle et al., 2015; Wang et al., 2015). However, semantic commonalities fail to explain why individuals are also able to match soundtracks to other basic tastes with above-chance accuracy.

The hedonic matching hypothesis is an alternative explanation of sound-taste correspondences (Knöferle & Spence, 2012). This proposition is based on the assumption that some tastes are globally deemed more pleasant than others. Indeed, the sweet taste is thought to be innately preferred due to its association with maternal milk. In contrast, the bitter taste is often rejected as a protective caution against possible toxicity (Ventura & Mennella, 2011). Although adults may show different taste preferences, it is possible that conceptually, such a heuristic could account for some taste-sound correspondences. It has been shown that the choice of instrument sounds is associated with pleasantness ratings (e.g., piano associated with pleasantness and sweetness; brass associated with unpleasantness and bitterness; Crisinel & Spence, 2010; Crisinel & Spence, 2012). While the choice of instrument was significantly affected by pleasantness, the same was not always true for the choice of pitch. As Crisinel and Spence (2012) argue, the lack of a consistent association with pitch may be due to participants' difficulty in agreeing on how pleasantness and pitch relate (i.e., some higher-pitched sounds may be more pleasant, whereas others may not). Guetta and Loui (2017) also found support for a hedonic matching hypothesis in music-taste matching, as individuals who judged a sweet chocolate ganache as more pleasant also rated the sweet soundtracks as more pleasant. In contrast, those who preferred a salty ganache also rated a salty soundtrack as more pleasant. Similarly, Guedes, Prada, Garrido, and Lamy (2023) found several correlations between music-taste correspondences and emotional and affective variables (e.g., soundtracks evaluated as sweet were more associated with pleasant emotions, whereas the opposite pattern was found for bitterness).

Although the aforementioned conceptual hypotheses may help explain why people associate stimuli pertaining to the auditory and gustatory modalities in some instances, there are also findings that do not fit perfectly in the existing conceptual frameworks. For example, Knöferle et al. (2015) argue that some crossmodal associations (e.g., sour taste and high tempo) are not easily framed in either of the existing working hypotheses and require further research and theoretical reflection.

4.3. Understanding sonic seasoning

Spence et al. (2019) have argued that the mere existence of a taste-sound association does not assure that a given auditory stimulus will result in changes in taste perception. Previously, five mechanisms underlying the modulatory role of audition in taste perception have been posited (Wang, 2017): response bias, sensory expectations, attention capture, physiological response, and emotion mediation (for a summary, see Table 2.8.).

In one study reviewed here, participants tasted chocolate with a soundtrack delivered before, during, or after the tasting (Wang et al., 2020). Notably, taste ratings were affected when the soundtrack was delivered during the tasting but not after tasting (Experiment 1), suggesting that sonic seasoning corresponds to an actual perceptual effect rather than a mere response bias. No differences were observed when the soundtrack was played before (vs. during) tasting (Experiment 2), which seems consistent with the idea that auditory stimuli may alter taste expectations. These, in turn, may influence how food or drinks are perceived (see also Wang et al., 2017). These findings support a sensory expectations account but not a response bias explanation.

An attention-capture account has been used to explain findings in TDS studies. Wang et al. (2019) argue that crossmodal associations may direct individuals' attention toward congruent attributes of a gustatory stimulus, thus making it appear dominant in the flavor matrix. Alternatively, evidence emerging from other TDS studies shows that physiological responses may have an important role in modulating taste perception. Listening to music and soundscapes has been shown to elicit electrophysiological changes (e.g., skin conductance, heart rate, or respiratory rate), which seem to correlate with changes in flavor perception (Kantono et al., 2019; Xu, Hamid, Shepherd, Kantono, & Spence, 2019).

Based on the current evidence, physiological response mechanisms seem to depend on a second explanatory variable, namely, emotion. What the literature on TDS appears to suggest is that auditory stimuli change individuals' affective states, which, in turn, lead to a differentiated taste experience. Similar to what has been said about crossmodal correspondences, pleasant emotions are tendentially correlated with sweetness dominance, whereas unpleasant emotions highlight the bitter taste (Kantono et al., 2019; Lin et al., 2019; Xu, Hamid, Shepherd, Kantono, & Spence, 2019).

Similar to what has been described for TDS studies, research with "static" taste ratings also shows support for an effect of stimulus valence on sweetness ratings of juices and beers (Reinoso-Carvalho et al., 2019; Wang & Spence, 2018). Intriguingly enough, it has recently been argued that the emotional connotations of music may have a larger effect on taste ratings than crossmodal attributes alone. In two studies, participants tasted chocolate while listening to a soft (vs. hard) soundtrack or a positive (vs. negative) soundtrack (Reinoso-Carvalho, Gunn, Molina, et al., 2020; Reinoso-Carvalho, Gunn, ter Horst, & Spence, 2020). Although the pieces of music with crossmodal attributes were effective in modulating taste perception, the emotional music led to larger differences in taste ratings. One could argue that this result was perhaps due to the former pair of songs evoking textural rather than taste attributes more directly. Yet, the soft music had been previously shown to correspond to a sweet sensation, contrarily to the hard song, which was more associated with bitterness.

In a similar vein, the feelings evoked by auditory stimuli may also be transposed to the hedonic evaluation of foods and drinks. This process, usually known as "sensation transference", may help explain why liked music affects not only how participants evaluate the taste of foods but also how much they enjoy them (Guedes, Prada, Lamy, & Garrido., 2023; Kantono et al., 2016; Reinoso-Carvalho, Wang, van Ee, et al., 2016). Sensation transference has also been proposed as a potential mechanism to explain differences in taste ratings, as the pleasantness of a song may also be transferred to the evaluation of attributes such as sweetness or bitterness, which are positively and negatively associated with pleasantness, respectively (Reinoso-Carvalho, Touhafi, et al., 2016).

In future studies, it would be of interest to unravel the effects of emotional and crossmodal attributes, for instance, by testing pairs of sweet (vs. bitter) soundtracks with average valence ratings and positive (vs. negative) soundtracks controlling for crossmodal correspondences. Disentangling these effects would provide a valuable contribution to the field since knowing which attributes to look for in sound stimuli would be of major importance for informing future studies and interventions. If emotional connotations were solely responsible for leading sonic seasoning effects, one would perhaps expect emotional variables to fully mediate the effect of sound on taste ratings. However, that was not the case in Wang's et al. (2020) study, where soundtrack-taste associations fully mediated this relationship while valence did not. Further research would be needed to check whether the same findings would be obtained with different stimuli and/or other affective dimensions (e.g., arousal, dominance).

Table 2. 8. *Summary of Putative Explanatory Mechanisms for Crossmodal Correspondences and Sonic Seasoning Effects*

Proposed mechanism	General principle	Empirical example
Crossmodal correspondences[1]		
Statistical co-occurrence	Individuals match features of stimuli from gustatory and auditory modalities based on natural co-occurrences	Association of brand names containing stop and voiced consonants with saltiness based on the frequency of real-world brands of salty products whose names contain those sounds (Motoki et al., 2020)
Intensity matching	Increases in the magnitude of one attribute of gustation are mapped onto the magnitude of one attribute of audition	Consistent matching between higher sound loudness and higher concentrations of tastants (e.g., sugar) (Wang et al., 2016)
Semantic matching	Correspondences stem from the shared use of a same term or concept to describe sensations from different sensory modalities	The easier association of sound attributes to the sweet taste could be due to the use of the word "sweet" to describe musical attributes (Guedes, Prada, Garrido, & Lamy, 2023)
Hedonic matching	Individuals match sounds and tastes based on shared affective attributes, such as pleasantness	Matching of more pleasant instrument sounds (e.g., piano) with pleasant tastes (e.g., sweetness) (Crisinel & Spence, 2010; Crisinel & Spence, 2012)
Sonic seasoning[2]		
Response bias	Differences in taste ratings could reflect influences in individuals' evaluation process rather than actual perceptual changes	Taste ratings are affected when a soundtrack is delivered during the tasting but not after (Wang et al., 2022 - Study 1)
Sensory expectations	Sounds induce sensory expectations which influence the subsequent tasting experience	No significant differences in taste ratings when a soundtrack is delivered before rather than during eating (Wang et al., 2022 - Study 2)
Attention capture	Auditory stimuli may direct attention to specific components of the taste experience	Sonic attributes commonly linked with sourness are associated with the perceived dominance of this taste in wine (Wang et al., 2019)
Physiological response	Sounds may induce physiological responses similar to those associated with the taste experience	Sounds elicit electrophysiological changes (e.g., heart rate), which correlate with changes in flavor perception (Kantono et al., 2019; Xu, Hamid, Shepherd, Kantono, & Spence, 2019)
Emotion mediation	Sounds influence participants' emotions, and these, in turn, shape the subsequent taste evaluation	Correlation between pleasant emotions induced by music/ soundscapes and sweetness perception (Lin et al., 2019; Reinoso-Carvalho et al., 2019).

[1] See Knöferle & Spence (2012)

[2] See Wang (2017)

4.4. The nature-nurture of crossmodal perception and individual differences

There is a longstanding debate around the universal/innate or learned/culture-dependent nature of crossmodal associations. Support for an innatist outlook of crossmodal perception may come from comparative studies (e.g., Ludwig et al., 2011) as well as developmental research showing the early emergence of crossmodal mappings (Dolscheid et al., 2014; Walker et al., 2010). On the other hand, it has been shown that individuals are able to learn to integrate stimuli from different sensory modalities that were previously unrelated, such as stiffness and luminance (Ernst, 2007). Perhaps one of the most famous examples of multisensory links, the Bouba-Kiki effect, has been cited as a widely shared crossmodal association (Ćwiek et al., 2021). Interestingly, Bremner et al. (2013) found that the Himba, a remote population in Namibia with no written language, were able to match sounds and shapes just as Western participants do. However, they matched sweeter chocolates with angular rather than rounded shapes, contrary to what is commonly found with Western participants.

Currently, cross-cultural comparisons of taste-sound associations are scarce. This is potentially problematic, considering that while some aspects of music perception seem cross-culturally shared, others are not (Knöferle et al., 2015; Qi et al., 2020). Similarly, if some crossmodal correspondences depend on linguistic features, such as shared concepts to describe stimuli in different modalities (e.g., the "sweet" word may be used to describe tastes, aromas, and sounds), the generalizability of findings could be constrained by language boundaries as well (Wang, 2017). In the case of the taste-pitch correspondence, Qi et al. (2020) found that Chinese participants behaved similarly to Western participants in matching higher pitch with sweet and sour tastes and lower pitch with bitter. Ngo et al. (2013) found that Colombian and British participants agreed on matching sweeter juices (e.g., pineapple, mango) with rounder sounds (e.g., "Bouba") and lower-pitched sounds (although no actual sound stimuli were used here, but rather a visual scale ranging from "low-pitched" to "high pitched"). Some specificities were also observed, such as British participants associating passion fruit juice with sharp sounds (e.g., "Takete"), while Colombian participants did not show a clear preference for rounded or sharp sounds.

Regarding the ability to decode taste attributes in more complex sound stimuli (e.g., soundtracks), Knöferle et al. (2015) found that participants from India and the USA performed with above-chance accuracy. Even so, US participants showed higher accuracy, particularly for the sweet taste. In another study, Chinese and Danish participants showed a similar ability to decode sweet and salty soundtracks (Peng-Li et al., 2020). When these soundtracks were played, there was a higher likelihood of selecting a congruent food (e.g., choosing a sweet food when listening to a sweet soundtrack), regardless of culture. However, some differences emerged when including a silence condition. Notably, Danish participants were more likely to choose salty foods when listening to the salty soundtrack (vs. silence), whereas no differences were observed for Chinese participants. When a sweet soundtrack was played (vs. silence), participants were more likely to choose a sweet food than a salty one. However, this difference was only marginal for Danish participants.

Recently, soundtracks previously associated with soft (vs. hard) sensations were shown to have a negligible effect on basic taste ratings of chocolates in a study with South Korean participants (Reinoso-Carvalho, Gunn, ter Horst, et al., 2020). Instead, emotional (i.e., positive vs. negative) music led to more pronounced sonic seasoning effects. Similar results were obtained in a direct cross-cultural comparison with Japanese and Colombian participants (Reinoso-Carvalho, Gunn, Molina, et al., 2020). This result was somewhat surprising, given that soft/hard soundtracks had been previously shown to affect the taste evaluation of chocolates in a study with Western participants (Reinoso-Carvalho, Wang, et al., 2017). However tempting as it may be to interpret these results in light of cultural differences, there are important methodological differences between these studies that should be considered. Notably, soundtrack condition varied within-participants in the latter study, whereas the former two followed a between-participants design. Moreover, Reinoso-Carvalho et al. (2017) contrasted only the two (soft and hard) soundtracks. Thus, it is yet unknown whether the sonic seasoning effects of crossmodally-corresponding music and emotional music differ between cultures.

Apart from cultural differences, a more empirical inquiry is needed regarding the role of individual differences in multisensory perception (for a recent discussion, see Spence, 2022). For instance, in one study, participants with no musical training were more likely to associate one music piece with sweetness, whereas musically trained individuals exhibited more frequent bitter taste associations (Wang et al., 2015). In the first large-scale norming study with sound-taste correspondences, some weak but significant correlations were observed between taste ratings and facets of musical sophistication (Guedes, Prada, Garrido, & Lamy, 2023). In addition, associations between taste preferences and taste correspondences were also observed. For example, participants who reported a higher preference for sour foods provided more frequent sourness correspondences. In another study, taste sensitivity (namely, bitter sensitivity) was shown to influence taste-pitch mappings, as more sensitive individuals matched bitter solutions with lower-pitched sounds (although the small number of participants in this group advises caution in interpreting this result, Wang et al., 2016).

One important matter for debate is whether researchers should treat auditory stimuli nomothetically (i.e., assuming that sounds communicate crossmodal and/or emotional attributes similarly to all individuals) or ideographically (i.e., seeking to treat each individual differently according to their idiosyncratic evaluation of sounds). One of the reviewed studies suggests that this may be an important distinction since individual pairings (in this case of soundtracks and chocolates) may originate somewhat different sonic seasoning effects compared to pairings based on the sample's average (Reinoso-Carvalho, van Ee, Rychtarikova, Touhafi, Steenhaut, Persoone, Spence, et al., 2015). Similarly, opting for self-selected sound stimuli may be a proper strategy for eliciting emotional effects. In effect, individual music preferences can modulate subjective reactions to musical stimuli (Fuentes-Sánchez et al., 2022). Hence, while some people may feel displeased by a heavy metal song, others may report an intensely enjoyable experience. Following this notion, previous studies have taken an idiographic approach to determine the most adequate stimuli based on individual selections of liked and disliked music genres (Kantono et al., 2016, 2019; Lin et al., 2022). From an applied perspective, the two approaches may serve complementary goals. While an idiographic strategy may best fit the purpose of individualized interventions, understanding shared mappings between sounds and tastes may be relevant for interventions in collective meal contexts, such as restaurants or canteens.

4.5. Limitations

The current paper is based on a systematic outlook on the growing body of literature regarding audition-gustation interactions. This approach aimed at ensuring a comprehensive understanding of the current state of knowledge while minimizing the risk of bias that hinders the reliability of traditional reviews. By defining the interactions between these two sensory modalities as the scope of the review, the resulting findings encompass a vast and diverse body of literature. While this may be advantageous in a relatively young field of inquiry, it also has limitations regarding the conclusions to be drawn from the reviewed data. The heterogeneity of data in a broad-scope review may challenge data synthesis and interpretation (Higgins et al., 2019) and can, perhaps, open more questions than it answers. In effect, future narrow-focused reviews are still needed to address more specific questions, such as those regarding the efficacy of specific sound-based interventions for changing taste-related outcomes. Although the current review protocol opened the spectrum of studies to be considered for analysis, there are still limitations, for instance, in terms of the lack of grey literature. The current protocol relied on central sources (i.e., databases) to obtain data, thus excluding findings that may have been disseminated outside the traditional scientific publishing channels (Mahood et al., 2014). In addition, the formulation of the search string may have resulted in a larger representation of crossmodal research based on auditory stimuli such as soundtracks or musical notes, compared to other stimuli such as phonemic sounds. Thus, it would be appropriate to complement the findings of this review with further readings of research in the field of sound symbolism (e.g., Athaide & Klink, 2012; Klink, 2000; Motoki et al., 2021; Pathak et al., 2021, 2022; Pathak & Calvert, 2020).

An additional limitation concerns the "file drawer problem" (otherwise known as publication bias), which refers to the null results that remain unpublished or unwritten (Franco et al., 2014). Thus, it is possible that some studies resulting in statistically insignificant results were not captured by the present review, which could result in an over-representation of "positive" results.

This search strategy allowed the identification of a significant body of peer-reviewed studies, which were summarized in a table of data extraction (provided as a supplement to this review). The data extraction strategy aimed at obtaining a synthesis of findings as well as information regarding methods, procedures, and other general characterization data. One less explored aspect of the data extraction protocol regards the theoretical underpinnings and conceptual hypothesis underlying the studies. Since many of the reviewed papers did not explicitly test explanatory mechanisms nor derive their hypothesis from known theoretical frameworks, the data extraction protocol did not include the assessment of theoretical/conceptual data. Future works may wish to bridge this gap, for instance, by integrating findings according to overarching theoretical frameworks (for an example, see Motoki et al., 2022).

4.6. Applicability and future directions

The current review aimed at summarizing the existing evidence on sound-taste associations as well as reflecting on the future directions of the field. As the interest in this area of research seems to be gaining momentum (as seen by the large slice of studies published in the past five years), it is perhaps the moment to seek to bring coherence to the field. For example, as a growing number of auditory stimuli becomes available, it is relevant to test them comprehensively, under similar circumstances, and based on comparable measurement scales (e.g., Guedes, Prada, Garrido, & Lamy, 2023; Wang et al., 2015). Similarly, replication studies also contribute to the robustness of findings and the confidence in how to read them (Höchenberger & Ohla, 2019; Watson & Gunther, 2017). Currently, there is a great diversity in the use of measurement scales, as well as in research designs, which hinders the comparability of different studies. For example, in sonic seasoning studies, it is unclear whether comparisons are to be made between contrasting stimuli (e.g., a sweet vs. a bitter song) or between music/soundtracks and other sonic stimuli (e.g., white noise, silence). So far, the different options regarding what is to be compared with what have led to disparate findings. In some cases, including a silence condition instead of comparing pairs of contrasting soundtracks may be sufficient to overshadow the effects of music (Höchenberger & Ohla, 2019; Reinoso-Carvalho, Wang, van Ee, et al., 2016). It is also highly questionable whether two sweet soundtracks are as equivalent as to be used interchangeably. The fact that music differs in taste associations but also other conceptual dimensions should be taken into account when comparing findings, as two sweet soundtracks are hardly perceived alike. Validating stimulus sets and testing sonic stimuli across contexts will perhaps allow for greater comparability and, consequently, a more robust quantitative synthesis (such as meta-analyses). Similarly, the full reporting of results (including non-significant findings) and pre-registration of studies will undoubtedly contribute to a more coherent and robust body of evidence. Moreover, reporting effect sizes (or improving data availability to allow calculation) will be of most importance to future efforts toward providing quantitative syntheses of findings.

Another relevant challenge concerns the diversification of samples, given the widely discussed pitfalls of convenience sampling of undergraduate students that seems to plague the reproducibility of behavior research in general (Peterson & Merunka, 2014). Several studies reviewed here rely on samples of visitors or customers of shops, restaurants, or public events. Yet, it is unknown whether these provide an adequate approximation to the general population (e.g., in terms of sociodemographic characteristics, such as educational attainment, but also in engagement or openness to multisensory eating experiences). Likewise, while several of the reviewed studies were conducted in so-called real-world settings (e.g., stores, restaurants), experimental apparatus are still often artificial and lab-like in some respects (e.g., individual booths, use of headphones). Isolating sonic stimuli from the broader context is somewhat problematic since real eating environments are likely to involve a combination of music, speech sounds, and background noise (although, for an approximation, see Lin et al., 2022). Of particular importance is the prevalent use of headphones in most studies. It is likely that this feature of most sonic seasoning studies (not commonly shared in real-world situations) may be important to bring about the desired crossmodal effects, not only by directing attention to the auditory stimuli but also by evoking the notion that gustatory and auditory stimuli origin from the same location (i.e., inside the head, Spence et al., 2019). In sum, the question of ecological validity will be a likely challenge for future studies that will require an effort to bring research closer to real-life circumstances.

To date, there have been exciting applications of sonic stimuli to improve the multisensory experience with foods. One popular example, the dish "Sound of the Sea" by British chef Heston Blumenthal[7] illustrates how audition may be convened to design novel and memorable multisensory experiences in fine dining settings (Spence & Shankar, 2010). With growing digitalization and technological advancements, it also becomes possible to deliver accessible multisensory experiences at home. In the past years, a variety of applications have been released to enhance customers' experience of products like champagne, beer, or chocolate through sound (for a review, see Spence et al., 2019). Initiatives like these undoubtedly contribute to the enjoyment of the eating situation, which may be an important motivation for changing eating habits. As far as sonic seasoning is concerned, there is a sharp predominance of research on highly palatable products, including alcoholic beverages and sweet products. For other sensory modalities, multisensory strategies have been called upon as potential avenues for enhancing sensory acceptance and enjoyment of healthier products, such as sugar-reduced foods (Alcaire et al., 2017; Hidaka & Shimoda, 2014; Hutchings et al., 2019). It is feasible to hypothesize that sound stimuli may also contribute to mitigating the effects of sugar or salt reduction, both on sensory and hedonic grounds. Recently, Peng-li et al. (2021) demonstrated that music might be selectively engineered to communicate healthiness attributes and, consequently, shape healthier food choices. Similarly, background music and noise may systematically nudge participants toward healthier food choices (Biswas et al., 2019). It would be interesting to test whether crossmodally-corresponding background sounds in meal settings could also contribute to promoting healthier eating by means of their effect on taste perception. A recent experiment suggested that this may be a feasible endeavor for sugar consumption, as sweet music was shown to influence taste perception and the acceptance of products with lower sugar levels (Guedes, Prada, Lamy, & Garrido, 2023).

5. Conclusions

The literature on the multisensory interactions between audition and taste perception is rapidly growing. In this work, we sought to provide an outlook of the current understanding of how sound and taste relate by systematically reviewing the existing body of literature. This review allowed the identification of a great variety of points of contact between the two sensory modalities. Two main lines of research were outlined, namely, showing that people

[7] The signature dish consists of sea products served in a shell containing an iPod. A seaside soundscape overlaying sounds of waves and seagulls is delivered through headphones.

systematically associate attributes from gustatory and auditory domains and that taste perception may be liable to the influence of auditory stimuli.

This review sought to synthesize the current evidence to inform future empirical inquiry. Practitioners interested in developing multisensory integration techniques to improve taste perception may also find this review useful for informing the scope and methodological approach of their work.

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The Taste & Affect Music Database: Subjective Rating Norms for a New Set of Musical Stimuli

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Abstract

Music is a ubiquitous stimulus known to influence human affect, cognition, and behavior. In the context of eating behavior, music has been associated with food choice, intake and, more recently, taste perception. In the latter case, the literature has reported consistent patterns of association between auditory and gustatory attributes, suggesting that individuals reliably recognize taste attributes in musical stimuli. This study presents subjective norms for a new set of 100 instrumental music stimuli, including basic taste correspondences (sweetness, bitterness, saltiness, sourness), emotions (joy, anger, sadness, fear, surprise), familiarity, valence, and arousal. This stimulus set was evaluated by 329 individuals (83.3% women; M_{age} = 28.12, *SD* = 12.14), online (*n* = 246) and in the lab (*n* = 83). Each participant evaluated a random subsample of 25 soundtracks and responded to self-report measures of mood and taste preferences, as well as the Goldsmiths Musical Sophistication Index (Gold-MSI). Each soundtrack was evaluated by 68 to 97 participants (*Mdn* = 83), and descriptive results (means, standard deviations, and confidence intervals) are available as supplemental material at osf.io/2cqa5. Significant correlations between taste correspondences and emotional/affective dimensions were observed (e.g., between sweetness ratings and pleasant emotions). Sex, age, musical sophistication, and basic taste preferences presented few, small to medium associations with the evaluations of the stimuli. Overall, these results suggest that the new Taste & Affect Music Database is a relevant resource for research and intervention with musical stimuli in the context of crossmodal taste perception and other affective, cognitive, and behavioral domains.

