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Tasty Vibes: Uncovering Crossmodal Correspondences Between Tactile Vibrations and Basic Tastes

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Abstract

The interest in crossmodal correspondences individually involving the sense of touch and taste has grown rapidly in the last few decades. Several correspondences involving different tactile dimensions (e.g., hardness/softness, roughness/smoothness) have been uncovered, such as those between sweetness and softness and between roughness and sourness. However, a dimension that has been long overlooked, despite its pervasiveness and importance in everyday experiences, relates to tactile vibrations. The present study aimed to fill this gap and investigate crossmodal correspondences between basic tastes and vibrations. In the present study (N = 72), we uncovered these associations by having participants sampling basic taste (i.e., sweet, salty, sour, bitter, umami) aqueous solutions and chose the frequency of vibrations, delivered via a consumer-grade subwoofer wristband on their dominant hand, that they most strongly associated with each taste. We found that sourness was most strongly associated with frequencies around 98 Hz, and that sweetness and umami were associated with frequencies around 77 Hz. These correspondences may, to different extents, be based on affective and semantic mechanisms. The findings have relevant implications for theoretical research on multisensory integration and perception and the potential future applications of these associations, through wearable technologies, to enhance eating experiences and promote healthier eating habits.

Keywords: crossmodal correspondences, vibrations, touch, frequency, basic tastes, affect, semantic.

1. Introduction

In the last few decades, the interest in crossmodal correspondences from both researchers and practitioners has experienced rapid growth, in part because of their role in multisensory integration and hence how people make sense of the world (Spence, 2022a). Two types of crossmodal correspondences that have received a great deal of attention are those based on the sensory modality of touch (Spence, 2020) and those involving gustation. Touch is the submodality of the somatosensory system that encompasses the sensations of pressure, vibration, and texture (McGlone & Reilly, 2010). Touch is critical for how individuals interact with the world, as it provides a great deal of information about objects in the environment with which individuals physically interact, such as their microgeometry (Bergmann Tiest, 2010; Lieber & Bensmaia, 2022). Many crossmodal correspondences involving touch have been uncovered, and they include dimensions like weight (Walker et al., 2017), hardness/softness (Ludwig & Simner, 2013; Slobodenyuk et al., 2015; Steer et al., 2023), roughness/smoothness (Hamilton-Fletcher et al., 2018; Slobodenyuk et al., 2015; Speed et al., 2021), temperature (Wang & Spence, 2017), and temperature concepts (Barbosa Escobar et al., 2023b). In addition, researchers have investigated different crossmodal correspondences between tastes and tactile properties (e.g., Pistolas & Wagemans, 2023; Slocombe et al., 2016; Van Rompay & Groothedde, 2019). For example, Pistolas and Wagemans (2023) found consistent associations between sweetness and softness. Nevertheless, a tactile dimension that has been understudied relates to vibrations, despite its importance and pervasiveness in the interaction with the world. Although often overlooked, vibrotactile stimuli are a pervasive part of the everyday life, from the experience of touching objects and interacting with living beings to the vibratory alerts from phones and wearables (Delazio et al., 2017). To the best of our knowledge, only a limited number of correspondences involving vibrotactile stimuli have been uncovered, namely associations between colors and vibrations (Delazio et al., 2017). The latter authors found that vibrations at 10, 20, and 35 Hz were associated with violet hues at low amplitudes (10 and 20 dB) and with red hues at high amplitudes (30 and 40 dB), whereas vibrations at 60, 120, and 200 Hz were mostly associated with green hues at low and high amplitudes (10, 20, 30, 40 dB).

The present study aimed to fill the abovementioned gap in academic literature and investigate crossmodal correspondences between tactile vibrations and basic tastes. To this end, we conducted an experiment in which participants found vibrotactile frequencies that they associated with different basic taste stimuli. We used a consumer-grade subwoofer wristband to convert auditory pure tones in the low frequency (i.e., 10–250 Hz) range into vibrotactile feedback. Participants searched for a frequency that they intuitively associated with each of various aqueous basic taste solutions. Our research contributes to the literature on crossmodal correspondences by uncovering a novel set of associations related to the understudied dimension of vibrotactile information. Moreover, it can spur further investigation as to whether touch and gustation are more tightly connected than previously thought.

2. Theoretical Background

Sound and touch are tightly linked given that waves moving through a medium like air can be felt both auditorily through the ears and tactually via vibrations in the skin (Verrillo, 1992). For instance, sound waves in the low frequency range (0–200 Hz; Beveridge et al., 2022) generate the most pronounced sensations of vibrations, which can be commonly experienced as the bass in concerts. In addition, physical stimuli, in direct contact with the skin, vibrating at frequencies in the low range, generate increased tactile sensations. Furthermore, the perception of vibrations and sounds can overlap at low frequencies, and fundamental properties of sound (e.g., frequency) are correlated to perceptual factors of sounds (e.g., pitch; Merchel & Altinsoy, 2020). Thus, considering the connection between the auditory and tactile perception of waves, there may be parallels between the associations studied here and those involving basic tastes and different auditory features such as pitch (Knöferle & Spence, 2012; Wang et al., 2015, 2016), which may elucidate the direction of potential associations between vibrations and basic tastes. Using tones corresponding to 19 different keys of a MIDI keyboard and tastants corresponding to the five basic tastes, each at three levels of concentration, Wang et al. (2016) found that taste quality, but not concentration level, significantly influenced the pitch associated with the different basic tastes. Overall, the latter authors found that the frequency of tones associated with sourness was the highest, followed by the frequencies associated with sweetness. In turn, the frequency of tones associated with bitterness was the lowest. Importantly, the authors found that these associations are somewhat influenced by perceived intensity and that they may be mediated by valence. In addition, as the authors argued, sound–pitch correspondences may be matched based on semantic mappings.

The physical and perceptual link between the auditory and tactile perception of waves suggests that the literature on sound–taste associations can inform the haptic–taste associations studied here and their potential underlying mechanisms. The literature thus far has identified four theoretical accounts that may underpin the existence of crossmodal correspondences, namely the structural, statistical, lexical, and affective mediation accounts (Spence, 2011, 2020, 2022a). Both the affective mediation and the lexical accounts may explain potential associations between vibrations and basic tastes based on shared affect and terms to describe sensory experiences in these dimensions.

2.1. Affective Mediation Account

The affective mediation account of crossmodal correspondences poses that pairs of dimensions or stimuli may be matched together because they share affective associations, hedonic evaluations, or because they evoke congruent affective reactions (Collier, 1996; Spence, 2020; Whiteford et al., 2018). Affective reactions can be examined through the lens of the circumplex model (Russell,1980), which characterizes affective experiences in a three-dimensional space of valence, arousal, and dominance. Given that this model treats each of these dimensions orthogonally, it allows them to be analysed independently, but does not hinder analysing them interactively. The affective mediation account can help explain several correspondences involving different dimensions and stimuli, especially in the absence of statistical regularities in the environment that link pairs of stimuli (Spence, 2020). Related to auditory stimuli, individuals may match certain properties of sounds, such as pitch or timbre, to specific basic tastes based on shared affective evocations (e.g., Crisinel & Spence, 2009, 2010, 2012; Knöferle & Spence, 2012; Wang et al., 2016; see also Guedes et al., 2023, for a review between the senses of audition and taste). For example, people tend to associate the sound of piano with sweetness, whereas the sound of brass instruments tends to be associated with bitterness and sourness.

Based on the affective mediation account of crossmodal correspondences, it is possible that associations between tactile vibrations and basic tastes may arise because they can be matched based on shared affective sensations, as described by any of the three dimensions mentioned earlier (i.e., valence, arousal, and dominance). It is worth noting that analysing these dimensions independently is important, as some crossmodal correspondences may be mediated by some affective dimensions but not others (e.g., pitch – taste correspondences; Wang et al., 2016). Regarding the sense of taste, different basic tastes have been shown to evoke different affective and emotional responses, as measured by explicit ratings and by a battery of autonomic nervous system parameters (i.e., skin conductance, blood flow, temperature and heart rate; Rousmans, 2000), facial skin blood flow (Kashima & Hayashi, 2011), and skin conductance (Spinelli et al., 2023). Overall, sweetness evokes positive affective responses, whereas bitterness evokes negative ones. In terms of the tactile modality, touch is tightly linked to affect and pleasure through the somatosensory system. The "slow" touch system of the cutaneous submodality is responsible for encoding pleasant touch (Löken et al., 2009; McGlone & Reilly, 2010), generated especially by gentle stroking and sound vibrations (McGlone & Reilly, 2010). In addition, there is a direct link between touch and tactile vibrations. The interaction between the skin and the fine textural features of surfaces (at the nanometer scale) during tactile exploration causes the skin to deform, which generate vibrations that provide information about the texture being touched (Bensmaïa & Hollins, 2005; Grigorii et al., 2022; Klatzky & Lederman, 2010). Vibrotactile stimuli can generate specific affective responses. Relevant for the present study, previous research has investigated the relationship between different parameters of vibrotactile stimuli and affect (Akshita et al., 2015; Hasegawa et al., 2019; Seifi & MacLean, 2013; Wilson & Brewster, 2017; Yoo et al., 2015). For instance, using three levels of frequencies (i.e., 90, 200, and 300 Hz) Wilson and Brewster (2017) found a significant negative relationship between frequency and valence and a significant positive relationship between frequency and arousal. The findings of these literature have revealed a highly consistent positive effect of the frequency of vibrotactile stimuli on arousal. However, the findings related to the effect of frequency on valence are less consistent.