Keywords: Soundtracks, Music, Auditory stimuli, Normative data, Subjective ratings, Emotion, Taste, Familiarity, Valence, Arousal

1. Introduction

Music is everywhere. It has been part of the human experience since ancient times (Zatorrea & Salimpoor, 2013) and has acquired a ubiquitous presence in most daily activities, from shopping to driving, working, or even eating. Accordingly, musical stimuli have been the subject of interest for researchers, given their potential impact on how people feel, think, and behave. Considering the need for validated musical stimulus sets in research, the current study aimed to obtain subjective norms for a new set of 100 instrumental soundtracks. The soundtracks were evaluated for basic taste correspondences (e.g., sweetness, sourness), discrete emotions (e.g., joy, anger), and affective dimensions (e.g., valence, arousal).

The interest in the implications of music listening is not recent. For instance, since the introduction of the auto radio in the 1950s, researchers, manufacturers, and even insurance companies have been concerned with how music impacts people's psychological state and driving performance (Millet et al., 2019; van der Zwaag et al., 2012). Similarly, the effects of music on daily activities, such as working (Landay & Harms, 2019; Rastipisheh et al., 2019; Shih et al., 2012), shopping (Biswas et al., 2019; Hynes & Manson, 2016; Knöferle et al., 2017; Michel et al., 2017; Yi & Kang, 2019), or exercising (Hutchinson et al., 2018; Moss et al., 2018; Terry et al., 2020) have been the focus of extensive empirical interest (see also Kämpfe et al., 2011). In most developed countries, music is also part of what is, perhaps, one of the most critical and recurring human activities: eating. Currently, several meal contexts, such as restaurants, cafés, or food courts, have background music as an important part of their atmosphere (one popular example is coffeehouse chain Starbucks, whose background music has been a key element for customers' experience and for the brand's identity; see Starbucks, 2014, 2015).

Previous research has documented how the presence of music may shape consumers' behavior, including meal duration (Stroebele & de Castro, 2006), drinking and eating rates (Mathiesen et al., 2020; McElrea & Standing, 1992; Roballey et al., 1985), or meal enjoyment (Novak et al., 2010). More recently, researchers have suggested that music not only affects behavior toward food but also how we perceive it (see Spence et al., 2019a, Spence et al., 2019b). A growing body of evidence shows that sound, in general, and music, in particular, may enhance (or dampen) the perceived sensory properties of foods and drinks. While ambient sounds and noise have been shown to alter taste perception to a significant extent (Bravo-Moncayo et al., 2020; Woods et al., 2011; Yan & Dando, 2015), particular attention has been paid to music, given its ability to convey different taste-related associations. Indeed, as

Kontukoski et al. (2015) noted, taste and music may be described using similar terms. Adjectives such as “sweet”, “light”, or “soft” seem to refer to common subjective experiences elicited by either foods or sounds.

In previous studies, manipulation of specific musical parameters or acoustic properties in music has resulted in different basic taste associations. For example, Mesz et al. (2011) found that trained musicians consistently manipulated specific musical parameters (such as pitch, loudness, or articulation) to convey meanings associated with basic tastes. For instance, when asked to improvise according to the word “bitter”, the resulting musical improvisations were more legato and lower pitched, whereas the word “sweet” resulted in slower, softer improvisations. When these same improvisations were presented to non-musical experts, they were able to decode the musicians’ intentions with above-chance accuracy.

Other studies have found similar consistencies in sound-taste mappings, particularly with pitch. Overall, high-pitched sounds were more frequently associated with either sweet and/or sour tastes (Crisinel et al., 2012; Crisinel & Spence, 2009, 2010a, 2010b; Knöferle et al., 2015; Reinoso-Carvalho, Wang, de Causmaecker, et al., 2016; Velasco et al., 2014; Wang et al., 2016), whereas low pitched sounds were more frequently associated with bitter tastes (Crisinel et al., 2012; Crisinel & Spence, 2009, 2010b; Knöferle et al., 2015; Qi et al., 2020; Reinoso-Carvalho, Wang, de Causmaecker, et al., 2016; Velasco et al., 2014; Watson & Gunther, 2017). Associations between basic tastes and musical instruments have also been documented, for example, between sweetness and piano or bitterness and brass (Crisinel & Spence, 2010b). Knöferle et al. (2015) also found systematic associations between basic tastes and several sonic properties such as roughness, sharpness, discontinuity, and consonance.

The growing understanding of sound-taste associations has allowed researchers and sound designers to design customized soundtracks to modulate taste perception (Wang et al., 2015). For example, Crisinel et al. (2012) developed a low-pitched brass soundtrack (“bitter”) and a high-pitched piano soundtrack (“sweet”) and found that participants rated a bittersweet cinder toffee as tasting significantly more bitter when listening to the bitter soundtrack, compared to the sweet (see also Höchenberger & Ohla, 2019). Subsequent research extended the evidence on the modulatory potential of customized music to the perception of different foods and beverages, including chocolate (Reinoso-Carvalho et al., 2015, 2017), juices (Wang & Spence, 2016, 2018), and beers (Reinoso-Carvalho, Velasco, et al., 2016; Reinoso-Carvalho, Wang, van Ee, & Spence, 2016).

Other studies have also tested the effects of familiar music on taste, such as rock and pop songs or classical music pieces (De Luca et al., 2018; Hauck & Hecht, 2019; Kantono et al., 2019; Kantono, Hamid, Shepherd, Yoo, Carr, & Grazioli, 2016; Reinoso-Carvalho et al., 2019; Reinoso-Carvalho, Velasco, et al., 2016; Spence et al., 2013; Stafford et al., 2012; Wang et al., 2019; Wang & Spence, 2015). The fact that most music has the potential to elicit not only implicit taste associations but also (and, perhaps, most notoriously) emotions raises questions about the role of affective variables in the crossmodal associations between audition and taste (Crisinel & Spence, 2012). Indeed, participants tend to match tastes that are commonly thought to be pleasant (e.g., sweetness) with sounds that are also deemed pleasant (e.g., piano) and vice-versa (Crisinel & Spence, 2010b). Previous studies (Kantono et al., 2019; Kantono, Hamid, Shepherd, Yoo, Grazioli, & Carr, 2016) also found that listening to self-selected, liked music increased the salience of sweetness attributes of gelati, whereas disliked music seemed to enhance its bitterness.

The existing literature seems consistent with the view that emotions mediate sound-taste correspondences and contribute to the multisensory experience with foods. However, the role of discrete emotions and affective variables in this context remains insufficiently explored (Reinoso-Carvalho et al., 2019; Reinoso-Carvalho, Gunn, Horst, & Spence, 2020; Wang et al., 2016). Moreover, this domain of inquiry seems to lack a systematic and integrated assessment of auditory stimuli. Despite some efforts in replicating previous findings (Crisinel & Spence, 2010b; Höchenberger & Ohla, 2019; Rudmin & Cappelli, 1983; Watson & Gunther, 2017), the existing empirical studies are based on a great diversity of auditory stimuli, often created independently (i.e., for each new study) and rarely assessed together, in a similar setting and based on equivalent assessment parameters.

Wang et al. (2015) contributed with one of the first integrative efforts by simultaneously testing 24 soundtracks previously created for scientific research or artistic performances. The soundtracks were selected based on their ability to elicit crossmodal associations with specific tastes or on their ability to shape the perception of taste in foods and drinks. The results suggested that participants were able to decode the basic taste associated with each soundtrack with above-chance accuracy, and those associations were partly mediated by pleasantness and arousal dimensions. In Wang et al.'s (2015) study, only customized soundtracks (i.e., music composed to elicit taste correspondences) were tested. However, a large body of evidence suggests that crossmodal effects may also be found for music not intended to modulate taste perception (De Luca et al., 2018; Hauck & Hecht, 2019; Kantono et al., 2019; Kantono, Hamid, Shepherd, Yoo, Carr, & Grazioli, 2016; Kantono, Hamid, Shepherd, Yoo, Grazioli, & Carr, 2016; Reinoso-Carvalho et al., 2019; Reinoso-Carvalho, Velasco, et al., 2016; Spence et al., 2013; Stafford et al., 2012; Wang et al., 2019; Wang & Spence, 2015). More importantly, these studies used musical stimuli spanning different moods and genres (e.g., pop, classical, or jazz), which may be closer to what one would expect to hear in a real-world eating environment (e.g., a restaurant) than the more abstract and homogenous soundtracks that were specifically created to mimic basic tastes (Wang et al., 2015). This point is particularly relevant for practitioners interested in designing multisensory eating experiences, for which familiarity and pleasantness could be important determinants for customer satisfaction. In the present study, we sought to extend the existing pool of stimulus materials by obtaining subjective ratings for a comprehensive set of instrumental musical stimuli that could be useful both for laboratory experiments and real-world environments (i.e., music that one could expect to hear in a restaurant). Thus, stimuli were selected to span different musical genres, as well as different "moods". We also intended to overcome the lack of integration of emotional and affective variables in crossmodal research by concurrently testing taste correspondences, discrete emotions (e.g., joy, anger), and affective dimensions (e.g., valence, arousal).

2. Method

2.1. Participants

A sample of 329 respondents (83.3% women; M_{age} = 28.12, *SD* = 12.14) volunteered to participate in this study. Participants were recruited via email, social media (Facebook, WhatsApp, and LinkedIn), internal university channels, and online press. Undergraduate students made up 71% of the sample, and 29% were active workers. Most participants (93.9%) were native Portuguese, and all reported having a normal audition. Only 6.5% of participants had current or past professional experience in music-related activities. Data was collected online (n = 246) and in the laboratory (n = 83).

Based on previous norming studies with auditory stimuli, a minimum of 50 evaluations per stimulus was considered adequate (Belfi & Kacirek, 2021; Imbir & Golab, 2017; Souza et al., 2020). The number of ratings per stimulus ranged from 68 to 97 (*Mdn* = 83) when considering the entire sample (55 to 69 for the online sample alone).

2.2. Development of the stimulus set

The stimulus set is composed of 100 royalty-free soundtracks retrieved from www.epidemicsound.com. All files were obtained from the music catalog, which spans over 35.000 tracks, 160 genres (e.g., jazz, pop, small emotions), and 34 "moods" (e.g., sentimental, mysterious, relaxing).

The stimuli were searched through the moods directory with the aim of covering different quadrants of the affective space. For this purpose, we used Russell's (1980) circumplex model of affect to define four search categories based on the possible combinations of arousal (high vs. low) and valence (positive vs. negative). For instance, the high arousal/positive valence quadrant was composed of soundtracks that were tagged in the moods directory as “happy”, “euphoric”, or “funny”, whereas the low arousal/negative valence quadrant included soundtracks from collections such as “sad”, “dark” or “sentimental”. The stimuli were chosen to include different genres and musical instruments. All were instrumental only to control for the potential influence of lyrics (e.g., Brattico et al., 2011; Mori & Iwanaga, 2014).

From an affective standpoint, music styles may differ in their affective charge or the type of emotions they elicit. Previous studies have provided affective norms for music of specific genres or families of genres, such as western classical (Lepping et al. (2016), film soundtracks (Eerola & Vuoskoski, 2011; Vieillard et al., 2008), or Latin music (e.g., tango, pagode; dos Santos & Silla, 2015). Considering the crossmodal associations between tastes and music parameters, such as pitch, loudness, articulation, or even instrument types (e.g., Mesz et al., 2012), it was deemed adequate to extend the search through various categories of the “genre” directory.

All soundtracks used in this study were original and not marketed directly to the general public, so they would be new and unfamiliar to most participants. In that regard, this stimulus set complements previous validation studies, which tested highly popular, familiar music. Examples include Belfi and Kacirek's (2021) Famous Melodies Stimulus Set (of highly popular, familiar, western songs, such as the “Star Wars theme”, “Jingle Bells”, or the “Happy Birthday” tune), or Song et al.'s (2016) and Imbir and Golab's (2017) datasets, primarily composed of chart-topping western hits (e.g., “November Rain” by Guns N’ Roses, “Ultraviolence” by Lana del Rey). The latter dataset also includes jazz and classical music.

The stimulus set presented in the current study comprises 100 soundtracks with 25 items per valence/arousal quadrant. All files were trimmed to a standardized duration of 30 s with a 2.5 s fade out.

2.3. Procedure and measures

This study was approved by the Ethics Committee of Iscte-Instituto Universitário de Lisboa. The survey was programmed using Qualtrics. Participants in the online data collection sample were instructed to use headphones and choose a quiet place for participation. The laboratory data collection took place in soundproof booths equipped with similar desktop computers and headphones. The materials and procedures for both samples were the same.

Before initiating the survey, irrespectively of the data collection method, participants were asked to confirm they did not suffer from any permanent or transient hearing impairment at the time of study that could be detrimental to their performance. The informed consent provided information on the general goals of the study and stated compliance with the applicable norms of ethical conduct in research. Specifically, individuals were informed that all collected data would be treated anonymously (i.e., no information would be asked that allowed personal identification) and that their participation was voluntary (i.e., they could abandon the study at any point).

After agreeing with the terms of the informed consent and confirming having no hearing impairments, participants answered sociodemographic questions about sex, age, nationality, and occupation. Afterward, participants were asked to provide subjective ratings for 25 stimuli, randomly selected from the pool of 100 stimuli. Finally, mood and individual differences in preference for basic tastes and musical skills and behaviors were assessed using self-report scales.

2.3.1. Subjective ratings

Participants were told they should listen attentively to each sound clip in its entirety and rate it in several attributes (e.g., basic tastes, emotions, valence, arousal, and familiarity). For the basic taste correspondences, participants were provided two examples of foods stereotypically associated with each taste (e.g., lemon and vinegar for sourness, coffee and brussels sprouts for bitterness, potato chips and salt for saltiness, and honey and sugar for sweetness). The examples were provided to reduce ambiguity and avoid confusion between tastes, particularly between sourness and bitterness (O'mahony et al., 1979).

To avoid fatigue, each participant assessed only a random subset of 25 soundtracks. Each stimulus was presented alone on a blank screen. After 30 s, a forward button appeared on the screen, allowing participants to rate the soundtrack in 14 attributes (for instructions and scale anchors, see Table 2.9.). A forced-choice item was presented for basic tastes, in which participants had to report if they considered the soundtrack to be sweet, bitter, salty, or sour (presented in random order). Although umami is commonly considered the fifth basic taste, Western individuals are usually less capable of discriminating this taste (Cecchini et al., 2019; Sinesio et al., 2009). For this reason, and in line with previous research testing the crossmodal associations between audition and taste, we opted to retain only four of the basic tastes (e.g., Wang et al., 2015).

The affective connotations of the auditory stimuli were assessed both from a dimensional and a categorical perspective (Lindquist et al., 2013). Psychological constructionist models of emotion postulate the existence of a core affective system underlying emotional experience. The core affect is characterized as the fluctuations in organisms' neurophysiological and somatovisceral states in response to current events, varying in valence and arousal (Barrett, 2009, 2011). These two axes have been documented as essential across different dimensional models of affect (see Yik et al., 1999) and are relevant subjective descriptors in several databases of auditory stimuli, including natural and environmental sounds (Bradley & Lang, 2007; Fan et al., 2017; Hocking et al., 2013; Yang et al., 2018), vocalizations (Belin et al., 2008; Lassalle et al., 2019; Parsons et al., 2014), audio stories (Bertels et al., 2014), and music (Belfi & Kacirek, 2021; Imbir & Golab, 2017; Lepping et al., 2016; Song et al., 2016; Vieillard et al., 2008). In line with previous research (Ali & Peynircioğğlu, 2010; Schubert, 2007; Zentner et al., 2008), we differentiated perceived (P) and felt (F) affective dimensions such that participants were asked to rate valence and arousal dimensions in two ways. First, these dimensions were rated as attributes of the stimulus ("This soundtrack is…", i.e., perceived), and second, they were used to describe the subjective emotional experience ("This soundtrack makes me feel…", i.e., felt). In both cases, valence and arousal items were answered using seven-point rating scales.

Advocates of discrete theories of emotion contend that emotional categories like "joy", "anger", or "fear" elicit distinct patterns of change in cognition, judgment, experience, behavior, and physiology (Lench et al., 2011). Most theoretical accounts adhere to a functionalist perspective, in which emotions are seen as evolutionary adaptive responses, among which basic emotions represent the most primitive and universal forms of emotional expression (Ekman & Cordaro, 2011; Tracy & Randles, 2011). Although no broad consensus exists about the number and kind of emotions considered "basic", some emotions seem to be present in most theoretical models (Ortony & Turner, 1990; Tracy & Randles, 2011). In this study, we included five discrete emotions commonly described in the literature (joy, sadness, anger, fear, and surprise) that have been previously studied in the context of music (Eerola & Vuoskoski, 2011; Juslin, 2013; Mohn et al., 2011) and sound associations (Yang et al., 2018). Individuals were asked to rate each soundtrack for each of the five emotions, using a seven-point rating scale ranging from 1 (*not at all*) to 7 (*very much*).

One relevant factor when pondering the relationship between music and emotions is familiarity. Repeated exposure may positively or negatively influence enjoyment depending on factors such as the valence of the stimulus (Witvliet & Vrana, 2007) or the focused or incidental type of exposure (Schellenberg et al., 2008; Szpunar et al., 2004). However, the effects of familiarity seem to occur even when participants have no explicit memory of the musical stimulus (van den Bosch et al., 2013). Popular music, in particular, may become personally meaningful due to associations with people, places, and past events (Krumhansl, 2002). Schulkind et al. (1999) found that older individuals preferred and showed more favorable emotional responses to songs from their youth, whereas younger individuals favored contemporary music. Although familiar music is generally more likely to evoke autobiographical memories, Janata et al. (2007) found that some participants may still report some degree of autobiographical associations in response to unfamiliar stimuli. Even though, in theory, the stimuli in the present study are likely to be unknown to participants, we assume that differences in familiarity could be observed due to individuals' ability to make implicit associations with personally meaningful events. In this study, we asked participants to rate how familiar each soundtrack was, using a scale ranging from 1 (*very unfamiliar*) to 7 (*very familiar*).

Table 2. 9. *Evaluative Dimensions, Instructions, and Item Scales*

Dimension/Attribute	Instruction: This soundtrack…	Response options
1. Basic tastes	… is…	Forced choice: sweet, bitter, salty, sour
2. Emotion: Joy	… conveys…	1 = *Not at all* to 7 = *Very much*
3. Emotion: Sadness	… conveys…	1 = *Not at all* to 7 = *Very much*
4. Emotion: Anger	… conveys…	1 = *Not at all* to 7 = *Very much*
5. Emotion: Fear	… conveys…	1 = *Not at all* to 7 = *Very much*
6. Emotion: Surprise	… conveys…	1 = *Not at all* to 7 = *Very much*
7. Valence (P)	… is…	1 = *Very unpleasant* to 7 = *Very pleasant*
8. Arousal (P)	… is…	1 = *Very mild* to 7 = *Very intense*
9. Familiarity	… is…	1 = *Very unfamiliar* to 7 = *Very familiar*
10. Valence (F)	… makes me feel…	1 = *Bad* to 7 = *Good*
11. Arousal (F)	… makes me feel…	1 = *Relaxed* to 7 = *Tense*

Note. P = Perceived (i.e., referring to the attributes of the stimuli); F = Felt (i.e., referring to the subjective affective experience)

2.3.2. Mood

After the stimulus rating task, participants completed a brief mood self-report scale as a post-experimental control measure. We used six pairs of bipolar adjectives (e.g., positive-negative) based on Garcia-Marques (2004). Participants answered each item using a seven-point scale.

2.3.3. Preference for basic tastes

There are several ways to assess basic taste preferences. While several studies employ taste testing (of aqueous solutions, odorants, or real foods) to assess preferences (Keskitalo, Knaapila, et al., 2007; Keskitalo, Tuorila, et al., 2007; for a review, see Drewnowski, 1997), these methods are logistically complex and challenging to adapt for online studies. One common alternative is using self-report questionnaires, generally based on hedonic ratings of food items presented verbally (Kaminski et al., 2000) or visually (Jilani et al., 2019). For instance, Meier et al. (2012), asked participants to rate their liking of foods belonging to five taste/flavor groups, using a six-point scale ranging from *dislike strongly* to *like strongly*. In the present study, we asked participants to rate their overall liking of each food group ("please indicate how much you enjoy the following tastes"), using two examples for each taste group, based on the list of food items used in Meier et al.'s (2012) study. To avoid ambiguity, the same examples were provided here and in the basic taste association task. Participants indicated their preference using a seven-point scale (*I don't like it at all* to *I like it very much*).

2.3.4. Musical skills and behaviors

People relate to music to different degrees. Individual differences in involvement and engagement with music and musical activities have been described under many guises, such as musicality, musical intelligence, or musical talent (Baker et al., 2020). Müllensiefen et al. (2014a, 2014b) proposed the overarching concept of musical sophistication to describe different degrees of musical skills or behaviors which allow responding flexibly and effectively to different musical situations. This continuous, multidimensional conception of musical sophistication was psychometrically operationalized by the Goldsmiths Musical Sophistication Index (Gold-MSI, Müllensiefen et al., 2014a, 2014b), a self-report inventory of skilled musical behaviors for musicians and non-musicians. The Gold-MSI comprises one general sophistication index and five subscales covering active musical engagement behaviors (Active Engagement), self-assessed cognitive musical ability (Perceptual Abilities), the extent of musical training and practice (Musical Training), activities and skills particularly related to singing (Singing Abilities), and emotional responses to music (Emotions). The Gold-MSI was validated for the Portuguese population by Lima et al. (2020). The European Portuguese version of the scale (Gold-MSI-P) replicates the original factor structure and presents appropriate psychometric properties, including good internal consistency (α = .82 to .91) and test-retest reliability (r = .84 to .94). A confirmatory factor analysis suggested good fit values between the model and the observed data, $\chi^2(627) = 1615.56$, $p < 0.001$; CFI = 0.86; TLI = 0.84, RMSEA = 0.06, SRMR = 0.06, in line with the indices obtained with previous versions of the scale for other nationalities.

3. Results

The complete normative data for the 100 stimuli on the subjective dimensions of taste, emotions, valence, arousal, and familiarity are provided as supplemental material (see Supplementary File 1 at osf.io/2cqa5). In the following section, we provide the results of a) the preliminary analyses (e.g., outlier detection; impact of data collection method on ratings); b) the subjective rating norms for each dimension; c) the associations between evaluative dimensions; and d) the associations between subjective ratings and individual differences in sex, age, basic taste preferences, and musical sophistication.

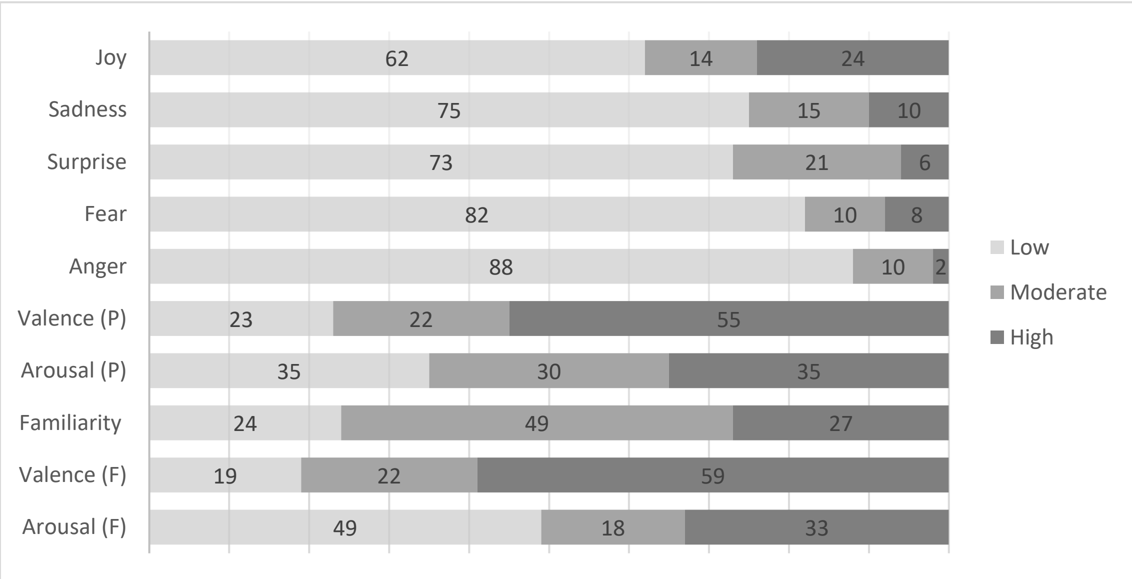
3.1. Preliminary analysis

Since only completed surveys were retained, no missing data were observed. Values situated 2.5. standard deviations above or below the mean evaluation of each stimulus were considered outliers (1.24%). Moreover, no indication of systematic or random responses was observed (e.g., consistent use of a single point of the scale). Therefore, no participants were excluded.

To test the response consistency of participants' ratings in each dimension, we compared two halves of the total sample with cases selected randomly (n_1 = 165; n_2 = 164) (for a similar procedure, see Garrido et al., 2017; Prada et al. 2016). No significant differences between the subsamples emerged, with all p > .193. Additionally, we tested for differences between ratings provided in the laboratory and a random subsample of equal size (n = 83) balanced for age and gender of the data collected online. We did not observe significant differences according to the data collection method for any of the taste correspondences and evaluative dimensions (all p > .071). Therefore, all subsequent analyses were conducted using the total sample. The comparison between ratings of online and laboratory participants is provided in Supplementary File 2.

3.2. Subjective rating norms

In order to define subjective rating norms, the data was coded and analyzed by soundtrack. The frequencies, means, standard deviations, and confidence intervals on each dimension for each soundtrack are provided as supplemental material (see Supplementary File 1 at osf.io/2cqa5). Based on these results, we further categorized the soundtracks as low, moderate, or high in each dimension (for a similar procedure, see Garrido & Prada, 2017; Prada et al., 2016; Rodrigues et al., 2018; Souza et al., 2021). Specifically, a soundtrack was considered moderate on a given dimension if the confidence interval included the rating scale's midpoint. If the upper bound of a given stimulus was lower than the scale's midpoint, the stimulus was considered low on that dimension, and if the lower bound was higher than the midpoint, the stimulus was considered high. The frequencies of low, moderate, and high stimuli are presented in Figure 2.4.



Note. P = Perceived, F = Felt.

Figure 2. 4. *Distribution of Items Across Dimension Levels (Low, Medium, High)*

Most stimuli were considered moderately familiar (n = 49) and highly pleasant (n = 55), with a fair distribution across perceived arousal levels. The majority of the soundtracks elicited moderately or highly pleasant states (n = 22; n = 59) and were rated as lowly arousing (n = 49). Most of the soundtracks were rated low in discrete, unpleasant emotions like anger (n = 88), fear (n = 82), and sadness (n = 75). More than half of the soundtracks were also considered low in joy (n = 62) and surprise (n = 73). The intersection between levels of the ten dimensional variables is presented in Table 2.10. As can be seen, a very small number of soundtracks were evaluated as high in two discrete emotions simultaneously. Except for the emotions of fear and surprise, all the other discrete emotions presented no overlap at the high level. Felt and perceived affective dimensions (valence and arousal) were also in consonance. Specifically, no items were evaluated as low in the perceived dimension and high in the corresponding felt dimension.

For basic taste correspondences, we calculated the choice proportion of each basic taste for each soundtrack. All four tastes presented choice rates above what would be expected by chance (i.e., 25%). The total number of soundtracks above 25% and 50% levels, as well as range and mean proportions, are presented in Table 2.11. Overall, the mean proportion of taste correspondences across the 100 stimuli was higher for sweetness (32.5%), whereas bitterness, saltiness, and sourness presented more similar means (ranging from 20.1% to 24.2%). The highest proportion of correspondences with a given taste was observed for sweetness (for soundtrack 69, “Fruit of Lore”), corresponding to 80.5% of participants’ choices. The highest proportion of bitterness correspondences was observed for soundtrack 26 (“Intentional Evil”) with 64.4% of choices, whereas for sourness, the largest agreement was found for soundtrack 42 (“Animal Kingdom”) with 59.8%. The highest proportion of salty taste correspondences was observed for soundtrack 93 (“La Festa in Cucina”), with an accordance rate of 50.6%.

More than half of the soundtracks (*n* = 58) were associated with sweetness by at least 25% of participants, and 26 of these soundtracks were evaluated as sweet by more than 50% of respondents. Bitterness was associated with 43 soundtracks by at least 25% of participants, of which 11 were evaluated as bitter by more than half of the sample. Sourness was selected by more than 25% of respondents in 28 soundtracks. However, only three of these were evaluated as sour by more than half of the sample. Similarly, saltiness was associated with 38 soundtracks by more than 25% of participants. However, only one soundtrack had salty taste correspondences marginally above the 50% cut-off.

Overall, these results suggest that participants more easily decoded sweetness than the other basic tastes (see Table 2.11.). Moreover, while some soundtracks led to a convergence of responses towards a single taste correspondence, others seemed to elicit more than one taste association. For instance, soundtrack 40 (“Liquid Core”) had an equal proportion of 41% correspondences with both bitter and sour tastes, whereas soundtrack 5 (“Not Ready to Go”) presented a bittersweet pattern of associations, with 41.2% of sweet and 43.5% of bitter correspondences.

Table 2. 10. *Frequency Distribution Across Dimension Levels*

		Joy			Sadness			Surprise			Fear			Anger			Valence (P)			Arousal (P)			Familiarity			Valence (F)		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Sadness	L	37	14	24																								
	M	15	0	0																								
	H	10	0	0																								
Surprise	L	41	11	21	48	15	10																					
	M	16	2	3	21	0	0																					
	H	5	1	0	6	0	0																					
Fear	L	44	14	24	61	13	8	68	12	2																		
	M	10	0	0	6	2	2	5	5	0																		
	H	8	0	0	8	0	0	0	4	4																		
Anger	L	50	14	24	63	15	10	68	18	2	76	10	2															
	M	10	0	0	10	0	0	3	3	4	4	0	6															
	H	2	0	0	2	0	0	2	0	0	2	0	0															
Valence (P)	L	23	0	0	19	2	2	7	12	4	6	9	8	15	7	1												
	M	17	3	2	13	5	4	16	6	0	21	1	0	19	2	1												
	H	22	11	22	43	8	4	50	3	2	55	0	0	54	1	0												
Arousal (P)	L	12	10	13	31	4	0	33	2	0	35	0	0	35	0	0	0	2	33									
	M	17	2	11	18	7	5	23	7	0	29	1	0	30	0	0	3	10	17									
	H	33	2	0	26	4	5	17	12	6	18	9	8	23	10	2	20	10	5									
Familiarity	L	22	2	0	21	2	1	10	13	1	13	7	4	20	4	0	16	5	3	5	5	14						
	M	33	8	8	32	11	6	41	6	2	43	3	3	42	5	2	6	15	28	20	12	17						
	H	7	4	16	22	2	3	22	2	3	26	0	1	26	1	0	1	2	24	10	13	4						
Valence (F)	L	19	0	0	17	0	2	4	11	4	3	8	8	12	7	0	19	0	0	0	1	18	14	4	1			
	M	21	1	0	8	8	6	19	3	0	20	2	0	18	2	2	4	15	3	0	11	11	5	14	3			
	H	22	13	24	50	7	2	50	7	2	59	0	0	58	1	0	0	7	52	35	18	6	5	31	23			
Arousal (F)	L	17	10	22	41	6	2	46	3	0	49	0	0	49	0	0	0	1	48	34	15	0	4	24	21	0	0	49
	M	13	3	2	6	6	6	14	3	1	17	1	0	18	0	0	1	13	4	1	12	5	3	11	4	0	12	6
	H	32	1	0	28	3	2	13	15	5	16	9	8	21	10	2	22	8	3	0	3	30	17	14	2	19	10	4

Note. P = Perceived, F = Felt; L = Low; M = Moderate; H = High.

Overall, these results suggest that participants more easily decoded sweetness than the other basic tastes (see Table 2.11.). Moreover, while some soundtracks led to a convergence of responses towards a single taste correspondence, others seemed to elicit more than one taste association. For instance, soundtrack 40 (“Liquid Core”) had an equal proportion of 41% correspondences with both bitter and sour tastes, whereas soundtrack 5 (“Not Ready to Go”) presented a bittersweet pattern of associations, with 41.2% of sweet and 43.5% of bitter correspondences.

Table 2. 11. *Mean Proportions and Absolute Frequencies of Soundtracks Above 25% and 50% Cut-offs (n = 100 soundtracks)*

	Sweet	Bitter	Sour	Salty
Mean proportion	32.5	24.2	20.1	23.2
> 25%	58	43	31	38
> 50%	26	11	3	1
Range	0 - 80.8	1.2 - 64.4	0 - 59.8	3.53 - 50.59

3.3. Associations between evaluative dimensions

The correlations (Pearson’s *r*) between evaluative dimensions and corresponding effect sizes (Cohen’s *d*) are presented in Table 2.12. To test the associations between the quantitative rating dimensions and the choice of basic tastes, four new variables were computed based on each participants’ frequency of basic taste correspondences. For instance, if a given participant categorized four of the 25 soundtracks as being “sweet”, a score of four was assigned to the sweet taste variable. The same procedure was employed for bitterness, saltiness, and sourness ratings. The associations between the four taste variables were negative and significant (all $p < .004$).

Several significant correlations were also found between taste and affective variables. For instance, sweetness ratings were positively correlated with joy ($r = .29$, $d = 0.61$), and negatively correlated with sadness ($r = .12$, $d = 0.24$), fear ($r = .20$, $d = 0.41$), and anger ($r = .21$, $d = 0.43$). Sweetness was also positively correlated with both perceived ($r = .39$, $d = 0.85$) and felt valence dimensions ($r = .31$, $d = 0.65$), and negatively with felt arousal ($r = .35$, $d = 0.75$).

Bitterness ratings were positively correlated with sadness ($r = .15$, $d = 0.30$), fear ($r = .26$, $d = 0.54$), and anger ($r = .27$, $d = 0.56$), and negatively correlated with joy ($r = .12$, $d = 0.24$). Bitterness was also negatively correlated with both perceived and felt valence dimensions ($p < .001$), and positively correlated with felt ($r = .23$, $d = 0.47$) arousal.

Sourness ratings were negatively correlated with joy (*r* = .15, *d* = 0.30) and perceived valence (*r* = .12, *d* = 0.24). A significant negative correlation with felt arousal (*r* = .14, *d* = 0.28) was also observed. Saltiness ratings presented weak associations with most affective variables, except for a moderate negative correlation with perceived valence (*r* = .11, *d* = 0.22).

All discrete emotions were interrelated, and most of these variables were also significantly associated with valence and arousal dimensions. For instance, joy ratings were correlated with both valence dimensions and perceived arousal (all $p < .001$) and negatively with felt arousal (*r* = .28, *d* = 0.58). Anger and fear were significantly correlated with both arousal dimensions and inversely correlated with valence dimensions (all $p < .001$). Sadness presented a similar pattern, but no association with perceived valence was observed. Surprise ratings were associated with arousal dimensions (both $p > .050$) but not with valence.

3.4. Associations between subjective ratings and individual differences

When comparing the ratings on the 10 emotional/affective dimensions and the four taste correspondences between men and women, based on independent-samples t-tests, no significant differences were observed, except for surprise ratings. Men provided higher mean ratings (*M* = 5.36, *SD* = 0.95), compared to women (*M* = 3.20, *SD* = 0.98), *t*(325) = 2.43, *p* = .016, *d* =2.24 [8]. Descriptive statistics (means and standard deviations) for the two groups and mean difference test results are provided in Supplementary Table A2.

Pearson's correlations between the evaluative dimensions and age indicate a tendency for older participants to provide higher sadness (*r* = .25, *d* = 0.52) and perceived arousal ratings (*r* = .23, *d* = 0.47), and more saltiness (*r* = .14, *d* = 0.28) and sourness correspondences (*r* = .13, *d* = 0.26). Inversely, age was negatively associated with bitterness correspondences (*r* = .17, *d* = 0.35). No other significant associations were observed.

The associations between subjective ratings and individual differences in self-report measures were explored in two ways. First, the correlations between preference for basic tastes and soundtrack-taste correspondences were analyzed. Second, the associations between taste correspondences, subjective ratings, and the different dimensions of musical skills and behaviors assessed by the MSI were explored.

[8] When comparing the mean ratings between men (n = 53) and a random subsample of 53 women, the difference in surprise ratings remains significant. Moreover, small differences were also observed in sadness ratings (p = .035) and sweetness correspondences (p = .049), with higher means being provided by men.

Table 2. 12. *Pearson's Correlations (and Effect Sizes, Cohen's d) Between Evaluative Dimensions*

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Sweetness	-												
2. Bitterness	-.35*** (*d* = 0.75)	-											
3. Sourness	-.44*** (*d* = 0.98)	-.27*** (*d* = 0.56)	-										
4. Saltiness	-.44*** (*d* = 0.98)	-.33*** (*d* = 0.70)	-.16** (*d* = 0.32)	-									
5. Joy	.29*** (*d* = 0.61)	-.12* (*d* = 0.24)	-.15** (*d* = 0.30)	-.10 (*d* = 0.20)	-								
6. Sadness	-.12* (*d* = 0.24)	.15** (*d* = 0.30)	-.02 (*d* = 0.04)	.01 (*d* = 0.02)	.21*** (*d* = 0.43)	-							
7. Surprise	-.09 (*d* = 0.18)	.07 (*d* = 0.14)	.05 (*d* = 0.10)	-.02 (*d* = 0.04)	.45*** (*d* = 1.00)	.44*** (*d* = 0.98)	-						
8. Fear	-.20*** (*d* = 0.41)	.26*** (*d* = 0.54)	.07 (*d* = 0.14)	-.08 (*d* = 0.16)	.17** (*d* = 0.35)	.60*** (*d* = 1.50)	.59*** (*d* = 1.46)	-					
9. Anger	-.21*** (*d* = 0.43)	.27*** (*d* = 0.56)	.04 (*d* = 0.08)	-.05 (*d* = 0.10)	.23*** (*d* = 0.47)	.52*** (*d* = 1.22)	.58*** (*d* = 1.42)	.77*** (*d* = 2.41)	-				
10. Valence (P)	.39*** (*d* = 0.85)	-.24*** (*d* = 0.49)	-.12* (*d* = 0.24)	-.11* (*d* = 0.22)	.45*** (*d* = 1.00)	-.09 (*d* = 0.18)	.00 (*d* = 0.00)	-.27*** (*d* = 0.56)	-.28*** (*d* = 0.58)	-			
11. Arousal (P)	-.04 (*d* = 0.08)	.04 (*d* = 0.08)	.07 (*d* = 0.14)	-.05 (*d* = 0.10)	.18** (*d* = 0.37)	.25*** (*d* = 0.52)	.29*** (*d* = 0.61)	.33*** (*d* = 0.70)	.33*** (*d* = 0.70)	.02 (*d* = 0.04)	-		
12. Familiarity	.15** (*d* = 0.30)	-.13* (*d* = 0.26)	.00 (*d* = 0.00)	-.06 (*d* = 0.12)	.26*** (*d* = 0.54)	.06 (*d* = 0.12)	.01 (*d* = 0.02)	-.03 (*d* = 0.06)	-.02 (*d* = 0.04)	.45*** (*d* = 1.01)	.25*** (*d* = 0.52)	-	
13. Valence (F)	.31*** (*d* = 0.65)	-.28*** (*d* = 0.58)	-.10 (*d* = 0.20)	.00 (*d* = 0.00)	.33*** (*d* = 0.70)	-.28*** (*d* = 0.58)	-.11 (*d* = 0.22)	-.45*** (*d* = 1.01)	-.44*** (*d* = 0.98)	.75*** (*d* = 2.27)	-.19** (*d* = 0.39)	.19*** (*d* = 0.39)	-
14. Arousal (F)	-.35*** (*d* = 0.75)	.23*** (*d* = 0.47)	.14** (*d* = 0.28)	.06 (*d* = 0.12)	-.28*** (*d* = 0.58)	.28*** (*d* = 0.58)	.14* (*d* = 0.28)	.40*** (*d* = 0.87)	.34*** (*d* = 0.72)	-.63*** (*d* = 1.62)	.23*** (*d* = 0.47)	-.17** (*d* = 0.35)	-.69*** (*d* = 1.91)

Note. P = Perceived; F = Felt.

* Correlation is significant at the .05 level (two-tailed); ** Correlation is significant at the .01 level (two-tailed); *** Correlation is significant at the .001 level (two-tailed);

Overall, the associations between preference for basic tastes and soundtrack-taste correspondences were scarce, meaning that preferring foods with the predominance of a given basic taste (e.g., sweet-tasting foods, such as honey or sugar) was not significantly associated with higher identification rates for that same taste in the subset of auditory stimuli. There were, however, a few exceptions for bitter- and sour-likers. Participants who reported liking more the taste of sour foods tended to provide higher sourness ratings (r = .11, d = 0.22) and lower saltiness ratings (r = .11, d = 0.22). Liking of bitter-tasting foods was associated with higher sourness ratings (r = .13, d = 0.26) and lower saltiness ratings (r = .14, d = 0.28).

Individual differences in musical skills and behaviors seemed to have a small impact on the subjective evaluations of the soundtracks across the taste correspondences and affective dimensions. Overall, higher scores on the Musical Sophistication Index had small, but significant associations with perceived valence ratings (r = .11, d = 0.22) and bitterness correspondences (r = .11, d = 0.22). The Active Engagement subscale was associated with higher perceived (r = .15, d = 0.30) and felt valence ratings (r = .12, d = 0.24), as well as sweetness correspondences (r = .15, d = 0.30). The subscale Musical Training was inversely related with sourness correspondences (r = .12, d = 0.24), whereas the subscale Singing Abilities was correlated with bitterness correspondences (r = .16, d = 0.32). The Emotions subscale was not associated with neither of the emotional/affective scales, however, a weak positive correlation was observed with Familiarity ratings (r = .12, d = 0.24) and negatively with sourness correspondences (r = .11, d = 0.22).

To further understand whether musical sophistication may contribute to more reliable decoding of taste-sound correspondences, we compared the response consistency of individuals with high and low scores on the full musical sophistication index. The two groups were composed of individuals above (n = 155) or below (n = 174) the median score. The agreement rate was estimated with Krippendorff's alpha test (Hayes & Krippendorff, 2007). The results indicated an overall low agreement for both groups (α < .667, Krippendorff, 2004), with those in the low sophistication group presenting lower agreement (α = .145) compared to more sophisticated individuals (α = .181).

4. Discussion

This article presents the first normative study with the Taste & Affect Music Database, which includes 100 instrumental soundtracks spanning different moods and genres. These soundtracks were evaluated for four basic taste correspondences and 10 affective dimensions, including discrete emotions, familiarity, as well as perceived and felt affective dimensions (Valence and Arousal). The subjective norms data and research materials are available at osf.io/2cqa5.

Notwithstanding the importance of music for several research domains, finding and selecting the most appropriate musical stimuli may prove an important methodological challenge. Several datasets of sounds (e.g., Bradley & Lang, 2007; Fan et al., 2017; Hocking et al., 2013) and music (e.g., Belfi & Kacirek, 2021; dos Santos & Silla, 2015; Eerola & Vuoskoski, 2011; Imbir & Golab, 2017; Lepping et al., 2016; Song et al., 2016; Vieillard et al., 2008) have been developed for specific stimuli categories (e.g., everyday sounds, classical music, or famous melodies) and subjective dimensions (e.g., discrete emotions, affective dimensions). However, norming studies in the auditory domain are still scarce compared to other sensory modalities, such as visual stimuli (Gerdes et al., 2014; Yang et al., 2018).

In the present study, we sought to obtain subjective norms for basic taste associations based on the literature on crossmodal taste perception. Research in this field has found interesting regularities in how individuals match tastes, flavors, or aromas with sound attributes. Moreover, this literature has shown that audition may play a role in modulating how foods and beverages are perceived (Spence et al., 2019a). As flavor refers to a panoply of combinations between gustatory and olfactory attributes, which are more commonly product-specific (i.e., the flavor lexicon may vary greatly between food categories or even between different products within the same food category; Suwonsichon, 2019), here we focused on the broader basic tastes categories, namely, sweetness, bitterness, sourness and saltiness. This stimulus set adds to the research in multisensory taste perception by testing a large set of musical stimuli regarding not only taste correspondences but also emotional and affective variables, whose relevance for the multisensory tasting experience is becoming increasingly recognized (e.g., Reinoso-Carvalho, Gunn, Horst, & Spence, 2020). Providing subjective norms for large stimulus sets also allows overcoming the technical obstacles associated with stimulus development, offering a less costly and time-consuming alternative to producing stimuli for the purpose of each experiment and allowing for greater comparability and replicability between studies (Lepping et al., 2016; Shafiro & Gygi, 2004).

4.1. Basic taste correspondences and emotional and affective dimensions

The results presented here indicate that individuals were able to associate tastes and sounds in a reliable way, even though the soundtracks were not produced to elicit taste associations, as in previous studies in the field (e.g., Wang et al., 2015). Sweetness was the most easily perceived taste, as shown by the higher mean choice proportion of this taste category, as well as the higher number of soundtracks with above 25% and 50% agreement levels. Although taste matching accuracy rates vary among studies, easier recognition of sweetness in music excerpts has been previously reported (Knöferle et al., 2015; Wang et al., 2015; although see also Guetta & Loui, 2017; Mesz et al., 2011). These studies hypothesize that sweetness may be more readily attributable to music considering the metaphorical associations between certain sounds and the sweet attribute (at least in the Western culture), but also because people tend to prefer the sweet taste more, and thus, they may heuristically associate sweetness with sounds that are also pleasant.

Some of the soundtracks in this database showed clear patterns of association with a single taste, making them suitable for "sonic seasoning" experiments aiming at enhancing specific taste attributes in foods and drinks. Other soundtracks conveyed a combination of more than one taste, which may provide more adequate pairings for foods and drinks with more complex flavor matrices. For instance, for bittersweet foods, the effect of a highly sweet soundtrack that is low on bitterness may be different from that of a highly sweet soundtrack that is also bitter (Crisinel et al., 2012; Höchenberger & Ohla, 2019). Hence, understanding the configuration of taste correspondences may assist in better tailoring the choice of soundtracks and avoiding possible confounds between taste attributes.

Across the 100 stimuli, it is also possible to find various patterns of taste and emotional/affective associations. The strong interrelation between taste and affect has been a thorny issue in crossmodal research, as it is often difficult to disentangle basic taste properties (e.g., sweetness) from emotional attributes (e.g., positive valence) (e.g., Wang et al., 2015). Likewise, studies focusing on the modulatory effects of music varying in emotional content may benefit from knowing the extent to which the selected music pieces communicate gustatory attributes as well (e.g., Kantono, Hamid, Shepherd, Yoo, Grazioli, et al., 2016). Despite the noticeable correlations between emotional/affective dimensions and basic taste correspondences in this dataset, the subjective rating norms presented here indicate that it is possible to select stimuli to evoke basic taste correspondences while controlling for relevant emotional/affective variables and vice-versa. This may allow researchers to overcome puzzling situations, such as when a positive-valenced stimulus is perceived as sweeter than a stimulus crafted to evoke crossmodal correspondences (e.g., Reinoso-Carvalho, Gunn, Molina, et al., 2020).

Despite the growing awareness regarding the relationship between emotion and taste perception, these variables were seldomly tested together in a systematic way (Kantono et al., 2019; Reinoso-Carvalho, Gunn, Horst, & Spence, 2020; Xu et al., 2019). One of the goals of the present study was to examine how affective and taste perceptive dimensions relate when evaluated concurrently. From that perspective, several results should be highlighted. For instance, sweet taste ratings were positively associated with positive valence dimensions and the pleasant, discrete emotion of joy. Conversely, bitter taste ratings were significantly associated with unpleasant affective dimensions and the emotions of anger, sadness, and fear. Previous studies found similar links between sweetness and positive valence, as well as between bitterness and negative valence (Wang et al., 2015, 2020). One possible explanation for this relationship stems from the implicit associations between tastes and hedonic outcomes. Evolutionary accounts suggest that sweetness may be innately preferred due to its presence in foods rich in carbohydrates, whereas bitterness may spark hardwired aversive reactions based on its role in signaling toxicity in foods (Beauchamp, 2016; Ventura & Mennella, 2011). These associations are also culturally disseminated through bodily metaphors linking sweetness to pleasant or nurturing affect (e.g., “love is sweet”) and bitterness and sourness with aversive emotional states (e.g., “tasting sour grapes” or “bitter with jealousy”) (Chan et al., 2013). These results also seem to align with an emotion-mediation hypothesis, which posits that shared emotional connotations may help explain the links between stimuli in different sensory modalities (Aryani et al., 2020; Spence, 2020; Walker et al., 2012). For instance, the crossmodal associations between music and colors are thought to reflect a common underlying emotional interrelation, with strong correlations between the emotional associations of music pieces and those of the colors that participants chose to match each music (Palmer et al., 2013, 2016). Similar mediation explanations have also been put forward to explain associations with other sensory modalities, such as music-odor (Levitan et al., 2015) or sound-texture associations (Spence et al., 2016).