2.2. Lexical Account

The lexical account of crossmodal correspondences may also provide a basis for the origin of potential associations between vibrotactile frequencies and taste. This account suggests that some crossmodal correspondences may originate from the use of the same terms to describe different aspects of sensory experiences (see Martino & Marks, 1999, 2000, 2001). Following this, vibrations and basic tastes may be matched because people tend to use terms related to the tactile dimension to describe basic tastes. For instance, people commonly use words related to texture, such as smooth and sharp, to describe tastes (Burke, 2014). Indeed, Pistolas and Wagemans (2023) recently found consistent associations between sweetness and softness and between saltiness and crispiness. Hence, correspondences between tactile vibrations and tastes may also originate from the use of words such as sharp and soft to describe stimuli in both sensory dimensions.

Drawing on the parallels with crossmodal correspondences between auditory frequency and basic tastes, and the different affective and semantic factors presented earlier that demonstrate a close connection between touch and tastes, we expected to observe a similar pattern in the associations studied here as in the basic taste–pitch correspondences. More specifically, we expected the frequencies associated with sourness to be the highest, followed by those associated with sweetness and the ones associated with bitterness to be the lowest. Associations involving sweetness and bitterness may be driven by an affective account given their highly consistent affective evocations which can tie to the pleasantness of vibrations at specific frequencies. In addition, associations involving sweetness and sourness may have lexical underpinnings given the use of common words to describe both tastes and vibrotactile feedback.

3. Methods

3.1. Participants

The required sample size was determined via a power analysis based on a within-factor ANOVA using G*Power (Faul et al., 2007) for a statistical power of at least .80 using an effect size of Cohen's f = 0.15 with an alpha level of .05. The power calculation yielded a required sample size of 55 participants. A total of 72 individuals (52 females, 20 males), aged 18 – 42 years (M_{age} = 28.18 years, SD_{age} = 4.53) took part in the experiment. The participant pool consisted of students, staff, and visitors at the University of Copenhagen. Participants did not have professional tasting experience. They were required to have a normal sense of smell and taste, and to not eat or smoke 30 minutes prior to participating in the study. Participants received a bag of chocolate covered nuts, valued at DKK 60, for their participation. The experiments complied with the World Medical Association's Declaration of Helsinki, and it was approved by the University of Copenhagen's Research Ethics Committee, as institutional review board, under the case #504-0404/23-5000.

3.2. Apparatus and Materials

The basic taste stimuli consisted of water-based solutions of the different basic tastes (i.e., sweet, salty, sour, bitter, umami) with concentrations based on previous literature studying crossmodal correspondences between basic tastes and pitch (Wang et al., 2016). More specifically, the concentrations of the solutions for each basic taste were 138.80 g/L of sucrose (for sweet), 9.61 g/L of sodium chloride (for salty), 2.40 of citric acid (for sour), 2.21 g/L of caffeine monohydrate (for bitter), and 44.95 g/L of monosodium glutamate monohydrate (for umami). The solutions were prepared with tap water and were served in 50 mL black plastic cups with approximately 20 mL of solution at 15 °C. Two replicates of each basic taste were prepared and presented to participants. Each sample had a label with randomly generated three-digit numeric code from 100 to 999. For each basic taste, the three-digit code of one of the replicates was above 500 while the other was below 500 in order to mitigate potential anchoring effects driven by the value of the codes.

The haptic stimuli consisted of tactile vibrations delivered through a commercial subwoofer wristband, Basslet (Lofelt, Germany). The wristband converts low-frequency sound signals into haptic feedback. It can produce vibrations within the frequency range of 10 to 250 Hz. Using an online pure tone generator (https://www.szynalski.com/tone-generator/), participants manipulated the frequency of the pure tone, which was reproduced as vibrotactile feedback by the wristband without generating any sound. The waveform used was a sinusoidal (sine) wave. The intensity of the vibrations was kept constant for all participants.