4.2. Individual differences

Overall, individual differences, such as sex, age, taste preferences, or musical sophistication, had a small impact on taste correspondences and subjective ratings. For example, men seemed to provide higher surprise ratings. Older individuals provided higher sadness and perceived arousal ratings and made more frequent correspondences with sourness and saltiness. On the other hand, younger individuals made more frequent correspondences with bitterness. Although these differences are generally small in magnitude, future research and interventions with these stimuli should, nevertheless, consider the sociodemographic characteristics of their samples.

When looking at the associations between preferences for basic tastes and correspondences for that same taste, a significant association was found only for the liking of sour-tasting foods. According to these results, preferences for the other tastes (sweetness, bitterness, and saltiness) were less consequential to the identification rates of each corresponding taste.

In this sample, only a small percentage of individuals reported having current or previous involvement with musical activities. However, quantitative differences in terms of musical sophistication (as assessed by the Gold-MSI) seemed to have a small impact on the way participants assessed the musical stimuli. Some significant associations between subscales of the Gold-MSI and the subjective ratings were observed, although no clear pattern emerged from these comparisons. One could expect higher ratings in felt affective dimensions, given that feeling moved by music is one attribute of highly sophisticated individuals (Müllensiefen et al., 2014a, 2014b). Similarly, one could expect higher consistency in sound-taste correspondences among musically sophisticated individuals. For instance, music experts are expected to have richer mental representations of audio-related information and are likely to access a broader range of music-related associations (Hauck & Hecht, 2019; Mesz et al., 2011; Talamini et al., 2022). One often-cited example involving a taste attribute is the musical term "dolce" (Italian for "sweet"), which refers to a soft, tender way of playing an instrument. The assumption that musical ability or expertise may facilitate the understanding of sound-taste mappings is also reflected in past experiments, where expert musicians have been asked to create musical improvisations to mimic basic tastes (Mesz et al., 2011) or to curate music pieces to be crossmodally congruent with wines (Spence et al., 2013).

The current findings seem to suggest that the ability to recognize affective and emotional dimensions in music is not simply a reflection of musical sophistication. Likewise, previous studies (e.g.,Song et al., 2016) also reported a lack of association between subscales of the MSI and emotion ratings in musical excerpts. Notably, in the present study, we did not examine musical expertise per se, but rather a broad range of individual differences in musical behavior in a sample of the general population. When examining the consistency of sound-taste mappings among high and low scorers on the musical sophistication index, there was a tendency towards higher agreement in the first group. However, both groups presented overall low agreement levels. One may question whether larger differences in agreement rates were to be expected if we were to compare experts and non-expert groups.

4.3. Limitations and future directions

The subjective rating norms seem to indicate a fair distribution of stimuli across most dimensions. A few exceptions were found for neutral to negative emotions, such as anger, fear, sadness, and surprise, for which few items elicited ratings in the higher range (that is, items whose lower bound of the confidence interval was above the midpoint of the rating scale). One possible explanation for this result is the differentiation between "felt" and "perceived" emotion. Although individuals may identify the dysphoric emotions conveyed in a music piece (perceived emotion), they could be less likely to report feeling angry or fearful towards that same music (felt emotion). Anger, for instance, is usually felt in response to interpersonal situations of boundary invasion, violation of rights, being hurt, or frustration of a person's wants and needs (Greenberg, 2002). Therefore, it is unlikely that a strong anger reaction would occur in response to an aesthetic stimulus such as music. Although some degree of contagion may occur between the anger conveyed by the music and the perceiver's emotions, that relationship is not perfect (Schubert, 2013; Song et al., 2016). In fact, felt and perceived emotions may differ as sharply as to be seemingly contradictory. For instance, listening to sad music may evoke a pleasant emotion in the listener due to the aesthetic appeal or the experience of feeling moved by the song (Eerola et al., 2016; Vuoskoski & Eerola, 2017). Sachs et al. (2015) argue that the sadness portrayed in music may be pleasurable when perceived as non-threatening, aesthetically pleasing, and/or when it allows psychological benefits, such as mood regulation or empathic reflection.

Another issue regarding the emotional connotations of musical stimuli is that subjective ratings are based on between subjects' comparisons. It is likely that beyond the nomothetic conceptual connotations, a stimulus will also evoke idiographic associations based on past experience and individual memories, which could cause different individuals to attach different meanings to the same music piece. One example of the implications of adopting a nomothetic versus an idiographic approach can be found in the self-selection of musical stimuli literature. It has been previously shown that self-selected music may differ from experimenter-selected music in several ways. For instance, one study found that self-selected sad music seemed to trigger more complex and intense emotional expressions and stronger feelings of sadness and nostalgia (Weth et al., 2015). Salimpoor et al. (2009) also found evidence that self-selected music could allow for higher emotional contagion between perceived and felt emotion, whereas with experimenter-selected music, felt and perceived emotion were less associated.

Cultural variability in the assessment of auditory stimuli should also be taken into account when using the Taste & Affect Music Database. First, differences in perception of musical attributes could account for different interpretations of musical excerpts (Stevens, 2012). For instance, one study with Tunisian and French participants found that individuals synchronize differently with familiar and non-familiar music (Drake & El Heni, 2003). When asked to tap their fingers in accordance with the tempo of the musical excerpts, participants did so at a slower pace when listening to music from their own culture compared to foreign music. Second, decoding the affective attributes of the stimuli could also be liable to cultural influence. Cultural proximity seems to allow for more accurate emotional recognition in musical stimuli, with participants from the same culture as the stimuli outperforming participants from other cultures (Argstatter, 2016; Laukka et al., 2013). However, there seems to be some degree of commonalities in the way musical attributes express emotion across cultures. The accuracy in emotion identification in musical stimuli appears to be somewhat comparable to movement, facial, or verbal emotion expression (Argstatter, 2016; Fritz et al., 2009; Juslin & Laukka, 2003; Sievers et al., 2013). Some sonic attributes seem to facilitate cross-cultural recognition of affective connotations, at least for the most prototypical emotions. Joy, for instance, could be identified from fast tempo and melodic simplicity, whereas anger is usually attributed to louder volume and more complex melodies (Balkwill et al., 2004).

When it comes to the crossmodal correspondences between audition and taste, cross-cultural comparisons are still scarce. Since most of the existing evidence relies on research with Western samples, a recent study sought to test the “sonic seasoning” effect on the chocolate tasting experience of Asian and Latin-American participants (Reinoso-Carvalho, Gunn, Molina, et al., 2020). Although similar results were observed between these two groups of participants, the authors noted that the effects of the crossmodally-corresponding music stimuli were less pronounced for Asian and Latin participants than previous research with Western participants would suggest. In Knöferle et al. (2015), both American and Indian participants were able to decode the basic tastes intended by the composers of music pieces with above-chance accuracy. However, American participants seemed to have an overall “better” performance (that is, they were more likely to identify as sweet a music piece composed to convey sweetness attributes).

Ngo et al. (2013) found that tasting sour juices elicited more frequent associations with low pitch and sharper speech sounds (e.g., “kiki”), while juices low in sourness were more strongly associated with high-pitched sounds and rounded speech sounds (e.g., “bouba”). This pattern of associations was observed both for Colombian and English individuals, regardless of the degree of familiarity with the juices in question. In Peng-Li et al.'s (2020) study, Chinese and Danish individuals spent more time fixating on pictures of sweet (vs. salty) foods when listening to “sweet” soundtracks and more time fixating on salty foods when listening to a “salty” soundtrack, regardless of culture. When asked to choose the food they would rather eat at the moment, Chinese participants chose more sweet foods when exposed to the sweet music condition (vs. no music), while that difference was only marginal for Danish participants. The opposite pattern was found, with Danish participants, but not the Chinese, choosing more salty foods on the salty music condition than on the no-music condition. Overall, findings on the universality of crossmodal correspondences across different sensory modalities have been mixed (Levitan et al., 2015), and more research is needed in the case of sound-taste correspondences. Particularly, if culture-specific metaphors influence crossmodal associations, perhaps research should extend beyond broad comparisons (such as Western vs. non-Western countries) to investigate which culturally situated meanings could drive sound-taste pairings.

Another question that may interest researchers is whether it is equally valid to collect data with musical stimuli online and in the laboratory. Considering the growing internet use in everyday lives, data collection through online means is also becoming increasingly popular among researchers (Bohannon, 2016; Denissen et al., 2010; Palan & Schitter, 2018). In the past years, several validation studies have been conducted through web-based surveys, including stimuli in various sensory modalities, such as sound (e.g., Belfi & Kacirek, 2021; Lassalle et al., 2019), images (e.g., Ma et al., 2020; Prada et al., 2017, 2018), and videos (e.g., Ack Baraly et al., 2020; O’Reilly et al., 2016), however, some limitations should be taken into account. Particularly, the lower control over environmental conditions could mean that stimuli presentation is less standardized compared to laboratory settings. In the case of auditory stimuli, factors such as the properties of physical equipment, sound presentation volume, or background noise are expected to present a few variations among participants. In this study, we collected data online and in the laboratory. The full comparison of the two data collection methods is provided as supplemental material (Supplementary Table A1). As these results suggest, when comparing the subjective ratings of participants in the lab with those provided by a comparable sample of online respondents (balanced for gender and age), no significant differences were observed. Thereby, it seems that, for this stimulus set, both taste correspondences and emotional/affective ratings are consistent across data collection contexts.

4.4. Final remarks

In this study, the soundtracks of the new Taste & Affect Music Database were shown to adequately convey different taste associations and emotional/affective connotations. While this is, to our best knowledge, the first large-scale database to support crossmodal research between audition and taste, the results encourage its application across different experimental and intervention settings, such as in cognitive (e.g., learning, decision making), affective (e.g., mood regulation), or behavioral (e.g., eating, buying behavior) domains. Particularly, the subjective norms across valence and arousal dimensions, as well as discrete emotions, are in line with previous validations of musical stimuli, thus complementing and extending the existing datasets.

As research on sound-taste associations grows, more attention is being paid to the applications of a multisensory framework to modulating taste perception and changing eating habits in real-world settings. Recent evidence suggests that emotion-laden music and soundtracks evoking taste associations may shape taste perception and create more pleasant tasting experiences (e.g., Reinoso-Carvalho, Gunn, Horst, & Spence, 2020; Reinoso-Carvalho, Gunn, Molina, et al., 2020). These insights may be applied by brands interested in enhancing customer's experience but also by those interested in promoting healthier eating, for instance, by enhancing perceived sweetness or saltiness in foods and drinks with reduced sugar and salt contents (Biswas & Szocs, 2019; Thomas-Danguin et al., 2019).

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CHAPTER 3

Shaping Taste Perception Through Music: Empirical, Theoretical, and Methodological Issues

Despite the growth in scientific production surrounding sound-taste interactions, some aspects remain poorly understood. In what concerns the perceptual effects of these interactions, most research to date appears to deal with the question of how sound contributes to shaping the intensity at which participants evaluate taste or flavor sensations. The definition of sonic seasoning is, however, more encompassing when it states that sounds can match and potentially modify the taste (or flavor) properties of foods and drinks (Spence et al., 2019b). The emphasis on modifying perception (rather than merely enhancing or suppressing taste sensations) can implicate other parameters of taste perception besides intensity alone. Indeed, the literature surrounding other sensory modalities provides an example of how the senses can impact perception, for example, at the level of taste sensitivity.

The first paper presented in this chapter (Guedes, Prada, Garrido, Caeiro, et al., 2023) investigated whether extrinsic auditory stimuli can impact sweet taste sensitivity, akin to other sensory modalities like vision (Liang et al., 2013) and olfaction (Djordjevic et al., 2004). It expanded the current literature on the role of audition in taste perception to also encompass the ability to detect and recognize taste sensations.

Another aspect that has been overlooked in most sound-taste research is the possibility that the crossmodal associations between the two senses may also impact the evaluation of auditory stimuli. As the systematic review presented in Chapter 2 showed, although sound-taste correspondences are bidirectional (in the sense that sounds may be systematically associated with tastes and vice-versa), the perceptual implications of these correspondences have remained mostly limited to the evaluation of gustatory stimuli. The second paper presented in this chapter tested the bidirectional consequences of these crossmodal correspondences (Guedes, Prada, Lamy, & Garrido, 2023a). This paper contributed to demonstrating that gustatory sensations may shift the evaluation of the crossmodal attributes of music in a congruent direction. In addition, it also addressed a longstanding methodological issue surrounding the use of within- versus between-participants designs in sonic seasoning research. Notably, these findings provide the first empirical support for the hypothesis that direct contrast between auditory conditions may be a necessary condition for sonic seasoning effects to become evident. As such, this result also supports the notion of relativity in sound-taste correspondences (Spence, 2011; Spence, 2019).

The current literature shows that music selected based on crossmodal or emotional/affective attributes may contribute to shaping the experience with basic taste sensations. Although a significant share of studies opts to manipulate either of the two attributes in isolation, some authors have argued for the advantages of determining the most effective means to achieve the desired modulatory effects (Reinoso-Carvalho, Gunn, Horst, et al., 2020; Reinoso-Carvalho, Gunn, Molina, et al., 2020). The role of emotional and affective variables in sonic seasoning thus remains an important question for theoretical debate. For example, the notion of sensation transference lies in the idea that positive or negative feelings toward music not only transfer to the hedonic evaluation of foods but also to their taste in a congruent fashion. Here, the idea of congruence implicates the implicit associations between tastes and emotions, such as that between sweetness and positive affect (Ventura & Mennella, 2011; Zhou & Tse, 2022). This implies, for instance, that pleasant music impacts both taste and hedonic attributes, whereas crossmodal music influences the first but not the latter (Reinoso-Carvalho et al., 2016, 2017; Wang & Spence, 2016, 2018). It should be noted that this idea is not entirely supported by more recent evidence where enhancing effects of crossmodal music on hedonic variables are also found, even if to a lesser extent (Reinoso-Carvalho, Gunn, Horst, et al., 2020; Reinoso-Carvalho, Gunn, Molina, et al., 2020).

Understanding these intriguing and apparently conflicting findings requires us to look deeper into how cross-modality and affect are being operationalized across studies. As the previous chapter showed, affective and crossmodal attributes are rarely examined together in experimental studies (Guedes, Garrido, Lamy, Cavalheiro, et al., 2023). Importantly, the strong correlations between taste and affective variables (e.g., between sweetness and positive valence) have hindered the ability to effectively compare the individual contribution of both variables and made disentangling cross-modality and affect virtually impossible (Guedes, Prada, Garrido, & Lamy, 2023; Wang et al., 2015).

The last paper in this chapter is dedicated to this theoretical issue. This study investigates the contribution of cross-modality and affect for sweet taste perception by testing two pairs of soundtracks varying in sweetness (Experiment 1a: high vs. low sweetness) and valence (Experiment 1b: high/positive vs. low/negative valence). These findings reinforce the complexities of fully disentangling cross-modality and affect, although the results point to a more prominent effect when comparing a pair of soundtracks where the differences in sweetness are more pronounced than in the pair of soundtracks differing more strongly in valence.

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Sensitive to Music? Examining the Crossmodal Effect of Audition on Sweet Taste Sensitivity

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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.

Keywords: Crossmodal taste perception, Music, Sound, Sweet taste, Taste sensitivity

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, 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; Reinoso-Carvalho, Dakduk, Wagemans, & Spence, 2019; Spence et al., 2013; Wang et al., 2019; Wang & Spence, 2015), 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 suprathreshold 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 = .80, alpha = .05, effect size f = .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 Figure 3.1.). 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). 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 Figure 3.1.). Participants were instructed to keep the samples in their mouths for at least five sec 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.

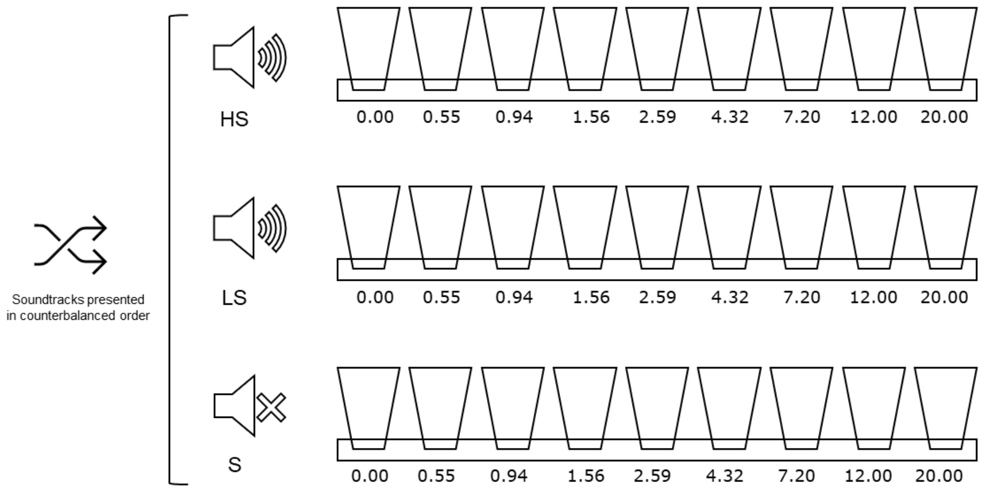


Figure 3. 1. *Overview of the Experimental Procedure*

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 3.1. 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 sec. 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 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 3.1.).

Table 3. 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"

2.4.3. Mood self-report

Participants were asked to describe their mood (valence and arousal) at the end of each condition, using two nine-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 suprathreshold 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)

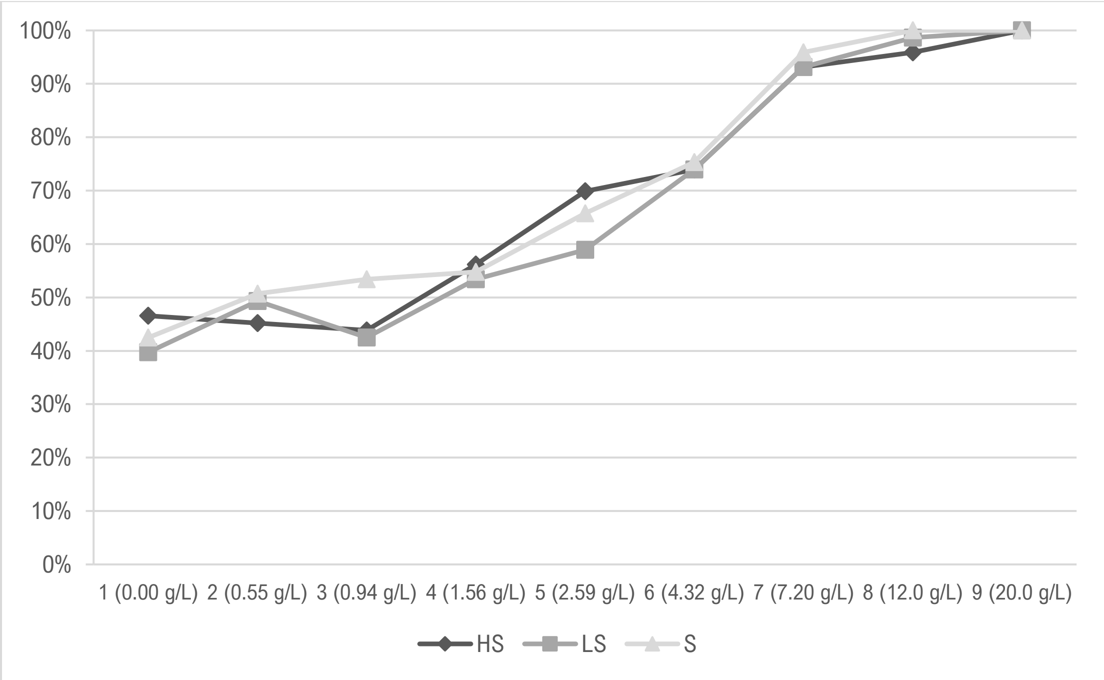
We did not find a significant impact of experimental condition on detection thresholds, $F(2,144) = 1.23$, $p = .296$, $\eta_p^2 = 0.02$. On average, taste detection thresholds were 2.62 (*SD* = 3.11 g/L) in the Silence condition, 3.22 (*SD* = 3.75 g/L) in the LS condition, and 3.34 (*SD* = 4.51 g/L)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

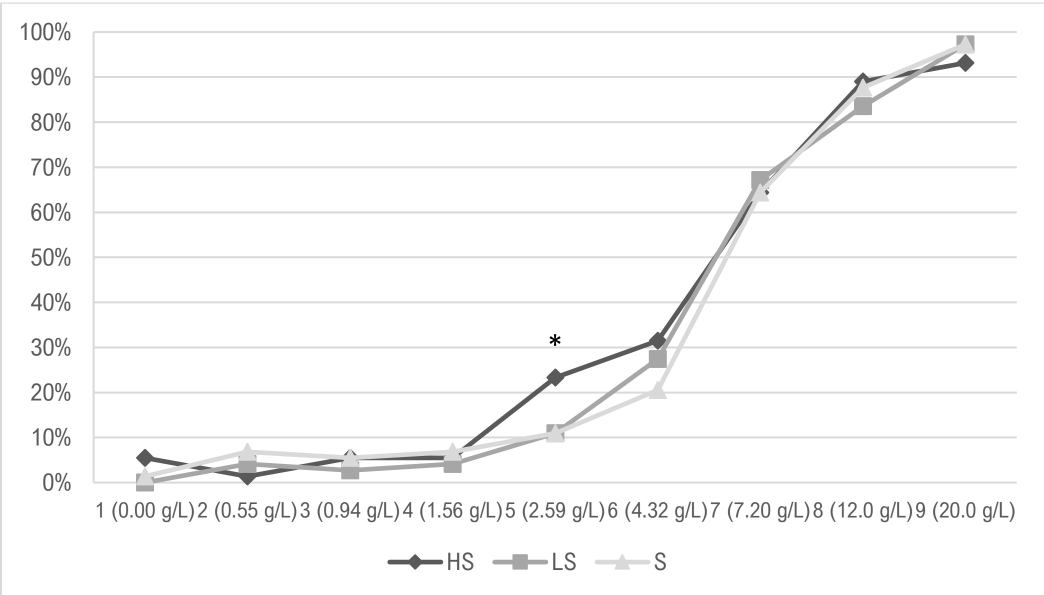
Figure 3.2 presents the proportion of taste detections (i.e., perception of a taste sensation different from water) obtained for each sucrose concentration for the three sound conditions (Detailed data is available in Supplementary Table B1). Detection rates increased with sucrose concentration, starting 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.

Figure 3.3 presents the variation in recognition rates across the samples for the three conditions (Detailed data is available in Supplementary Table B1). 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 Figure 3.3 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, $\chi^2(2) = 6.000$, $p = .05$.



Note. HS = High sweetness; LS = Low sweetness; S = Silence

Figure 3. 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

Figure 3. 3. *Variation In the Percentage of Participants Recognizing the Sweet Taste, for Each Sucrose Concentration, in the High Sweetness, Low Sweetness, and Silence Conditions*

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 $p > .155$).

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.

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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.

Keywords: cross-modality, crossmodal correspondences, sweet taste perception, audition, basic tastes

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).

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 bidirectionality 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 C1.

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 30s 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 1h 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 nine-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*).

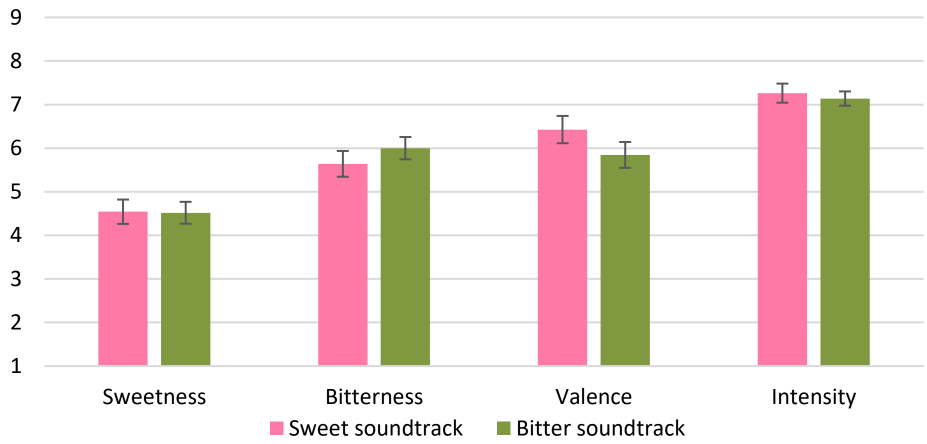
In the soundtrack evaluation task, participants rated each excerpt on sweetness (1 = *not sweet at all* to 9 = *very sweet*), valence (1 = *very negative* to 9 = *very positive*), and intensity (1 = *not intense at all* to 9 = *very intense*) using nine-point scales. All scales were presented in randomized 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 Figure 3.4.



Note. Error bars represent standard errors.

Figure 3. 4. *Mean Ratings of the Chocolate Sample in the Sweet Soundtrack and Bitter Soundtrack Conditions*

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 C1.

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.

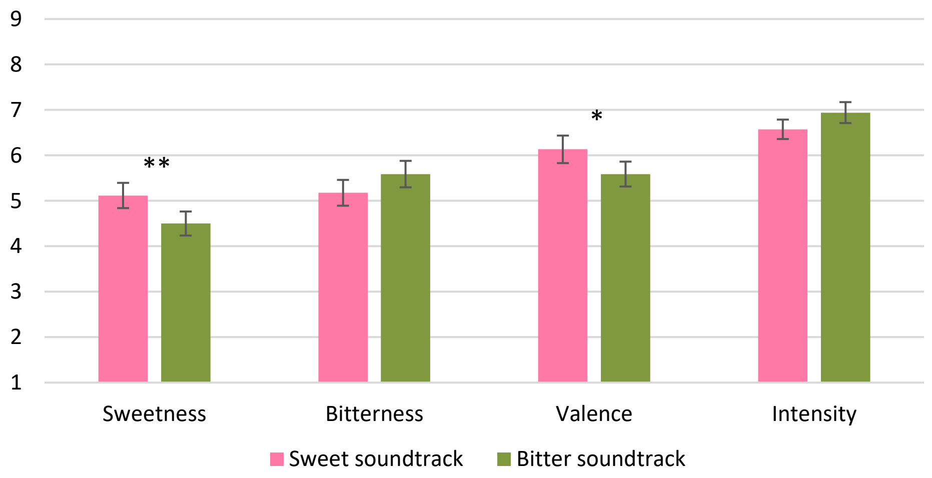
3.2. Data analytic plan

All analyses were conducted with IBM SPSS Statistics v28. We 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 Figure 3.5.



Note. Error bars represent standard errors.

* $p < .050$; ** $p < .010$.

Figure 3. 5. *Mean Ratings of the Chocolate Sample in the Sweet Soundtrack and Bitter Soundtrack Conditions*

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).

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

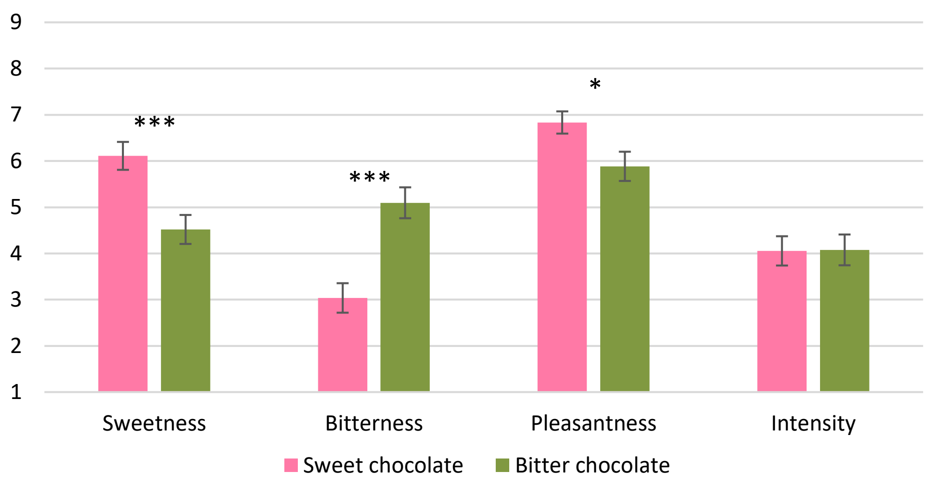
The soundtrack was evaluated in several affective and taste-related attributes using nine-point scales. The taste-related attributes of interest were sweetness (1 = *not sweet at all* to 9 = *very sweet*) and bitterness (1 = *not bitter at all* to 9 = *very bitter*). The affective attributes included 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 ($M = 3.04$, $SE = 0.32$), $p < .001$.



Note. Error bars represent standard errors.

* $p < .050$; *** $p < .001$.

Figure 3. 6. *Mean Ratings of the Musical Stimuli in the Sweet Chocolate and Bitter Chocolate Conditions*

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 ($p = .963$).

Figure 3.6. 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). 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).

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Disentangling Cross-Modality and Affect in “Sonic Seasoning”: The Effect of Music Associated with Different Degrees of Sweetness and Valence on Food Perception

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Abstract

The presence of music while eating can influence how foods are perceived. One line of inquiry has focused on the potential of music to evoke taste-related associations (such as perceiving a song as "sweet") to enhance the perception of congruent taste/flavor attributes in foods. However, music is also an expression of emotion, and its influence on mood has been put forward as an alternative explanation to why music changes taste perception. Disentangling both effects remains a challenge since taste and affective dimensions (e.g., valence) are usually highly correlated. This work examines the effectiveness of two pairs of soundtracks with different degrees of association with the sweet taste (Experiment 1a) or varying valence (Experiment 1b) in shaping food perception. In the two experiments, participants tasted foods differing in sugar content (i.e., cucumber, croissant, banana, and chocolate) while listening to the soundtracks and evaluated each sample on sweetness, liking, valence, and probability of future consumption. The results show that the higher (vs. lower) sweetness soundtrack significantly increased ratings in all dimensions. In contrast, no differences were observed in any of the dependent measures when listening to the higher valence (more positive) versus the lower valence (less positive) soundtrack. These findings seem to support the hypothesis that taste correspondences can contribute to modulating the multisensory eating experience. In contrast, it appears that when controlling for sweet taste correspondences, differences in the valence of music stimuli have a less salient impact on food evaluation. The theoretical implications of these findings and their potential applications to promoting healthier eating are discussed.

Keywords: multisensory taste perception, cross-modality, affect, music, sweet taste

1. Introduction

Sound is an important element of meal settings. Places like restaurants, cafés, or food courts have long integrated music into their atmosphere, for instance, to promote a more pleasant ambiance or subtly nudge customers' behavior (Karapetsa et al., 2015). While music selections in these contexts may sometimes be haphazard, researchers and practitioners have aimed to understand how aspects like musical style or specific acoustic attributes (e.g., loudness, tempo) may be deliberately engineered to improve consumer experience (Garlin & Owen, 2006; Spence et al., 2019). Music tempo, for instance, has been studied as a contributing variable to customer rotation and satisfaction, given its association with eating pace (Mathiesen et al., 2020, 2022), food enjoyment (Alamir & Hansen, 2021), as well as the time customers spend in a restaurant (Caldwell & Hibbert, 2002). The volume level of background music is yet another relevant acoustic attribute with important implications for how much customers drink (Guéguen et al., 2008; McCarron & Tierney, 1989).

In recent years, the potential role of music in fostering healthier eating has also been a subject of interest. For instance, soundtracks with lower volume (Biswas et al., 2019) or higher pitch (Huang & Labroo, 2020) have been shown to contribute to healthier eating choices. In a similar vein, music genre has been linked with a preference for healthy (vs. indulgent) foods. Across two experiments, Motoki et al. (2022) found that listening to jazz and classical music increased the preference for healthy savory foods, compared with rock/metal and hip-hop.

One alternative pathway to promote healthier eating is through the impact of music on taste perception. The field of "sonic seasoning" has produced compelling evidence that music (and other sound stimuli alike) may be deliberately selected to enhance specific taste/flavor attributes in foods and drinks (Spence, 2021; for a review, see Guedes, Garrido, et al., 2023). Recent research suggests that enhancing the perceived intensity of certain tastes (e.g., sweet, salty) through sound may improve the acceptance of products with lower sugar or salt contents with minimal compromises to consumers' satisfaction (e.g., Guedes, Prada, Lamy, et al., 2023; Swahn & Nilsen, 2023). While compensation for sugar reduction through multisensory enhancement has been acknowledged as a feasible strategy for other sensory modalities (e.g., adding vanilla flavor in low-sugar products; Alcaire et al., 2017), we are only now beginning to understand the potential of extrinsic auditory stimuli for this purpose.

In what concerns sugar consumption, one recent experiment found that music was able not only to improve the perceived sweetness of products with low sugar contents (e.g., vegetables and 0% sugar cookies) but also their acceptance (Guedes, Prada, Lamy, et al., 2023). Similar to other studies in the field, music pieces were selected based on their crossmodal associations with basic tastes. In this case, the two soundtracks were evaluated by participants as having different levels of association with the sweet taste. Other studies have shown that the associations people make between these two seemingly unrelated modalities (audition and taste) may have relevant perceptual implications (Guedes, Garrido, et al., 2023; Guedes, Prada, Lamy, et al., 2023a; Spence, 2016, 2020; Wang & Spence, 2015). Yet, the processes underlying these effects have remained elusive.

One likely hypothesis is that the crossmodal associations between sounds and tastes (e.g., perceiving a song as sweet) somehow shift the attention toward the congruent attributes in the oral modality, thus making it more salient in the flavor matrix (Wang et al., 2019). It has also been proposed that music may set up taste expectations that, in turn, influence the subsequent taste evaluation. This hypothesis seems consistent with recent findings, where delivering a soundtrack before tasting a chocolate had comparable effects on taste ratings to when music was presented during the tasting (Wang et al., 2020). What is less clear to date is whether crossmodal associations are necessary and/or sufficient to explain why such differences occur or whether these would be better explained by the influence of music on emotions and/or feeling states. For instance, Kantono et al. (2016) found that listening to liked music emphasized the sweet taste of gelati, whereas disliked music seemed to highlight its bitterness. Recently, it has also been argued that emotional (i.e., positive vs. negative) music may originate more prominent effects on the tasting experience than music selected based on crossmodal correspondences (in this case, “soft” vs. “hard” music; Reinoso-Carvalho, Gunn, Horst, et al., 2020; Reinoso-Carvalho, Gunn, Molina, et al., 2020).

One enduring challenge for understanding what drives sonic seasoning effects is that affective dimensions and crossmodal correspondences tend to be strongly associated. For instance, sweetness correspondences are usually highly correlated with positive emotions and affective dimensions, whereas the opposite pattern is commonly found for bitterness correspondences (Guedes, Prada, Garrido, et al., 2023). Considering the close link between affective evaluations and basic taste correspondences, there is still considerable uncertainty regarding the individual contributions of both variables to the multisensory perception of foods.

1.1. Current work and hypotheses

Notwithstanding the technical constraints of disentangling taste correspondences and affect, advancing research on this topic has important future implications. If affective dimensions, such as valence, prove to be the primary determinant of changes in taste perception in response to music, perhaps the field should move beyond mapping the taste correspondences of auditory stimuli and focus on emotions instead. In contrast, should taste correspondences be the main drivers of sonic seasoning, more attention should be devoted to unraveling how to convey gustatory attributes through sound. A third possibility could be that a thoughtful conjugation of both attributes results in better outcomes than any of the two alone.

To disentangle the influence of affect and cross-modality on taste perception, we conducted two experiments examining the influence of soundtracks varying in sweet taste correspondences and valence on the perception of different foods. In the first experiment, we investigated the effects of two soundtracks rated higher versus lower in sweetness (controlling for valence - Experiment 1a) and higher (i.e., more positive) versus lower (i.e., more negative) in valence (controlling for sweetness - Experiment 1b) on the taste perception (sweetness), hedonic (liking, valence) evaluation, and probability of future consumption of foods varying in sugar content.

Overall, we expected the soundtracks evaluated as higher (vs. lower) in sweetness and higher (vs. lower) in valence to increase ratings of sweetness (H1a) and hedonic dimensions (H1b). Still, if individuals directly transfer the attributes of the stimuli from the auditory to the gustatory modality, then we could expect the crossmodal attributes of music to have a more robust effect on taste than hedonic ratings, while the music's valence would be expected to impact more significantly hedonic rather than taste ratings (H2).

2. Pilot Study

A pilot study was conducted to select the most suitable auditory and gustatory stimuli for the main experiments.

2.1. Participants

Forty-three participants were recruited on Clickworker. The sample (M_{age} = 36.2, *SD* = 12.9 years) included 26 participants who identified as female and 17 as male. Participants received monetary compensation for completing the study.

2.2. Materials and Methods

Eight soundtracks were selected from the Taste & Affect Music Database (Guedes, Prada, Garrido, et al., 2023) based on sweetness and valence ratings. Two soundtracks were chosen

for each category of higher sweetness (moderate valence), lower sweetness (moderate valence), higher valence (moderate sweetness), and lower valence (moderate sweetness) stimuli.
The food stimuli were 24 pictures selected from the Food-Pics (Blechert et al., 2019). All images were in the medium range of valence ratings (mean ± 1 SD) and were chosen to reflect different sweetness and healthfulness attributes. The full auditory and visual stimuli description is available as supplemental material (Supplementary Tables D1 and D2).

A survey was programmed in Qualtrics and distributed online via the Clickworker platform. Participants were asked to evaluate the soundtracks (presented in random order) in sweetness (1 = *not sweet at all* to 9 = *very sweet*), valence (1 = *very negative* to 9 = *very positive*), and arousal (1 = *not arousing at all* to 9 = *very arousing*). The food pictures (presented in random order) were evaluated in the same dimensions, as well as healthiness (1 = *very unhealthy* to 9 = *very healthy*).

2.3. Results

The two soundtracks that differed more strongly in sweetness than valence were selected as the high sweetness (HS) and low sweetness (LS) soundtracks. The HS soundtrack was evaluated as significantly sweeter (M = 7.09, SD = 1.97), than the LS soundtrack (M = 5.19, SD = 2.57), $t(42) = 4.49$, $p < .001$, $d = 0.69$. The HS soundtrack was also evaluated as more positive (M = 6.81, SD = 2.12) than the LS soundtrack (M = 5.86, SD = 2.33), although to a lesser extent, $t(42) = 2.16$, $p = .037$, $d = 0.33$.

The two soundtracks differing more strongly from one another in valence than in the sweetness dimension were selected as the high valence (HV) and low valence (LV) soundtracks. The HV soundtrack was evaluated as significantly more positive (M = 6.56, SD = 2.05) than the LV soundtrack (M = 5.37, SD = 2.24), $t(42) = 3.56$, $p < .001$, $d = 0.54$. The HV soundtrack was also evaluated as sweeter (M = 5.72, SD = 2.11) than the LV soundtrack (M = 4.98, SD = 2.43), although with a less pronounced difference, $t(42) = 2.16$, $p = .036$, $d = 0.33$.

Four food items were selected based on perceived healthiness and sweetness ratings. Banana was selected as a healthy (M = 8.00, SD = 1.41) and sweet (M = 6.74, SD = 1.59) product, whereas cucumber was selected as a healthy food (M = 7.60, SD = 1.73) but lower in sweetness (M = 4.21, SD = 2.43). Likewise, a chocolate-caramel bar was selected as a less healthy (M = 5.07, SD = 2.63), sweet (M = 7.53, SD = 1.83) product, whereas croissant was selected as a lower healthiness (M = 5.86, SD = 1.77) product with lower sweetness (M = 5.33, SD = 2.02).

The two sweeter products (banana and chocolate) were rated significantly higher in sweetness (M = 7.14, SE = 0.22) than the two less sweet products (M = 4.77, SE = 0.29), $F(1,42) = 38.13$, $p < .001$, $\eta_p^2 = 0.48$. Likewise, the two healthier products (cucumber and banana) were rated significantly higher in the healthiness dimension (M = 7.80, SE = 0.20) than the two less healthy products (M = 5.47, SE = 0.28), $F(1,42) = 52.80$, $p < .001$, $\eta_p^2 = 0.56$.

Soundtracks' and food items' ratings are presented as supplemental material (see Supplementary Tables D3 and D4).

3. Experiments 1a and 1b: The influence of music on taste perception

To examine how the affective and crossmodal attributes of music affect food perception, we conducted two parallel experiments where participants were exposed to two pieces of music differing in their correspondences with the sweet taste (higher vs. lower - Experiment 1a) or in their valence levels (higher vs. lower; Experiment 1b). In both experiments, participants tasted samples of the four products selected based on the Pilot Study (in counterbalanced order) across two trials (each trial with a different soundtrack, also presented in counterbalanced order).

3.1. Participants

Two hundred and fourteen university students volunteered to participate in the two experiments. All participants received course credits as compensation for taking part in this study. Participant's knowledge or familiarity with the topic of crossmodal correspondences was not evaluated.

Experiment 1a had a sample of 107 participants (M_{age} = 21.9, SD = 4.9 years), with 74 participants who identified as women, 32 as men, and one as non-binary. Based on self-reported anthropometric measures, most participants (72%) were classified as normoponderal ($18.5 < \text{BMI} < 24.9$ kg/m^2), 9% as underweight (< 18.5 kg/m^2), and 19% as overweight or obese (> 25 kg/m^2).

Experiment 1b had a sample of 107 participants (M_{age} = 23.1, SD = 7.4 years), with 96 participants who identified as women and 11 as men. Based on self-reported height and weight, most participants (73%) were classified as normoponderal, 9% as underweight, and 18% as overweight or obese.

3.2. Materials and Methods

3.2.1. Gustatory stimuli

Four food products were selected based on the results of the Pilot Study. Objective average sugar contents were checked based on the information provided by the USDA FoodData Central (https://fdc.nal.usda.gov/) for the unprocessed products and the nutritional information provided by the manufacturer in the case of processed foods. These data supported the choice of banana as the sweeter healthy sample with an average sugar content of 15.8% and baby cucumber as the less sweet healthy sample with 1.38% sugar. To obtain comparable organoleptic properties (e.g., sweetness, astringency), bananas were served at similar ripening stages[9]. Among the less healthy products, commercially available versions of chocolate-caramel bars and croissants were selected. The chocolate bar (brand: Mister Choc®, variety: choco & caramel) had a 60% reported sugar content and consisted of a soft nougat, topped with caramel, and coated in milk chocolate. The croissant samples (La Cestera®) were packed plain croissants with a 17.2% reported sugar content. The samples were served on white disposable paper plates and identified with randomly generated three-digit codes (unrelated to the samples' identity).

3.2.2. Auditory stimuli

Four soundtracks were selected based on the results of the Pilot Study. For the crossmodal (sweet) pair, we chose two soundtracks that differed more strongly in sweetness than valence levels. Based on this criterion, soundtrack #58 ("Fruity Juice" by Jerry Lacey) was selected as the higher sweetness (HS) soundtrack, whereas soundtrack #11 ("What we used to know" by Farrell Wooten) was chosen as the lower sweetness (LS) soundtrack.

The affective music pair included soundtracks that differed more strongly in valence than sweetness levels. Soundtrack #88 of the database ("Balkan Wishes" by Trabant 33) was selected as the higher valence (HV) soundtrack, whereas soundtrack #27 ("Destiny Rising" by FormantX) was selected as the lower valence (LV) soundtrack. All soundtracks are available as supplemental material in the original paper (Guedes, Prada, Garrido, et al., 2023).

3.3. Procedure

The experiments were approved by the ethics committee of Iscte – Instituto Universitário de

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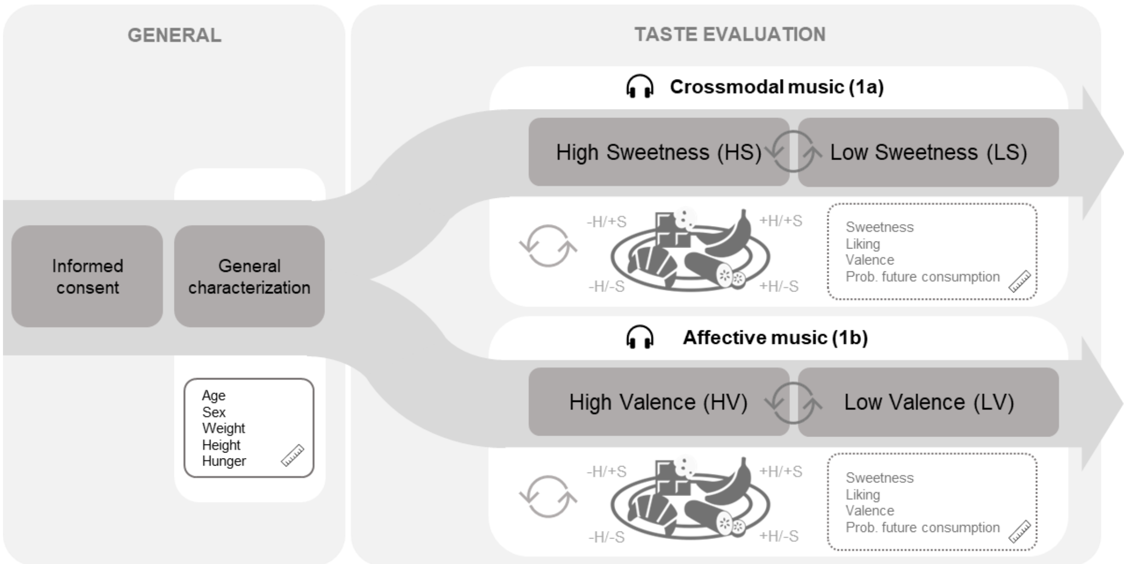
[9] Ripeness level was evaluated based on visual inspection of peel color and samples were preferred at around grade 5 (yellow with green tip) of von Loesecke's (1950) maturation scale.

Lisboa (Approval #117/2020). A pre-screening for food allergies and intolerances was conducted. Participants were informed in advance that the study involved food consumption, and this information was presented again in the informed consent before beginning the experiment. Participants were also instructed to refrain from eating, drinking coffee, brushing their teeth, or smoking the hour prior to participation.

Data were collected at the university lab in individual soundproof booths equipped with computers and headphones. All devices were kept at a comfortable sound volume level. Participants were told they would be asked to evaluate different food samples while listening to music. All instructions and measures were integrated into a web-based (Qualtrics) survey. The background music played automatically with sound controls invisible to participants.

Participants were randomly allocated to one of the two experiments. Depending on the experiment, participants completed the taste evaluation task with either the crossmodal (HS vs. LS) soundtracks or the affective (HV vs. LV) soundtracks. See Figure 3.7 for an overview of the survey flow.



Note. + = High, - = Low, H = Healthiness; S = Sweetness.

Figure 3. 7. *Overview of the Survey Flow in Experiments 1a and 1b*

After providing informed consent, participants were asked to fill out their sociodemographic information (e.g., age, gender) along with self-report measures of anthropometric (height, weight) and hunger/satiety levels. Two blocks of sample evaluations followed.

In the first block, participants tasted the four food samples in counterbalanced order while listening to one of the two soundtracks. After evaluating each food, participants were asked to drink water and wait 30 sec before proceeding to the following sample. In the second block, participants tasted the same products again (in counterbalanced order) while listening to the second soundtrack. The order by which soundtracks were presented was also counterbalanced across participants.

3.4. Measures

The food samples were evaluated using nine-point rating scales anchored by bipolar labels ("Please rate this food using the following rating scales"). The stimuli were assessed in the dimensions of sweetness (1 = *Not sweet at all* to 9 = *Very sweet*), liking (1 = *I don't like it at all* to 9 = *I like it very much*), and valence (1 = *Very negative* to 9 = *Very positive*). Additionally, participants were asked to rate the probability of choosing to consume each product again in the future using a continuous probability scale ranging from 1% to 100%.

3.5. Data analyses

All hypotheses and analytic plan were specified before data collection. Data were analyzed in IBM SPSS Statistics 28. Separate 2 (music) x 2 (sugar content) x 2 (healthiness) repeated-measures ANOVA tested the effect of music condition on each dependent variable: sweetness, liking, valence, and probability of future consumption. The independent variable "music condition" consisted of the two crossmodal soundtracks (HS and LS) in Experiment 1a and the two affective soundtracks (HV and LV) in Experiment 1b. Besides music, the model included the independent variables of foods' sugar content (higher: chocolate, banana vs. lower: cucumber, croissant) and healthiness (higher: banana, cucumber vs. lower: chocolate, croissant).

All main effects are reported in Tables 3.2 and 3.3. Interactions with the music condition were analyzed and reported when significant ($p < .050$). Participants' soundtrack evaluations were compared with Paired Samples *t*-tests.

3.6. Results

3.6.1. Experiment 1a: The influence of sweet music on the perception of taste and hedonic attributes

The original data is publicly available at OSF. Two participants refused to taste one of the food samples and, thus, were excluded from the analyses of variance.

The results of the ANOVA showed that music significantly influenced all dependent measures. The food samples were evaluated as significantly sweeter when listening to the HS soundtrack (*M* = 5.75, *SE* = 0.08) than the LS soundtrack (*M* = 5.60, *SE* = 0.08), $F(1,104) = 4.28$, $p = .041$, $\eta_p^2 = 0.04$. The products were also liked more, rated more positively, and evoked higher intentions of future consumption (all $p < .043$) in the HS (vs. LS) condition.

Additionally, the food samples' sugar content and healthiness also affected the dependent measures significantly (all $p < .001$), except for healthiness in the probability of future consumption ($p = .055$). Notably, participants provided higher ratings in all dependent variables for higher (vs. lower) sugar content and lower (vs. higher) healthiness. No significant interactions with music condition were observed. The descriptive statistics and main effects are reported in Table 3.2.

Table 3. 2. *Descriptives (M, SE) and Main Effects of Soundtrack Condition (A), Sugar Level (B), and Healthiness (C) Across the Dependent Measures in Experiment 1a*

(A) Soundtrack condition	HS		LS				
	M	*SE*	*M*	*SE*	*F*(1,104)	*p*	η_p^2
Sweetness	5.75	0.08	5.60	0.08	4.28	.041	0.04
Liking	6.76	0.09	6.58	0.10	8.40	.005	0.08
Valence	6.74	0.10	6.48	0.10	11.37	.001	0.10
Future consumption	73.05	1.44	71.60	1.44	4.21	.043	0.04
(B) Sugar contente	High		Low				
	M	*SE*	*M*	*SE*	*F*(1,104)	*p*	η_p^2
Sweetness	7.49	0.08	3.86	0.10	959.57	< .001	0.90
Liking	7.51	0.12	5.82	0.13	90.37	< .001	0.47
Valence	7.39	0.12	5.83	0.13	82.57	< .001	0.44
Future consumption	82.83	1.56	61.82	2.11	73.16	< .001	0.41
(C) Healthiness	High		Low				
	M	*SE*	*M*	*SE*	*F*(1,104)	*p*	η_p^2
Sweetness	4.39	0.10	6.96	0.08	461.39	< .001	0.82
Liking	6.20	0.15	7.13	0.11	23.90	< .001	0.19
Valence	6.18	0.15	7.04	0.11	22.51	< .001	0.18
Future consumption	69.78	2.02	74.87	1.80	3.76	.055	0.04

Note. HS = Higher sweetness; LS = Lower sweetness.

3.6.2. Experiment 1b: The influence of affective music on the perception of taste and hedonic attributes

The original data is publicly available at OSF. Three participants refused to taste one of the food samples and, thus, were excluded from the analyses of variance.

The results of the ANOVA did not show a significant main effect of music on any of the dependent measures (see Table 3.3.).

Once again, the food samples' sugar content significantly affected all dependent variables (all $p < .001$), and so did healthiness (all $p < .003$) in the same direction as Experiment 1a. A significant interaction between music condition and sugar content was observed on the valence ratings, $F(1,103) = 6.25$, $p = .014$, $\eta_p^2 = 0.06$ (not shown in tables). In the sweeter samples, participants provided higher valence ratings with the more positive music ($M = 7.60$, $SE = 0.12$) than with the less positive music ($M = 7.36$, $SE = 0.13$), $p = .016$. The opposite pattern was observed in the less sweet samples, where participants provided lower valence ratings with the more positive ($M = 5.68$, $SE = 0.16$) than with the less positive music ($M = 5.75$, $SE = 0.15$), although the difference was not significant ($p = .582$).

Table 3. 3. *Descriptives (M, SE) and Main Effects of Soundtrack Condition (A), Sugar Level (B), and Healthiness (C) Across the Dependent Measures in Experiment 1b*

(A) Soundtrack condition	HV		LV				
	M	*SE*	*M*	*SE*	$F(1,103)$	*p*	η_p^2
Sweetness	5.73	0.09	5.72	0.09	0.01	.929	0.00
Liking	6.67	0.11	6.63	0.11	0.30	.586	0.00
Valence	6.64	0.11	6.55	0.11	1.10	.298	0.01
Future consumption	71.11	1.72	70.77	1.73	0.16	.694	0.00
(B) Sugar content	High		Low				
	M	*SE*	*M*	*SE*	$F(1,103)$	*p*	η_p^2
Sweetness	7.50	0.09	3.94	0.11	828.80	<.001	0.89
Liking	7.59	0.12	5.71	0.16	99.30	<.001	0.49
Valence	7.48	0.11	5.71	0.15	106.81	<.001	0.51
Future consumption	81.96	1.75	59.92	2.38	77.61	<.001	0.43
(C) Healthiness	High		Low				
	M	*SE*	*M*	*SE*	$F(1,103)$	*p*	η_p^2
Sweetness	4.47	0.10	6.97	0.10	436.21	<.001	0.81
Liking	6.17	0.14	7.13	0.14	25.38	<.001	0.20
Valence	6.11	0.14	7.08	0.13	29.75	<.001	0.22
Future consumption	67.27	2.07	74.61	2.03	9.50	.003	0.08

Note. HV = Higher valence; LV = Lower valence.

4. Discussion

The empirical evidence accumulated thus far seems increasingly convergent in showing that music can modulate sweet taste perception (Guedes, Garrido, et al., 2023; Spence et al., 2019). While originally, these effects were thought to be a by-product of the implicit associations between attributes on the gustatory and auditory modalities, subsequent research has increasingly emphasized the role of emotional/affective factors in shaping the multisensory perception of foods (e.g., Reinoso-Carvalho, Gunn, Horst, et al., 2020; Reinoso-Carvalho, Gunn, Molina, et al., 2020). The current paper reports the results of two experiments where participants tasted products varying in sugar content and healthiness while listening to one of two pairs of soundtracks chosen to reflect contrasting crossmodal (higher vs. lower sweetness) or affective (higher vs. lower valence) attributes. The findings suggested that listening to higher (vs. lower) sweetness music increased the perceived intensity of the corresponding sweet taste, independently of the samples' healthiness or sugar content. Participants also reported liking the samples more, found them more positive, and showed higher intentions to consume them again in the future. Contrary to our expectations, this effect was larger on the hedonic (liking, valence) variables than on taste ratings. Also, in disagreement with the initial hypotheses, higher (vs. lower) valence music did not significantly affect any of the variables under analysis.

Previously, it has been suggested that emotions may affect not only the perception of taste/flavor attributes but also the hedonic experience with foods (Wang & Spence, 2018). According to an emotion mediation hypothesis, sounds may change individuals' affective states, and these, in turn, may highlight certain taste attributes (Kantono et al., 2019; Lin et al., 2019; Xu et al., 2019). Indeed, it is often the case that the taste attributes enhanced by music are those that are more associated with pleasure and affect. Most notably, pleasant music usually enhances the sweet taste, whereas unpleasant music more often intensifies bitter sensations (Kantono et al., 2016, 2019; Lin et al., 2022; Reinoso-Carvalho et al., 2019; Reinoso-Carvalho, Gunn, Horst, et al., 2020; Reinoso-Carvalho, Gunn, Molina, et al., 2020; Wang & Spence, 2016). This is thought to reflect implicit preferences of evolutionary origin, where sweetness is equated with pleasant subjective experience and bitterness with aversive reactions (Beauchamp, 2016; Ventura & Mennella, 2011).

The concept of "sensation transference" has also been called upon to explain the influence of emotional music on food perception. Originally put forward by Cheskin (1972), the concept has further been elaborated to refer to how the feelings elicited by music may transfer to the hedonic and sensory perception of foods and drinks (Reinoso-Carvalho et al., 2016). The basic tenet is that positive or negative feelings toward music would not only transfer to the hedonic evaluation of a product being tasted but also likely to its taste in a congruent fashion. Again, the idea of congruence here implicates the implicit associations mentioned above between emotions and tastes, such as that between sweetness and positive affect. Some studies have favored this hypothesis, showing, for instance, an effect of pleasant music both on taste and hedonic attributes, whereas crossmodal music seemed to impact the first but not the latter (Reinoso-Carvalho et al., 2016, 2017; Wang & Spence, 2016, 2018). This view has since been challenged in more recent experiments where crossmodal music has impacted hedonic measures too (Guedes, Prada, Lamy, et al., 2023; Reinoso-Carvalho, Gunn, Horst, et al., 2020; Reinoso-Carvalho, Gunn, Molina, et al., 2020).

While these findings might seem puzzling, it is important to note that studies have differed in the attributes they manipulate, as well as in the hedonic measures they intend to capture. To complicate matters further, it is yet virtually impossible to fully disentangle cross-modality and affect to the extent that taste correspondences and affective ratings are strongly and positively correlated, even when these variables are studied across large stimulus sets (Guedes, Prada, Garrido, et al., 2023). In the experiments presented here, we aimed at extricating sweetness associations from the affective dimensions of valence since this seems to be one of the main confounding variables in the sonic seasoning literature. Based on a pilot study, we selected two soundtracks that differed more strongly in sweetness than in valence (crossmodal pair) and two that differed more strongly in valence than in sweetness (affective pair). Although the results of the main experiments support the choice of soundtracks to some extent (e.g., by identifying a modulatory effect of the HS and LS soundtracks on sweet taste perception), fully disentangling cross-modality and affect remains a challenge. As the results from the Pilot Study suggest, the two dimensions (sweetness and valence) still appear to be positively correlated. Thus, instead of searching for fully controlling alternative variables, one may look at the attribute that is more dominant in each soundtrack.

While it might be tempting to interpret the current findings as suggesting a primacy of cross-modality over affect, it remains unclear whether these results are entirely attributable to differences in the subjective dimensions examined here or the characteristics of the stimuli used in these experiments. As with other studies in this field of inquiry, it is uncertain whether the effects obtained with a given stimulus are generalizable to others within the same class of stimuli (e.g., from a particular sweet music piece to other sweet music). Additionally, the fact that the affective music was perceived as more arousing could have contributed to it being considered less suitable to accompany food tasting. Indeed, the perceived fitness between music and food could be a measure of interest in future studies, as an adequate pairing between the senses may be key to the quality of the multisensory experience (Vandenberghe-Descamps et al., 2022). Pairing principles are particularly relevant in real-world settings where individuals seem to prefer to listen to music that is deemed adequate or appropriate to the eating situation (Wilson, 2003). In other words, music should blend and harmonize with the food rather than overshadow it. In effect, there have been efforts to achieve such harmonious effects by selectively pairing music with wine, similar to what is done unimodally (e.g., pairing wines with foods; Wang & Spence, 2015). While it seems apparent that a thoughtful selection of sounds in collective meal settings would result in a better dining experience, the choice of musical background seems generally unsystematic. More commonly, music is seen as a tool to build an atmosphere that matches a desired mood (Kontukoski et al., 2016) or alludes to a specific cuisine (Feinstein et al., 2002; Zellner et al., 2017). In what concerns crossmodal correspondences, it might be relevant to question how many unintended effects could be taking place in restaurants, cafés, or even in domestic contexts.

In sonic seasoning experiments, it has been common practice to test the effects of bespoke soundtracks deliberately composed to evoke taste associations. However, numerous studies to date have shown that different styles of music may also lead to changes in gustatory perception (e.g., Kantono et al., 2019; Kantono, Hamid, Shepherd, Yoo, Carr, et al., 2016; Spence & Deroy, 2013). That also appears to be the case of the Taste & Affect Music Database stimuli on which this study was based (Guedes, Prada, Garrido, et al., 2023). This stimulus set comprises 100 music excerpts retrieved from a music catalog designed to cover different moods and music genres. Still, despite the lack of intentions of composers to evoke taste associations, this stimulus set includes various soundtracks that were matched to basic tastes with above-chance agreement rates.

In addition to the effects in taste (sweetness) and hedonic (liking) measures, we also found that music influenced participants' reported intentions of consuming the food products again in the future. While this was beyond the scope of this study, future experiments might wish to examine how pairing less liked foods (e.g., bitter vegetables) with music with the right crossmodal characteristics could contribute to increase food acceptance and, potentially also food selection, for example, in addition to repeated exposure (Corsini et al., 2013). That might result not only in reduced sugar intake, but possibly also in higher consumption of healthier alternatives.

The samples used in the study varied in visual (color, shape) and textural (hardness) characteristics that might also suggest taste associations (e.g., color-taste, Spence & Levitan, 2021; shape-taste, Spence, 2023b; texture-taste, Barbosa Escobar et al., 2022). In future studies, it might be interesting to test whether the congruency between auditory and other sensory cues (e.g., color and shape of products) might lead to more robust effects than manipulating auditory stimuli alone (Wang, Mielby, et al., 2019). This investigation would be particularly relevant from an applied perspective, considering the multisensory nature of meal settings. Unlike controlled laboratory environments, real-world settings might include myriad sensory cues with potential interactive effects. Therefore, it becomes particularly challenging to ascertain whether a statistically significant effect obtained in the lab will result in meaningful changes in realistic environments.

Another limitation that should be mentioned regards how affective dimensions are to be interpreted. Indeed, there seems to be a lack of consensus regarding how valence should be measured (e.g., as a positive-negative continuum or a pleasantness dimension), and the difference between objective and subjective foci may also contribute to the mixed results. While "felt" (what the individual feels in response to music) and "perceived" (what the individual believes that music is intended to portray) affective dimensions tend to be correlated, they do not necessarily overlap (Guedes, Prada, Garrido, et al., 2023; Schubert, 2013; Song et al., 2016). Thus, guiding stimulus selection on felt instead of perceived valence could lead to different results. What is more, some studies have relied on subjective music preferences (i.e., liked music) rather than pleasantness or valence dimensions (e.g., Kantono et al., 2019; Kantono, Hamid, Shepherd, Yoo, Carr, et al., 2016; Kantono, Hamid, Shepherd, Yoo, Grazioli, et al., 2016). Concerning the crossmodal pair of music, these findings support the idea that lay individuals are capable of associating tastes to sounds in a non-arbitrary fashion. Previously, it was shown that individual differences in musical skills had a negligible impact on the ability to match sounds to tastes (Guedes, Prada, Garrido, et al., 2023) and that individuals with no musical training are able to decode the tastes that inspired musical improvisations by expert musicians with above-change accuracy (Mesz et al., 2011). Still, it is still unknown whether sonic seasoning effects might depend on participants' level of musical sophistication or, specifically, their knowledge of music-taste associations. In the present study we did not formally evaluate participants' prior knowledge of crossmodal correspondences. However, future studies might wish to address, for example, how familiarity with crossmodal correspondences might contribute to the results.

While disentangling cross-modality and affect remains a relevant theoretical endeavor, there are also important consequences from an applied standpoint. Whether one wishes to restructure environmental sounds to promote healthier eating or simply to foster a better multisensory experience, it is worth questioning what attributes to look for in music. Although we may still be far from determining precisely what sounds work best for what foods, environments, and attributes, the current research may provide relevant insights for this future transition. Importantly, the current findings reinforce the potential of music as a sensory cue to promote the acceptance of healthier foods. The sonic seasoning effect observed across foods with different sugar content further suggests that music may serve as a multisensory trick to allow for an improved balance in terms of the sugar contents of individual food products or meals.

Translating this knowledge into practical applications and creative solutions is an open challenge for scientists, chefs, baristas, gastronomists, nutritionists, and other professionals. Present and future technological advances, such as artificial intelligence and virtual/augmented reality, are also prone to offer new possibilities for selecting and delivering novel multisensory experiences involving sound (Spence, 2023a). Importantly, future developments in this area should not ignore the potential of multisensory interventions to respond to current public health challenges, namely by promoting healthier eating (Guedes, Prada, Lamy, et al., 2023; Hutchings et al., 2019; World Health Organization, 2015).

5. Conclusions and Implications

Disentangling cross-modality and affect in the context of sonic seasoning is an important step toward using music as a multisensory "sweetening" strategy. The findings presented here suggest that music selected based on sweet taste correspondences may effectively modulate the eating experience, not only by increasing sweet intensity ratings but also by fostering a more favorable hedonic evaluation and higher intentions of future consumption of the samples under analysis. Importantly, these results add to previous findings showing that music can improve the acceptance of products with varying sugar content (Guedes, Prada, Lamy, et al., 2023). From that standpoint, it appears that the potential of music stimuli reaches beyond simply delivering engaging multisensory experiences, as it may also contribute to promoting healthier eating habits.

Collective meal contexts, such as restaurants or cafeterias, are multisensory environments where music is often a key part of the ambiance. While some features of the auditory environment (e.g., loud noise) may deteriorate some aspects of taste perception (Woods et al., 2011), the growing body of literature on sonic seasoning may, in the future, allow practitioners to start developing smarter sonic spaces that can assist people in engaging in better eating behaviors.

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CHAPTER 4

"Sonic Sweetening" as a Path for Sugar Reduction

As discussed in the introduction section, the sonic influences on sweet taste perception have largely focused on products that appeal to most individuals (e.g., ice cream, desserts, see Table 1.1.). Although we should not disregard individual differences in taste preferences, there seem to be innate and contextual factors encouraging a preference for some of these products, particularly those with high sugar content (Mennella & Bobowski, 2015; Prada et al., 2021). In a time when environmental factors are increasingly acknowledged as relevant determinants of healthy dietary behaviors (Cohen & Babey, 2012; Graça et al., 2023; Micha et al., 2018), we are only starting to understand how auditory cues may contribute to this goal.

Recently, some studies have emerged which show that some attributes of music may contribute to shaping healthier food choices (Biswas et al., 2019; Huang & Labroo, 2020; Motoki et al., 2022). However, a healthy dietary pattern depends on the consistency of these choices through time. In the case of sugar consumption, the common perception that sugar reduction represents a loss in terms of hedonic appeal may be a barrier to long-term behavior change (Prada et al., 2022; Souza et al., 2021). Therefore, improving the sensory profile of products with lower sugar seems a feasible pathway to improve the acceptance of these products. The most common modifications at this level refer to the intrinsic properties more closely related to taste (e.g., sweeteners) and olfaction (e.g., aroma). Understanding the contribution of extrinsic factors to taste perception may thus be the next step toward improving the multisensory perception of healthier foods.

In this chapter, we present one study examining the influence of different auditory conditions in the sensory and hedonic evaluation of products with different sugar levels (Guedes, Prada, Lamy, & Garrido, 2023b). This paper is possibly the first empirical demonstration of the impact of auditory factors on the evaluation of foods with varying sugar contents, including different vegetables and 0% sugar cookies. This included not only changes in terms of sweet taste intensity but also in measures of hedonic response that may contribute to increasing their acceptance.

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Sweet Music Influences Sensory and Hedonic Perception of Food Products with Varying Sugar Levels

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Abstract

Reducing sugar intake is an important nutritional goal in most developed countries. Despite the health consequences of excessive sugar consumption (e.g., non-communicable diseases), individuals are often reluctant to shift dietary habits due to the high hedonic appeal of sugar-rich products. Manipulating the intrinsic sensory attributes of foods (such as color or aroma) has been put forward as a promising framework for enhancing taste perception and increasing acceptance of low-sugar products. So far, it is less known whether extrinsic sensory cues may have similar effects. In this within-subjects experiment (N = 106, 64% women), we tested how auditory stimuli (i.e., music) may impact the perception and acceptance of products varying in sweetness levels. Participants tasted samples of two product categories (vegetables and cookies), with higher (carrots and cookies) and lower sweetness levels (cucumbers and 0% sugar cookies), while listening to previously tested soundtracks that were strongly (vs. weakly) associated with sweetness. Results showed that the high "sweetness" soundtrack increased the sweetness ratings of all products compared to the low "sweetness" soundtrack. Participants also reported higher preference and more favorable intentions of future consumption when the high "sweetness" soundtrack was played. Overall, these findings suggest that extrinsic sensory cues, namely music, may aid in reducing sugar intake by increasing the acceptance of products with lower sugar content.

Keywords: crossmodal perception, sweet taste, healthy eating, sugar intake, music

1. Introduction

Sweets are among the most desired and palatable foods. Products like cookies, ice creams, or chocolates are commonly referred to as comfort foods due to their ability to trigger pleasant psychological states (Wansink & Sangerman, 2000). Human preference for sweet seems to result from a “perfect storm” of biological and psychological determinants. On the one hand, there are innate predispositions for seeking sweet- and avoiding bitter-tasting foods since early in ontogeny. On the other hand, in most Western countries, there is constant exposure to abundant, often highly processed, sweet foods, commonly associated with feelings of pleasure and reward (Mennella & Bobowski, 2015). Unsurprisingly, overconsumption of sugar is pervasive in most developed countries and is expected to continue rising, according to projections of OECD and FAO (2020). The worrisome implications of this nutritional imbalance include increased risks for obesity and non-communicable diseases, such as diabetes or cardiovascular and respiratory diseases (World Health Organization, 2015).

While several countries are implementing measures to reduce sugar intake, this may be a challenging endeavor due to the negative consequences of sugar reduction for eating enjoyment. For manufacturers, developing new sugar-reduced versions of food products often comes at the cost of sacrificing sensory appeal (e.g., taste, texture) and consumer acceptance (de Souza et al., 2021; Prada et al., 2022). While replacing sugars with artificial sweeteners is a common mitigation strategy, multisensory integration techniques may also improve sweetness perception by modulating other sensory attributes (Hutchings et al., 2019). Common strategies involve changes to foods’ intrinsic properties, such as adding aromas or manipulating products’ colors. For example, adding vanilla aroma to milk desserts was shown to be an effective strategy for mitigating the effects of sugar reduction (Alcaire et al., 2017). Likewise, adding red coloring to aqueous solutions led to higher sweet taste intensity ratings (Hidaka & Shimoda, 2014; for a discussion of mixed findings in color-taste associations, see Spence, 2019).

The multisensory influences that shape taste perception do not pertain exclusively to the intrinsic properties of foods. External cues, such as products’ packaging, plateware, or ambient sounds, may also modulate how individuals evaluate the taste of foods and drinks (Wang, Mielby, et al., 2019). The manipulation of auditory cues, such as delivering soundscapes or music during eating, has been termed “sonic seasoning” (Spence et al., 2019a, 2019b). In this line of research, auditory stimuli are either composed or selected to match a given taste or flavor sensation (e.g., a “sweet” ballad). In turn, the congruent pairing of auditory and gustatory stimuli (e.g., a sweet dessert and a “sweet” ballad) enhances or emphasizes the sensory properties of foods and drinks. One pivotal study in the field found that playing a soundtrack congruent with sweet taste enhanced the perceived sweetness of cinder toffee, whereas a "bitter" soundtrack enhanced its bitterness (Crisinel et al., 2012). This seems consistent with the view that attributes of the sonic atmosphere may be "transferred" to the evaluation of the product being tasted. Thus, the crossmodal associations of a soundtrack may accentuate (or suppress) certain sensory attributes of foods, while the feelings about these soundtracks are likely to contribute to the overall hedonic experience (for a discussion of the sensation transfer account, see Spence et al., 2019a)

A growing body of research has since sought to explore the role of musical stimuli in shaping the eating/drinking experience. A large portion of this literature has tested the effect of music in enhancing the taste of alcoholic beverages (e.g., beers, wines) and highly palatable food products (e.g., chocolate, gelati; for a review, see Spence et al., 2019a). While the results in this regard seem promising, it is yet unclear whether music can adequately enhance the acceptance of healthier foods, such as vegetables or low-sugar products. If music can effectively enhance sweet taste perception across food categories, then audition could add to the existing multimodal compensatory strategies for sugar reduction.

In this experiment, we sought to extend the current evidence on sonic seasoning by testing the effect of a "sweet" soundtrack on the sensory perception and acceptance of products with different sugar contents. In the first task, participants tasted two vegetables varying in sweetness (carrots and cucumbers) while listening to a high "sweetness" (vs. low "sweetness") soundtrack (HS and LS, respectively). The second task consisted of a replication, with the same participants tasting regular and 0% sugar cookies. We hypothesized that HS music would enhance the perceived sweetness of vegetables and cookies compared to the LS (H1). Since sweetness is a commonly desirable attribute, we hypothesized that products under the HS (vs. LS) condition would be liked more (H2) and lead to greater intentions of consuming that product again in the future (H3).

2. Methods

2.1. Participants

A total of 106 participants volunteered to take part in this study. The sample, aged 18-62 (M = 26.33, SD = 10.26), included 68 participants who identified as women, 35 as men, and three as non-binary. Most participants (66%) reported normal weight (BMI = 18.5-24.9). On average, liking (M = 6.89, SD = 2.26) and frequency of consumption of sweet foods (M = 6.17, SD =

2.22) were high. Participants were recruited via internal university communication channels (to the academic community), and external promotion means, including press articles and social media (e.g., LinkedIn, Facebook). Retail vouchers were used as incentives for participation.

2.2. Design

This study consisted of a 2 (soundtrack: high sweetness, low sweetness) x 2 (product: cookies, vegetables) x 2 (sugar level: high, low) full factorial within-participants design.

2.3. Study materials and procedures

The study was approved by the ethics committee of Iscte – Instituto Universitário de Lisboa (Approval #117/2020) and was conducted according to international guidelines for research with human participants (Declaration of Helsinki). Communication materials (e.g., study website) specified that the study involved food ingestion, and participants were encouraged to contact the research team in case they suffered from any allergy, intolerance, or other dietary restrictions. This information was provided again orally and in the informed consent form before beginning the experiment.

Participants were instructed to refrain from eating, drinking coffee, brushing their teeth, or smoking the hour prior to participation. Data collection took place at the university lab, equipped with computers and headphones. Participants were told they would be asked to evaluate different food samples while listening to music. Then, they were asked to put the headphones on and follow the instructions provided on the computer. For this purpose, a web-based survey was programmed in Qualtrics (see Figure 4.1. for an overview). The survey was programmed to play the soundtracks automatically, and the sound player controls remained hidden from participants. All devices were kept at the same comfortable volume level.

After providing informed consent, participants were asked to fill out their sociodemographic information (e.g., age, gender) along with self-report measures of anthropometric (height, weight) and homeostatic variables (thirst, hunger). Two blocks of sample evaluations followed. In the first block, participants tasted samples of a sweet vegetable (baby carrot) and a less sweet vegetable (baby cucumber). Both vegetables were tasted twice, each time paired with a different soundtrack. The four vegetable-soundtrack pairs were presented in counterbalanced order. The same procedure was followed in the second block of sample evaluation, this time with two versions of a chocolate chip cookie with different sugar contents. After tasting each sample, participants were instructed to drink water to cleanse the palate. Moreover, the two evaluation blocks were separated by a 1 min break in which participants saw a 60 s video-timer.

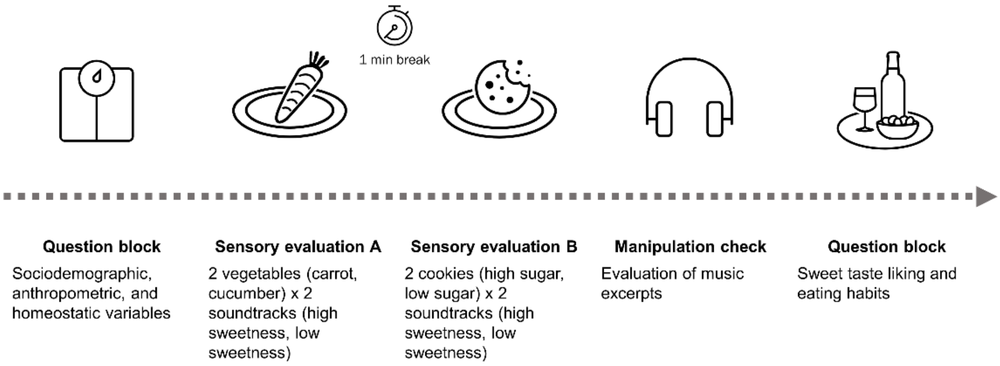

Figure 4. 1. *Overview of the Experimental Tasks*

In the following block, the two soundtracks that were played during the tasting task were presented again (in random order) to be evaluated in taste (sweetness) and affective (valence, arousal) dimensions. The last section of the survey comprised measures of sweet taste liking and eating habits.

2.2.1. Food samples

Baby carrots and baby cucumbers were chosen as the sweeter and less sweet vegetables, respectively. According to the Table of Food Composition 5.0. (INSA, 2021), raw baby carrots present an average of 4.8g of sugar per 100g, whereas raw cucumbers present an average of 1.6g of sugar per 100g. Both vegetables were cut into pieces of approximately 3cm and served raw at room temperature.

Two versions of commercially available chocolate chip mini cookies were selected for this study. According to the manufacturer, the standard cookies contain about 30% sugar, whereas the 0% sugar mini cookies present < 0.5g sugar per 100g of product. Each cookie has an approximate size of 2.5cm in diameter. All samples were presented in round disposable white paper plates, identified with three-digit codes.

2.2.2. Musical stimuli

Two instrumental soundtracks were selected from the Taste & Affect Music Database (Guedes, Prada, Garrido, & Lamy, 2023). The high sweetness soundtrack ("Fruit of Lore", 80 BPM) was evaluated as sweet by 80.52% of the sample in the norming study, whereas the low sweetness soundtrack (“Walk of Destiny”, 152 BPM) was rated as sweet by only 7.02% of participants[10]. The soundtracks were chosen to reflect contrasting sweet taste correspondences but approximate valence ratings (both excerpts were scored “High” in valence in the norming study). These music excerpts were not marketed to the general public and, thus, were unfamiliar to the participants.

2.3. Measures

The food samples were evaluated in several sensory and hedonic attributes using nine-point scales. Both product categories (vegetables and cookies) were evaluated in sweetness (1 = *Not sweet* to 9 = *Highly sweet*) and liking (1 = *I don’t like it at all* to 9 = *I like it very much*). The sample evaluation task also included attributes unrelated to the experimental manipulation (e.g., bitterness, healthfulness, crunchiness) to keep participants blind to the goal of the study. All items were presented in random order. At the end of each evaluation, participants were asked to indicate the likelihood of consuming that product again in the future, using a continuous scale ranging from 0% to 100%.

As a manipulation check, we also included a soundtrack evaluation task, asking participants to rate each excerpt on sweetness (1 = *Not sweet at all* to 9 = *Very sweet*), valence (1 = *Not pleasant at all* to 9 = *Very pleasant*), and arousal (1 = *Not arousing at all* to 9 = *Very arousing*) using nine-point scales. The last block of questions asked about participants' sweet taste liking and consumption (nine-point scales).

2.4. Data analyses

All analyses were conducted with IBM SPSS Statistics v26. First, participants’ evaluations of the HS and LS soundtracks were compared with Paired Samples *t*-tests. The two soundtracks were analyzed as HS and LS stimuli based on the group average. Thus, no observations were removed based on individual ratings on the manipulation check.

Three repeated-measures ANOVA models were conducted separately for each dependent variable, namely, sweetness ratings, liking, and future consumption intentions. The models included soundtrack (high sweetness, low sweetness), food category (vegetables, cookies), and sugar level (high, low) as within-subject factors. All main effects are reported in Table 4.1. Interaction effects were analyzed and reported when significant ($p \leq .05$).

[10] Basic taste correspondences were evaluated based on a forced-choice paradigm. Alternatives were sweet, bitter, salty, and sour.

3. Results

All participants reported compliance with the inclusion criteria (e.g., avoiding smoking, drinking coffee). Thus, all were retained for analysis.

3.1. Evaluation of high sweetness and low sweetness soundtracks

Congruently with the results of the norming study, the two soundtracks differed in sweetness ratings, such that the HS soundtrack was evaluated as sweeter (M = 6.90, SD = 1.77) than the LS soundtrack (M = 2.53, SD = 1.46), $t(106) = 19.56$, $p < .001$. Both soundtracks were rated high in valence, with higher mean ratings for the HS (M = 7.26, SD = 1.77) compared to the LS soundtrack (M = 5.37, SD = 1.95), $t(106) = 7.98$, $p < .001$. The LS soundtrack was evaluated as more arousing (M = 7.87, SD = 1.44) than the HS soundtrack (M = 3.73, SD = 2.06), $t(106) = 17.87$, $p < .001$.

3.2. Influence of soundtrack condition on sweet taste ratings

Descriptive statistics (means, standard errors) and the results of the within-subjects analysis of variance are presented in Table 4.1. A main effect of soundtrack condition showed that music had a significant influence on sweetness ratings, $F(1,105) = 8.85$, $p = .004$, $\eta_p^2 = 0.08$. Overall, and as hypothesized (H1), food products were rated as sweeter in the HS condition compared to the LS condition. No significant interactions were observed between soundtrack condition and either product type (cookies vs. vegetables), $F(1,105) = 0.02$, $p = .893$, $\eta_p^2 = 0.00$, or sweetness level (sweeter cookie/vegetable vs. less sweet cookie/vegetable), $F(1,105) = 3.33$, $p = .071$ $\eta_p^2 = 0.03$. In the latter case, the trend pointed to a larger effect of music in the less sweet (M_{HS} = 4.75; M_{LS} = 4.35) than in the sweeter (M_{HS} = 6.22; M_{LS} = 6.09) samples. The main effects of product type and sugar level were also significant (see Table 4.1).

3.3. Influence of soundtrack condition on liking

A significant main effect of soundtrack was observed on liking ratings of the samples, $F(1,105) = 8.03$, $p = .006$, $\eta_p^2 = 0.07$, supporting H2. On average, participants reported liking the samples more when listening to the HS soundtrack than the LS soundtrack. No significant interactions were observed with product type or products' sugar level (all $p > .414$). Thus, it seems that the effect of soundtracks on the hedonic ratings was not dependent on the products' characteristics. The main effects of product type and sugar level are reported in Table 4.1.

3.4. Influence of soundtrack condition on intentions of future consumption

The main effect of soundtrack was also observed in future consumption intentions, $F(1,105) = 6.54$, $p = .012$, $\eta_p^2 = 0.06$, supporting H3. Participants reported a higher likelihood of future consumption in the HS soundtrack condition compared to the LS condition. The effect did not depend on product type or sugar level, as seen by the absence of significant interactions with these variables (all $p > .160$). A main effect of sugar level (but not product type) was also observed (see Table 4.1).

Table 4. 1. *Means, Standard Errors, and Main Effects of Soundtrack Condition (A), Product (B), and Sugar Level (C) on Sweetness, Liking, and Intentions of Future Consumption*

(A) Soundtrack	HS		LS			
	M	*SE*	*M*	*SE*	*F*(1,105)	η_p^2
Sweetness	5.48	0.11	5.22	0.09	8.85**	0.08
Liking	6.7	0.12	6.51	0.13	8.03**	0.07
Future intentions	70.8	1.71	69	1.78	6.54*	0.06
(B) Product	Cookies		Vegetables			
	M	*SE*	*M*	*SE*	*F*(1,105)	η_p^2
Sweetness	6.52	0.12	4.18	0.13	179.75***	0.63
Liking	7.11	0.15	6.09	0.18	19.66***	0.16
Future intentions	70.99	2.17	68.81	2.43	0.50	0.01
(C) Sugar level	High		Low			
	M	*SE*	*M*	*SE*	*F*(1,105)	η_p^2
Sweetness	6.15	0.10	4.55	0.12	143.85***	0.58
Liking	7.09	0.12	6.11	0.15	50.29***	0.32
Future intentions	75.26	1.75	64.5	2.04	41.96***	0.29

Note. HS = High sweetness soundtrack, LS = Low sweetness soundtrack
* $p < .050$; ** $p < .010$; *** $p < .001$

4. Discussion

Multisensory integration strategies have been previously put forward as potential pathways to compensate for sugar reduction. In this study, we tested the feasibility of using music-taste interactions to enhance sweet taste perception of products varying in sweetness levels. Two product categories (vegetables and cookies) with higher and lower sugar levels were tasted along with high "sweetness" and low "sweetness" soundtracks.

Results showed that music significantly influenced the perception and acceptance of the samples. The HS soundtrack resulted in higher sweetness ratings, as well as higher liking and more favorable intentions towards future consumption. These results are in line with previous studies showing an effect of music on sweet taste intensity ratings. Notably, this study also adds to previous findings showing that music may impact taste perception even when soundtracks are incidentally (rather than purposely) associated with taste attributes (Hauck & Hecht, 2019; Wang, Mesz, et al., 2019). The music excerpts explored here are part of a validated database of instrumental soundtracks that showed reliable associations with basic tastes, even though they were not composed with crossmodal goals in mind (Guedes, Prada, Garrido, & Lamy, 2023). Thus, these findings may help shed light on how background music that could be found in meal settings (e.g., restaurants, cafeterias) may spark sound-taste correspondences and influence eating behavior.

The results presented here attest that the two soundtracks conveyed the taste sensations they were expected to express according to the validation data. The HS soundtracks presented higher sweetness ratings compared to the LS soundtracks, and this difference was the largest among all rating dimensions. The two soundtracks also differed significantly on affective ratings, which leaves the question of whether affect may contribute to sonic seasoning effects. Indeed, previous studies have shown that listening to liked music may impact sweet taste perception, for instance, in gelati (Kantono et al., 2016, 2019), whereas disliked music may enhance bitterness attributes. Recently, it has been argued that emotionality may be more impactful for the taste experience than crossmodal attributes, such as softness/hardness (Reinoso-Carvalho et al., 2020). Although differences in the affective ratings of the soundtracks were observed, it is unclear whether these reflected actual mood changes (as "perceived" and "felt" affective dimensions are not entirely equivalent, e.g., Guedes, Prada, Garrido, & Lamy, 2023). This may be a relevant distinction since mood changes induced by music (beyond "conceptual" affective associations alone) seem to contribute to shaping the gustatory experience (Kantono et al., 2019).

While this question is beyond the scope of the present study, we should note that the soundtracks tested here differed more strongly in taste correspondences than in valence associations and their effect, in turn, was more evident in taste attributes than in liking of the samples. This is consistent with the view that music attributes may be mapped onto gustatory stimuli in meaningful ways (North, 2012). Overall, these findings support the notion that hearing and, particularly, listening to music may impact taste perception. Without a "neutral" control condition, however, it is unclear whether the crossmodal effects on taste were due to the enhancing effect of a highly "sweet" soundtrack or a buffering effect of a less "sweet" stimulus. Thus, the inclusion of neutral conditions could help disentangle these possibly concurrent effects in future studies. We should also note that, in this context, high (vs. low) sweetness refers to average ratings, based on sample consensus, rather than individual judgements. Thus, individual differences in soundtrack evaluation were not taken into account when interpreting these results.

In both sets of products (vegetables and cookies), participants showed a higher preference for the sweeter versions (carrots and regular cookies), echoing the challenges of building adherence to products with lower sugar levels (de Souza et al., 2021; Hutchings et al., 2019). In the case of the cookies tested here, the 0% sugar version included an undisclosed amount of sweetener (maltitol) in its formulation. In any case – and as intended – these samples were still subjectively perceived as less sweet, according to participants' ratings. From that standpoint, the current findings suggest that crossmodal correspondences may contribute to minimizing the sensory and hedonic disadvantages of less sweet products. Furthermore, to our best knowledge, this was the first time a sonic seasoning approach was applied to promote vegetable acceptance. Extending these findings to a greater variety of healthy products (e.g., fruits and vegetables) may prove advantageous for promoting adherence to healthier eating with lesser compromises for enjoyment. Although adding a sweet soundtrack to the eating environment is hardly comparable to adding a spoonful of sugar, the crossmodal interactions between audition and taste may open a promising route for enhancing taste perception, either alone or as part of broader multisensory interventions.

5. Conclusions

This study presents new evidence on the contributions of audition to sweet taste perception and overall acceptance of healthier products. Results support the use of sonic seasoning principles with products with varying sugar levels, such as sweeter and less sweet vegetables and cookies. The study of crossmodal correspondences may offer relevant insights on how to support sugar reduction while minimizing the sensory and hedonic consequences of lower sugar levels. These findings could inform future interventions in naturalistic settings, namely in planning more appropriate soundscapes for restaurants or cafeterias where healthier eating is to be encouraged.

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CHAPTER 5

General Discussion

Could music become the next sugar? The past few years have seen a renewed interest in this intriguing possibility. The investigation surrounding the multisensory determinants of taste perception has unveiled surprising interactions between the senses. In this panorama, the role of audition was seemingly a late discovery. Still, more recent research is strongly suggestive that sonic cues may contribute to shaping our evaluation of taste, as well as more complex flavor or trigeminal sensations (Spence et al., 2019b).

Scientists in the field of multisensory perception have made a compelling case for the role of the senses in the eating experience and have shown that the multisensory nature of perception has surprising yet relevant applications for eating behavior, nutrition, marketing, art, gastronomy, and other domains alike (Spence et al., 2019a). In this project, we focused particularly on the possibility of transforming the way sweet taste is perceived. The main concern underlying this work is that excessive sugar consumption is problematic. What was once a rare delicacy for the elites has now a widespread, ubiquitous presence in the various processed foods consumed daily or is added in generous doses to foods and drinks prepared at home (Mela et al., 2018). Despite the pressure from health authorities advising sugar reduction, the hedonic appeal of sweetness persists as a significant challenge (WHO, 2015). Although consumers seem aware of the pernicious impact of high sugar consumption (Prada et al., 2022) and show themselves receptive to measures of intake reduction (Prada, Rodrigues, et al., 2020), they lack knowledge about sugars (e.g., recognizing ingredients like maltose or fructose as sugars) and its consumption guidelines (Prada, Saraiva, et al., 2020).

From a sensory perspective, reducing sugar without compromising acceptance and enjoyment is, at best, a thorny issue (Hutchings et al., 2019). Besides its unique taste profile, sugar also adds a significant value to structure, texture, flavor, as well as product preservation (Koeferli et al., 1996; Martínez-Cervera et al., 2014; Pareyt et al., 2009). The challenges of sugar reduction thus seem to connect to a broader and longstanding tension between hedonic and health motivations for consumption.

To a certain extent, reconciling health and taste might seem a natural yet overlooked potential of sonic seasoning research. Indeed, the importance of sound for the eating experience does not boil down to enhancements at the sensory level; it may also add value to the subjective experience with foods (Reinoso-Carvalho, Touhafi, et al., 2017; Reinoso-Carvalho, Gunn, Horst, et al., 2020; Reinoso-Carvalho, Gunn, Molina, et al., 2020; Swahn & Nilsen, 2023). Intriguingly enough, the field has not consistently responded to the issue of sugar reduction. For the most part, it has remained unclear whether what we know so far is bound to the narrow group of food types covered in the existing research or if they somehow express a more universal truth about audition and taste.

Envisioning the full potential of sonic seasoning research requires us to take a comprehensive look at the scientific evidence accumulated thus far. That was the ambition of the first study in this research package, consisting of a systematic examination of sound-taste research (Guedes, Garrido, Lamy, Cavalheiro, et al., 2023). This systematic review provided an up-to-date perspective on an expanding body of literature and allowed us to identify the various ways in which sounds and tastes have been associated, as well as the perceptual implications of being exposed to different auditory conditions during eating. The review was organized around three main focal topics within crossmodal correspondences, namely, the associations between tastes and (a) sound frequency (pitch) and specific classes of musical instruments; (b) sounds associated with speech production, as well as specific words and nonwords; and (c) more complex musical stimuli. Research on the implications of audition for taste perception has dealt mostly with exposure to musical stimuli during consumption, while a smaller subset of studies dealt with the consequences of exposure to different soundscapes (e.g., naturalistic sounds) or background noises. Overall, this review shows just how diverse and eclectic the literature is from a theoretical and methodological standpoint. However, the findings were also revealing of general trends and outstanding issues that may inspire future empirical inquiry.

Much of what is currently known about sonic seasoning has its origins in research with musical stimuli. The fact that music has attracted particular attention should come as no surprise. Unlike other categories of sounds, music has the ability to communicate concepts and emotions in abstract terms (Juslin, 2013; Zatorre & Salimpoor, 2013). It also differs from other forms of artistic expression, such as the visual arts, in that the communication of meaning through music does not epitomize itself to propositional content but rather to musical features and acoustic properties (Koelsch et al., 2004). Accordingly, early studies of music-taste associations have dealt with how variations in parameters like pitch, loudness, or articulation can contribute to evoke taste associations (Crisinel & Spence, 2009, 2010b, 2010a; Mesz et al., 2011, 2012).

Understanding what makes up a sweet or a salty soundtrack, although interesting in itself, was key to unveiling more encompassing principles about the nature of multisensory perception. The experimental research that followed revealed how the thoughtful combination of music and tastes can result in surprising effects on the eating experience (e.g., Crisinel et al., 2012; Reinoso-Carvalho et al., 2015, 2016). The encouraging findings of these early experiments inspired scientists and sound designers to develop novel soundtracks that aimed at musically mimicking the taste attributes we so far only knew how to experience with the mouth (Wang et al., 2015). Later research demonstrated that emotions also played a role in sonic seasoning. After all, emotional expression and experience are the *raison d'être* of music creation and fruition (Juslin & Västfjäll, 2008). Several studies now show that music selected based on valence or personal preference can also impact the evaluation of the tastes of foods, as well as their hedonic value (Kantono et al., 2016, 2019; Reinoso-Carvalho et al., 2019). Taken together, these findings suggest that a picture of sonic seasoning will not be complete without considering the intricate interplay between cross-modality and affect.

As such, the second output of this project sought to investigate the crossmodal and emotional associations in musical stimuli (Guedes, Prada, Garrido, & Lamy, 2023). The primary contribution of this study was of a methodological nature: it aimed to provide future empirical investigations with sound data for selecting the best auditory stimuli. In a rapidly evolving field of inquiry, scientific productivity often comes at the cost of fragmentation. In other words, what we know about music-taste associations results from a collection of empirical pieces differing in important procedural elements, including settings, participants, stimuli, and measures. Norming studies are one way to address this issue, as they allow comparing stimuli evaluated under equivalent conditions. Moreover, in the singular case of crossmodal research, it makes empirical decisions easier and more robust, as it allows the simultaneous weighing of basic taste correspondences and emotional/affective variables.

This possibility was key for designing and implementing the set of experiments that followed. Moreover, the comprehensive overview of sound-taste research emerging from the systematic review allowed us to identify literature gaps and empirical challenges with relevance to the study of sweet taste perception. One of these questions concerns the aspects of taste perception that might be liable to the influence of music. As the literature mentioned so far suggests, most of the studies in the sonic seasoning literature have dealt with the modulation of perceived taste intensity. In the first paper presented in Chapter 3, we sought to investigate whether sound may affect taste sensitivity as well (Guedes, Prada, Garrido, Caeiro, et al., 2023). This study found that listening to sweet music did not cue participants to detect sweet taste earlier in a taste sensitivity task using aqueous solutions. Put differently, the recognition thresholds for sweet taste did not change significantly between the high-sweetness music, low-sweetness music, and silence conditions. Although it could be tempting to dismiss the role of audition in sweet taste sensitivity altogether, one intriguing finding emerged from this experiment. In the near-threshold solution (one that is close to the sucrose level at which most individuals are able to recognize a sweet taste sensation), there was a higher proportion of participants reporting having detected a sweet taste sensation.

One putative explanation for this result is that sweet music might have contributed to solving a perceptual ambiguity. In other words, in an ambivalent solution (where sweetness is neither clearly absent nor easily detectable), music may cue some participants toward correctly recognizing the sweet taste. If that is the case, these findings may be interpreted as reinforcing the subtle nature of the sonic influences in taste perception. Moreover, the fact that similar results have been reported with extrinsic visual and semantic cues (Liang et al., 2013, 2016) suggests that the extent to which multisensory influences shape sweet taste sensitivity might depend on whether these factors pertain to the foods themselves (i.e., intrinsic) or the external environment (i.e., extrinsic; Wang et al., 2019). This aspect holds particular relevance in the case of audition since most research deals with extrinsic sensory information. While it is challenging to imagine how taste sensations may be translated into food sounds, perhaps one solution could involve manipulating auditory cues indirectly linked with sweetness (e.g., softness/hardness; Reinoso-Carvalho, Wang, et al., 2017), akin to previous experiments targeting the sounds of foods and drinks, such as those of crispiness (Zampini & Spence, 2004) or carbonation (Zampini & Spence, 2005).

As already mentioned, the finding that sounds and tastes can be matched consistently has raised interest in the perceptual consequences of these interactions for taste perception/evaluation. Intriguingly, the same has not occurred for sound evaluation. In the second paper presented in Chapter 3, we further investigated the implications of sound-taste interactions by examining the influence of listening to a sweet (vs. bitter) soundtrack on the sensory evaluation of a bittersweet chocolate as well as the influence of tasting a sweet (vs. bitter) chocolate on the evaluation of a bittersweet soundtrack (Guedes, Prada, Lamy, & Garrido, 2023a). This study showed, presumably for the first time, that gustation can influence the evaluation of crossmodal and emotional attributes of music. Second, it showed that music could shift the evaluation of chocolate in a congruent direction, albeit only when the two soundtracks (sweet and bitter) were presented to participants (i.e., in a within-participants design). Although it has been hypothesized that contrast between sound stimuli (such as that between sweet and bitter music) could be a relevant condition for sonic seasoning effects to emerge, there is scarce empirical support to back this claim for two main reasons. First, there are still few studies manipulating music conditions between participants (as shown in the systematic review presented in Chapter 2; see Guedes, Garrido, et al., 2023). Second, these studies were rarely performed under comparable conditions, for example, using the same auditory and gustatory stimuli or recurring to equivalent samples (e.g., in terms of sociodemographic characteristics).

The two first papers in Chapter 3 sought to expand the boundaries of sonic seasoning by exploring new ways by which sound-taste correspondences impact the evaluation of stimuli across the two sensory modalities. Yet, the question of why these changes occur remains not entirely understood. To date, the extent to which crossmodal correspondences simply reflect judgments in terms of affective evaluation (i.e., judging a sound as sweet merely because it is pleasant) has remained unknown. From the perspective of sonic seasoning research, this entanglement is also problematic since it is not entirely clear whether differences in taste evaluation are driven specifically by the crossmodal attributes of music. Instead, the extent to which participants enjoy the music they are listening to and/or its effects on mood may also exert influence over how tastes are evaluated (Reinoso-Carvalho et al., 2019).

Although this is not a novel problem per se, only recently has it become the subject of empirical attention. Notably, two large-sample studies compared for the first time the effects of music selected based on crossmodal correspondences[11] versus that of music with contrasting emotional effects (Reinoso-Carvalho, Gunn, Horst, et al., 2020; Reinoso-Carvalho, Gunn, Molina, et al., 2020). These studies gave a significant step forward in tackling this important theoretical issue. However, the authors noted that the possibility that emotions were also being triggered by the crossmodally-congruent music somewhat hindered the ability to draw definitive conclusions regarding the isolated role of cross-modality and affect.

In the last paper of Chapter 3, we presented one study dedicated to the issue of the entanglement between cross-modality and affect (Guedes, Garrido, Lamy, & Prada, 2023). Across two experiments, we evaluated the impact of music varying in the degree of sweetness associations (Experiment 1) and valence (Experiment 2). This study differed from previous research in two important respects. First, the choice of stimuli simultaneously considered the two evaluative dimensions a priori. In other words, the choice of a high (vs. low) sweetness pair of soundtracks took into account the valence ratings (and vice-versa). Second, the choice of

[11] It might be worth mentioning that the two crossmodal soundtracks in this study were previously validated as corresponding with softness and hardness, respectively. Their association with taste comes from one study reporting an effect of the smooth soundtrack in improving sweetness in chocolate (Reinoso-Carvalho, Wang, et al., 2017).

stimuli reflected an effort to keep the putative confounding dimension as constant as possible. Having followed this path, the results were somewhat surprising in that crossmodal music indeed shaped the evaluation of the sweet taste and the hedonic evaluation of foods in the expected direction, but music selected based on affective criteria did not.

While, at first glance, these findings may seem at odds with what has been reported in the literature thus far, the apparently conflicting results may say more about the differences in methodological practices in the field than about the nature of its object of study. In truth, despite the valuable efforts to disentangle the effects of crossmodal attributes from those of valence, this question will require further investigation and novel methodological approaches. This question is undoubtedly relevant on theoretical grounds, but there are also practical motivations to inquire further. If one seeks to make use of multisensory strategies to improve sweet taste perception, it is relevant to ascertain precisely what attributes should be looked for in music. If affective dimensions, such as valence, prove to be the primary determinant of change in taste evaluation, more attention should be devoted to classifying stimuli based on attributes like mood, genres, styles, or even personal preferences. Instead, if sonic seasoning is mostly a result of the crossmodal mappings between the senses, then the focus of attention should lie on these associative regularities and their relationship with acoustic and musical parameters.

In the case of sweetness perception, it seems plausible that a combination of crossmodal and affective ingredients would achieve the desired modulatory outcomes. That seems to be the case in the paper presented in Chapter 4. This experiment explored the implications of presenting soundtracks with contrasting sweetness (high vs. low) levels and positive valence[12] (Guedes, Prada, Lamy, & Garrido, 2023b). The results showed, once again, that music selected based on crossmodal correspondences can indeed enhance sweet taste perception. Interestingly, this effect was observed not only in sensory terms but also in hedonic measures (e.g., liking). One of the main contributions of this paper was to show that these effects held irrespective of foods' sugar contents, including vegetables with low sweetness and 0% sugar cookies. That was a novel contribution to a body of literature where, as previously mentioned, most experiments have focused on highly palatable foods and drinks (e.g., chocolate, wine). From a public health perspective, these findings advise us to ponder more carefully the role of sound, and particularly music, in promoting healthier eating. However, we must be cautious before announcing music as the best new sweetener in the market. The effects of music are rather

[12] Both excerpts were scored "High" in valence in the norming study (Guedes, Prada, Garrido, & Lamy, 2023).

subtle and possibly negligible in real-world settings if presented in isolation. Put differently, playing a sweet tune by the coffee table is hardly the same as adding a spoonful of sugar. Yet, these findings suggest that music can make a difference for better or for worse, and we should know enough to make sure that it is for better.

1. General considerations and suggestions for future research

Based on this short synthesis of the main findings of the current research project, three main research objectives emerge, which advise further critical analysis: i) synthesizing and integrating the accumulated evidence: identifying research challenges and potential avenues for future inquiry, ii) examining the role of emotion in sound-taste associations and sonic "sweetening"; and iii) exploring the applicability of music to enhance sweet taste perception and improve the acceptance of products with lower sugar contents.

1.1. The past and future of sound-taste research

One of the pivotal goals of this research project was to offer a comprehensive outlook on the literature on sound-taste interactions. This entailed looking at research on crossmodal correspondences, as well as on sonic seasoning studies. The systematic review that resulted from this ambition depicted a field of inquiry in frank expansion, which is expressed not only by an increment in empirical prolificity throughout the last decade but also by the diversification of theoretical and methodological approaches. Although the field has had several moments of self-scrutiny and reflection in narrative reviews that have been released throughout the years (Knöferle & Spence, 2012; Reinoso-Carvalho, Touhafi, et al., 2017; Spence, 2016; Spence et al., 2019b), it had not yet had a systematic examination of the literature following a pre-registered protocol. The advantages of following this approach include the more encompassing and exhaustive approach to data collection as well as the diminished liability to selection biases. However, one should not overstate the implications of such a review as it is also quite possibly blind to null or negative results that might be resting in university drawers worldwide. Crucially, the field still lacks in-depth systematic examinations of more specific research questions, which in the future should include elements of quantitative synthesis, namely, meta-analyses.

An additional shortcoming of this review is that it was able to produce only a superficial skimming of underlying theories and conceptual hypotheses. The majority of the reviewed literature did not explicitly address theoretical questions, although some could be seen as aligning with conceptual frameworks that have been proposed in the past (Knöferle & Spence, 2012; Wang, 2017). Put differently, more attention appears to have been devoted to understanding “what” and “how” tastes and sounds interweave than to “why” these interactions occur. From that perspective, it seems critical to encourage a more sustained theoretical dialogue and incentivize the explicit examination of competing hypotheses.

1.2. A role for emotion and affect in sound-taste interactions

One of the most enduring challenges in sound-taste literature concerns the role of emotion and affect in explaining crossmodal correspondences and sonic seasoning. The norming study presented here showed that affective dimensions are highly associated with taste correspondences, particularly sweetness and bitterness (the former with positive and the latter with negative emotions/affective dimensions). The fact that both (taste and emotional/affective) dimensions show a fair degree of overlap even when evaluated across a large set of stimuli suggests this is a rather pervasive association. Importantly, this overlap leaves doubts regarding whether sonic seasoning relies simply on the crossmodal associations between sounds and tastes or rather on changes in mood or emotion.

The study presented in Chapter 3 provides only a partial answer to this question (Guedes, Garrido, Lamy, & Prada, 2023). While music selected based on crossmodal criteria seemed to have a more pronounced effect on the sensory and hedonic evaluation of foods, the experimental design suffered from two main limitations. First, fully disentangling cross-modality and affect would seem to require an orthogonal relationship between the two dimensions. Yet, to date, it has not been possible to simultaneously convey high sweetness and negative valence in one musical stimulus. Second, the fact that the two experiments relied on pairs of contrasting stimuli (e.g., high vs. low sweetness) makes it difficult to ascertain whether the observed differences emerge due to an enhancing effect of the high sweetness music, a dampening effect of the low sweetness music, or both.

Relevant to this discussion, the findings of Guedes, Prada, Lamy, and Garrido (2023; see Chapter 3) showed that the contrast between sweet and bitter soundtracks was critical to the sonic seasoning effect. Given the predominance of within-participants experiments in the literature (Guedes, Garrido, Lamy, Cavalheiro, et al., 2023), it remains unknown if the mere presence of congruent music has a meaningful contribution to enhancing taste perception. If contrast is indeed a necessary condition for this end, it could represent a significant disadvantage of auditory stimuli in the applied domain. Crucially, it could be said that sonic seasoning is more of a methodological artifact than an effective multisensory cue to improve taste perception in real-world situations.

At the current time, a definitive conclusion in this regard seems not within our reach. For example, a recent study demonstrated that music significantly influenced the sensory evaluation of chocolate even in a between-participants setting (Reinoso-Carvalho, Gunn, Horst, et al., 2020). Interestingly, this effect occurred more prominently for music that evoked a combination of emotional and crossmodal attributes. It would thus seem plausible that seasoning effects may depend on characteristics of the music under analysis, where the balance between emotional/affective and crossmodal attributes might hold particular significance. Furthermore, this interpretation also cautions against any excessive generalization from individual stimuli to a broader class of music sharing only limited similarities. It could be relevant to examine, for instance, whether contrast is as relevant for emotional/affective music as it is for music selected based on crossmodal attributes. Moreover, it is also possible that the effect of music may also depend on the fit with the characteristics of the food/drink. Notably, participants may respond more positively to a harmonious crossmodal pairing (Spence & Di Stefano, 2022), a combination that feels more appropriate to an eating/drinking situation (Wilson, 2003), or one that promotes feelings of multisensory fluency (Knöferle & Spence, 2021).

2. Implications and applications of sonic ‘sweetening’: Healthy eating and sugar consumption

The literature on multisensory taste/flavor perception has inspired several gastronomic, artistic, and marketing initiatives intending to create novel and engaging experiences for consumers (Reinoso-Carvalho, Touhafi, et al., 2017; Spence et al., 2021). In the case of audition, this has included live performances and digital experiences where ingredients are tasted alongside matching music (Thompson-Bell et al., 2021) or commercial products like chocolate boxes containing also a CD with customized soundtracks (The Sound of Flavour, 2016). Besides its role in experience design, sound may be an important part of better eating as one that promotes better overall nutrition and health.

Most people seem unaware of the impact of soundscapes in the places where eating occurs. Yet, there is accumulating evidence showing that the sound atmosphere of places like restaurants, cafés or canteens can have significant consequences for food choice processes and consumption behaviors (Cui et al., 2021; Kaiser et al., 2016; McElrea & Standing, 1992; North et al., 1997; North & Hargreaves, 1998; Novak et al., 2010; Roballey et al., 1985; Stroebele & de Castro, 2006). In the case of perception, there are concerns that noise may have detrimental effects on how foods are perceived, particularly for the sweet taste (Woods et al., 2011; Yan & Dando, 2015). One possible consequence of this scenario may be that individuals may try to compensate for this sensory loss by increasing sugar intake (e.g., adding more sugar to the coffee). Conversely, if it proves possible to shape the auditory contexts to improve sweet taste perception, one could hope to achieve the opposite effect, that is, a reduction of sugar intake and potentially facilitating the acceptance of lower-sugar alternatives.

This possibility has been explored in some of the studies presented here with preliminary yet encouraging results (Guedes, Garrido, Lamy, & Prada, 2023; Guedes, Prada, Lamy, & Garrido, 2023b). In these experiments, sweet music improved the evaluation of products with different sugar contents and nutritional characteristics, making them appear sweeter but also more appealing. Although more research will be needed to examine the feasibility of similar interventions in real-world settings (for instance, see Lowe et al., 2018), it is possible to imagine that shifting from a noisy canteen environment to one with a pleasant and crossmodally congruent sonic atmosphere may improve not only sensory perception but the overall eating experience.

There are possibly other interesting sweetening applications for music that lie beyond the atmospherics of collective meal contexts. Among the initiatives that have been developed so far, one may mention, for instance, the "Sonic Sweetener" - a coffee cup with an embedded audio device that presents itself as a creative solution to reduce sugar consumption (Blecken, 2017) and a tableware collection ("Beyond Taste") that includes a dessert plate that reproduces music emulating sweet taste sensations (Hahn, 2020). With the ubiquity of personal digital devices, it might soon also be possible to access dedicated apps or curated playlists in mainstream platforms that may aid in reducing sugar intake. Artificial intelligence may possibly improve these solutions to also incorporate personal preferences alongside more general sonic seasoning principles. While digital experimentation surrounding multisensory perception is gaining momentum (for a review, see Spence et al., 2021), innovation in this domain should result not only from creative exploration but also from a solid ground of empirical research. Hopefully, one of the contributions of the present work may be not only to advance our understanding of the multisensory interactions between audition and taste but also to inform future practical applications with real value to the quality of eating habits.

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Appendix A

Supplementary Table A1. *Evaluations (Means and Standard Deviations) in Each Dimension for Online and Laboratory Samples, Along with Mean Difference Test Results*

Paper 2: The Taste & Affect Music Database: Subjective Rating Norms for a New Set of Musical Stimuli

	Online (n = 83)		Laboratory (n = 83)		Comparison	
Dimension	*M*	*SD*	*M*	*SD*	$t(164)$	*p*
Sweetness	7.98	2.79	7.99	2.40	0.03	.976
Bitterness	6.22	2.18	6.37	2.08	0.47	.636
Sourness	5.06	2.04	4.80	1.97	0.85	.395
Saltiness	5.75	2.42	5.84	2.32	0.26	.794
Joy	3.19	0.70	3.16	0.66	0.23	.817
Sadness	2.60	0.59	2.48	0.68	1.18	.238
Surprise	3.01	1.04	3.13	0.95	0.74	.459
Fear	2.46	0.77	2.33	0.59	1.18	.241
Angry	2.14	0.72	2.06	0.59	0.80	.422
Valence (P)	4.27	0.67	4.45	0.58	1.82	.071
Arousal (P)	4.12	0.74	4.06	0.81	0.56	.574
Familiarity	4.00	0.94	3.95	1.02	0.31	.756
Valence (F)	4.46	0.54	4.58	0.48	1.50	.135
Arousal (F)	3.89	0.55	3.89	0.47	0.10	.918

Note. P = Perceived. F = Felt

The results presented here were calculated by comparing the laboratory sample (n = 83) with a random subsample (n = 83) of online participants, balanced for age and gender

Supplementary Table A2. *Evaluations (Means and Standard Deviations) in Each Dimension for the Total Sample, Males, and Females, Along with Mean Difference Test Results*

Paper 2: The Taste & Affect Music Database: Subjective Rating Norms for a New Set of Musical Stimuli

	Total sample (N = 329)		Men (n = 53)		Women (n = 274)		Comparison	
Dimension	*M*	*SD*	*M*	*SD*	*M*	*SD*	$t(325)$	*p*
Sweetness	8.09*	2.77	8.62	2.88	7.94	2.67	1.68	.095
Bitterness	6.06	2.31	6.13	1.97	6.05	2.37	0.23	.815
Sourness	5.05*	2.19	4.81	2.09	5.12	2.20	0.94	.346
Saltiness	5.80*	2.32	5.43	2.05	5.89	2.36	1.31	.193
Joy	3.25*	0.69	3.40	0.70	3.21	0.68	1.88	.062
Sadness	2.68*	0.63	2.82	0.58	2.66	0.64	1.76	.080
Surprise	3.26*	0.98	3.56	0.95	3.20	0.98	2.43	.016
Fear	2.46*	0.74	2.61	0.79	2.44	0.72	1.56	.121
Angry	2.16*	0.68	2.27	0.69	2.14	0.68	1.22	.223
Valence (P)	4.38*	0.66	4.49	0.71	4.35	0.65	1.43	.153
Arousal (P)	4.23*	0.78	4.27	0.57	4.22	0.82	0.47	.642
Familiarity	4.03	0.98	4.25	1.09	3.98	0.95	1.82	.069
Valence (F)	4.51*	0.57	4.48	0.55	4.52	0.57	0.41	.683
Arousal (F)	3.91*	0.56	3.99	0.57	3.90	0.55	1.09	.276

Note. P = Perceived; F = Felt.
* Indicates a significant difference from the scale midpoint ($p < .050$), based on one-sample *t*-tests. For the basic taste variables, differences were calculated against the total number of items divided by the number of tastes (25/4 = 6.25)

Supplementary Table B1. *Percentage of Taste Detection and Sweet Taste Recognition for Each Sucrose Concentration in the High Sweetness, Low Sweetness, and Silence Conditions,*

Paper 3: Sensitive to Music? Examining the Crossmodal Effect of Audition on Sweet Taste Sensitivity

	Taste detection			Taste recognition		
	HS	LS	S	HS	LS	S
1 (0.00 g/L)	46.6%	39.7%	42.5%	5.48%	0.00%	1.37%
2 (0.55 g/L)	45.2%	49.3%	50.7%	1.37%	4.11%	6.85%
3 (0.94 g/L)	43.8%	42.5%	53.4%	5.48%	2.74%	5.48%
4 (1.56 g/L)	56.2%	53.4%	54.8%	5.48%	4.11%	6.85%
5 (2.59 g/L)	69.9%	58.9%	65.8%	23.29%	10.96%	10.96%
6 (4.32 g/L)	74.0%	74.0%	75.3%	31.51%	27.40%	20.55%
7 (7.20 g/L)	93.2%	93.2%	95.9%	64.38%	67.12%	64.38%
8 (12.0 g/L)	95.9%	98.6%	100.0%	89.04%	83.56%	87.67%
9 (20.0 g/L)	100.0%	100.0%	100.0%	93.15%	97.26%	97.26%

Note. HS = High sweetness (soundtrack); LS = Low sweetness (soundtrack); S = Silence

Supplementary Table C1. *Sociodemographic and Anthropometric Characteristics of Samples in Experiments 1a, 1b, and 2*

Paper 4: Bidirectionality in multisensory perception: Examining the Mutual Influences Between Audition and Taste

	Experiment 1a	Experiment 1b	Experiment 2
N			
Total	119	68	106
Condition 1 (sweet)[a]	61	68	54
Condition 2 (bitter)[b]	58	68	52
Age Mean (SD)	21.1 (4.9)	22.5 (5.7)	26.2 (10.3)
Sex			
Women	99 (83%)	52 (76%)	69 (65%)
Men	19 (16%)	16 (24%)	34 (32%)
Non-binary	1 (1%)	0	3 (3%)
BMI[c]			
Underweight (< 18.5 kg/m^2)	17 (15%)	2 (3%)	12 (11%)
Normoponderal (18.5 - 24.9 kg/m^2)	75 (67%)	50 (76%)	69 (66%)
Overweight or obese (> 25 kg/m^2)	20 (18%)	14 (21%)	24 (23%)

[a] Sweet music condition in Experiments 1a and 1b, sweet taste (milk chocolate) condition in Experiment 2.

[b] Bitter music condition in Experiments 1a and 1b, bitter taste (dark chocolate) condition in Experiment 2.

[c] Weight and Height were non-mandatory items. BMI was calculated only for complete responses (*N* = 112 in Experiment 1a; *N* = 66 in Experiment 1b; *N* = 105 in Experiment 2).

Supplementary Table D1. *Description of Auditory Stimuli (Guedes, Prada, Garrido, et al., 2023)*

Paper 5: Disentangling Cross-Modality and Affect in "Sonic Seasoning": The Effect of Music Associated with Different Degrees of Sweetness and Valence on Food Perception

Stimulus id	Title / Author
7	When You Believe / Miles Avida
11	What We Used to Know / Farrell Wooten
24	Rain and Wind / Medité
27	Destiny Rising / FormantX
44	Tell Me Something New (Tigerblood Jewel Remix) (Instrumental Version) / Wellmess feat. Tigerblood Jewel
57	A Soothing Breeze / Josef Bel Habib
58	Fruity Juice / Jerry Lacey
88	Balkan Wishes / Trabant 33

Note. The full norming data is available in Guedes, Prada, Garrido, et al. (2023) at https://doi.org/10.3758/s13428-022-01862-z

Supplementary Table D2. *Description of Food Stimuli (Blechert et al., 2019)*

Paper 5: Disentangling Cross-Modality and Affect in "Sonic Seasoning": The Effect of Music Associated with Different Degrees of Sweetness and Valence on Food Perception

Stimulus id	Description
14	Muffin
16	Pancakes
41	Donut with chocolate sprinkles
148	Round shortbread cookies
167	Some bars of chocolate (stacked)
254	Figs
255	Pomegranate
267	Cucumber with slices
290	Bars of white chocolate
294	Popcorn
296	Colored chocolate beans
339	Wine gum
341	Banana
351	Croissant
361	Carrots, cooked
365	Orange
413	Kiwis
424	Peas cooked
460	Tomato
466	Green apple
479	Papaya
504	Shortbread
525	Walnut
539	Almonds

Note. The full norming data is available in Blechert et al. (2019) at https://doi.org/10.3389/fpsyg.2019.00307

Supplementary Table D3. *Descriptive Statistics of the Evaluation of Musical Stimuli (N = 43)*

Paper 5: Disentangling Cross-Modality and Affect in “Sonic Seasoning”: The Effect of Music Associated with Different Degrees of Sweetness and Valence on Food Perception

	Valence		Arousal		Sweetness	
Stimulus	*M*	*SD*	*M*	*SD*	*M*	*SD*
7	5.74	2.36	5.02	2.31	5.12	2.60
11	5.86	2.33	5.26	2.42	5.19	2.57
24	6.60	1.84	5.58	2.22	6.42	2.28
27	5.37	2.24	5.77	1.99	4.98	2.42
44	6.19	2.15	6.09	2.04	5.28	2.39
57	6.74	1.85	5.49	2.34	6.77	2.10
58	6.81	2.12	5.67	2.07	7.09	1.97
88	6.56	2.05	5.93	2.00	5.72	2.11

Supplementary Table D4. *Descriptive Statistics of the Evaluation of Food Stimuli Presented Visually (N = 43)*

Paper 5: Disentangling Cross-Modality and Affect in “Sonic Seasoning”: The Effect of Music Associated with Different Degrees of Sweetness and Valence on Food Perception

		Healthiness		Sweetness	
	Stimulus	*M*	*SD*	*M*	*SD*
14	Muffin	5.51	1.58	6.35	1.72
16	Pancakes	5.63	2.41	7.37	1.79
41	Donut with chocolate sprinkles	5.21	2.57	7.58	1.76
148	Round shortbread cookies	5.63	2.18	6.42	1.65
167	Some bars of chocolate (stacked)	5.53	2.18	7.77	1.27
254	Figs	7.44	1.75	6.58	1.79
255	Pomegranate	8.05	1.60	7.26	1.57
267	Cucumber with slices	7.60	1.73	4.21	2.43
290	Bars of white chocolate	5.16	2.32	7.51	1.92
294	Popcorn	5.84	1.90	4.60	2.39
296	Colored chocolate beans	4.84	2.52	7.16	1.94
339	Wine gum	5.02	2.59	7.56	1.59
341	Banana	8.00	1.41	6.74	1.59
351	Croissant	5.86	1.77	5.33	2.02
361	Carrots, cooked	7.95	1.34	5.67	2.07
365	Orange	8.05	1.51	6.84	1.79
413	Kiwis	7.12	2.07	6.35	1.65
424	Peas cooked	7.79	1.34	4.86	2.41
460	Tomato	7.93	1.52	5.19	2.74
466	Green apple	7.91	1.52	6.72	1.71
479	Papaya	7.93	1.68	6.74	2.28
504	Shortbread	5.98	2.10	6.21	2.04
510	Chocolate bar, broken	5.07	2.63	7.53	1.83
539	Almonds	7.65	2.16	5.00	2.75