3.3. Procedure

The experiment was conducted in an experimental room kept at 21 °C. Participants sat at a table in front of a laptop to which the subwoofer wristband was connected. The experimental sessions comprised one participant at a time, and they responded to a questionnaire on the laptop. The experiment was programmed and conducted in Qualtrics (https://www.qualtrics.com/). Before beginning, participants provided their informed written consent to participate in the experiment. Then, they were asked to put on the wristband on their dominant hand as tight as comfortably possible, and later, they were presented with general instructions. Afterwards, participants were introduced to the pure tone generator and were asked to familiarize themselves with it by slowly moving a slider back and forth to adjust the frequency between 10 and 250 Hz. Participants were instructed to select frequencies between 10 and 250 Hz, inclusive. Subsequently, participants were instructed on how to taste the basic taste samples. More specifically, they were instructed to take a small sip from the cup and swirl the liquid around their mouth for a few seconds and then swallow. The instructions on how to taste the samples were presented again before each taste solution. After having read these instructions, participants began the experiment. The basic taste solutions were presented to participants all at once on a white tray. They tasted one sample at a time in random order prompted by the questionnaire, which indicated the three-digit code of the sample to take. Participants were first instructed to taste a sample and then adjust the slider in the pure tone generator to find the frequency of vibrations they felt best corresponded to the sample they had just tasted. The staring point of the pure tone generator's slider, either on the left-hand side at 1 Hz or on the right-hand side at 260 Hz (outside the reproducible range so they were not primed by any specific frequency from the beginning), was randomized for each sample. Participants typed the associated frequency in a text box in the questionnaire. Then, participants were asked why they chose the specific frequency, as a free-text response with no word or sentence limit. Specifically, the question was phrased as follows: "In a few words, explain why you selected this frequency." Next, they indicated what taste they just had from seven options (i.e., sweet, salty, sour, bitter, umami, metallic, and oleogustus). Metallic and oleogustus were added as distractors. Participants rinsed their mouth with water before tasting each sample. After tasting and evaluating all the samples, participants indicated their age and gender.

3.4. Data Analysis

All data processing and analyses were conducted in R (R Core Team, 2023). The data was first cleaned by removing data points below 10 and above 250 Hz, as this was the optimal working frequency range of the wristband. Moreover, frequencies equal to the three-digit code of the sample evaluated were removed, as this was an indication that participants did not perform the task conscientiously.

To analyse the frequency associated with the different basic tastes, a series of Generalized Linear Mixed Models (GLMMs) with Gamma distribution and identity link function were fitted to the data with frequency as dependent variable, as it better models data that is positively skewed and bounded on the left by zero. The GLMMs were performed using the *glmer* function of the {lme4} R package (Bates et al., 2015). As base model (M_1), the basic taste sampled was specified as fixed factor, and participant ID was specified as random effect. A second model (M_2) was specified adding a binary variable (i.e., Taste test) that indicated whether the participant correctly identified what basic taste they had was added as fixed effect to M_1. Furthermore, we specified a third model (M_3) adding age and gender as demographic covariates. The different models were sequentially tested via Likelihood Ratio Tests (LRTs) starting with a null model consisting only of participants' IDs as random effect. Moreover, the Akaike information criterion (AIC) and the Bayesian information criterion (BIC) were used to select the best fitting and most parsimonious model. Subsequently, Holm-corrected pairwise comparisons were computed with the *emmeans* function of the {emmeans} R package (Lenth, 2023) for the best fitting and more parsimonious model.

To perform the text analysis, participants' free-text responses were first pre-processed, following a similar method used by Li (2022). First, all words were converted to lowercase using the *tolower* function of the {base}R package. Then, via the {textclean} R package (Rinker, 2018), non-ASCII characters were converted to their correct form, symbols were converted to text, and contractions were expanded. Next, typos were identified with the {hunspell} R software package (Ooms, 2022) and corrected. Punctuation marks were kept in the responses, as they are crucial in maintaining the structure of the text and delimiting sentences, necessary for subsequent analysis. After the text responses were cleaned, a word frequency graph of all text responses with nodes corresponding to the five basic tastes was created via the {igraph} (Csardi & Nepusz, 2006) and the {ggprah} (Pedersen, 2022) R software packages. Subsequently, a sentiment analysis on the cleaned text responses was performed in order to explore whether participants matched taste with frequencies based on affective associations by extracting overall valence and arousal values at the sentence level. The sentiment analysis was performed following Li's (2022) approach. Valence values were extracted using the {sentimentr} (Rinker, 2021) R package, as it accounts for the sentence-level structure of responses, double-negatives, and valence shifters (e.g., amplifiers and de-amplifiers), which are critical in automated text analysis (Polanyi & Zaenen, 2006). To extract arousal values, the NRC VAD lexicon (Mohammad, 2018) was used via the *lexicon_nrc_vad* function of the {textdata} R package (Hvitfeldt, 2022) and later adjusted for valence shifters as identified by {sentimentr}. To make sure the sentiment analysis was working correctly, those responses containing modifiers and negations were manually checked.

4. Results

4.1. Data Screening

As part of the data cleaning process, seven observations were removed (<.01%), as the frequency selected was greater than 250 Hz. In addition, for three of these seven data points, the frequency selected was the same as the random three-digit code of the corresponding sample. The final data set comprised 72 participants and 713 observations.

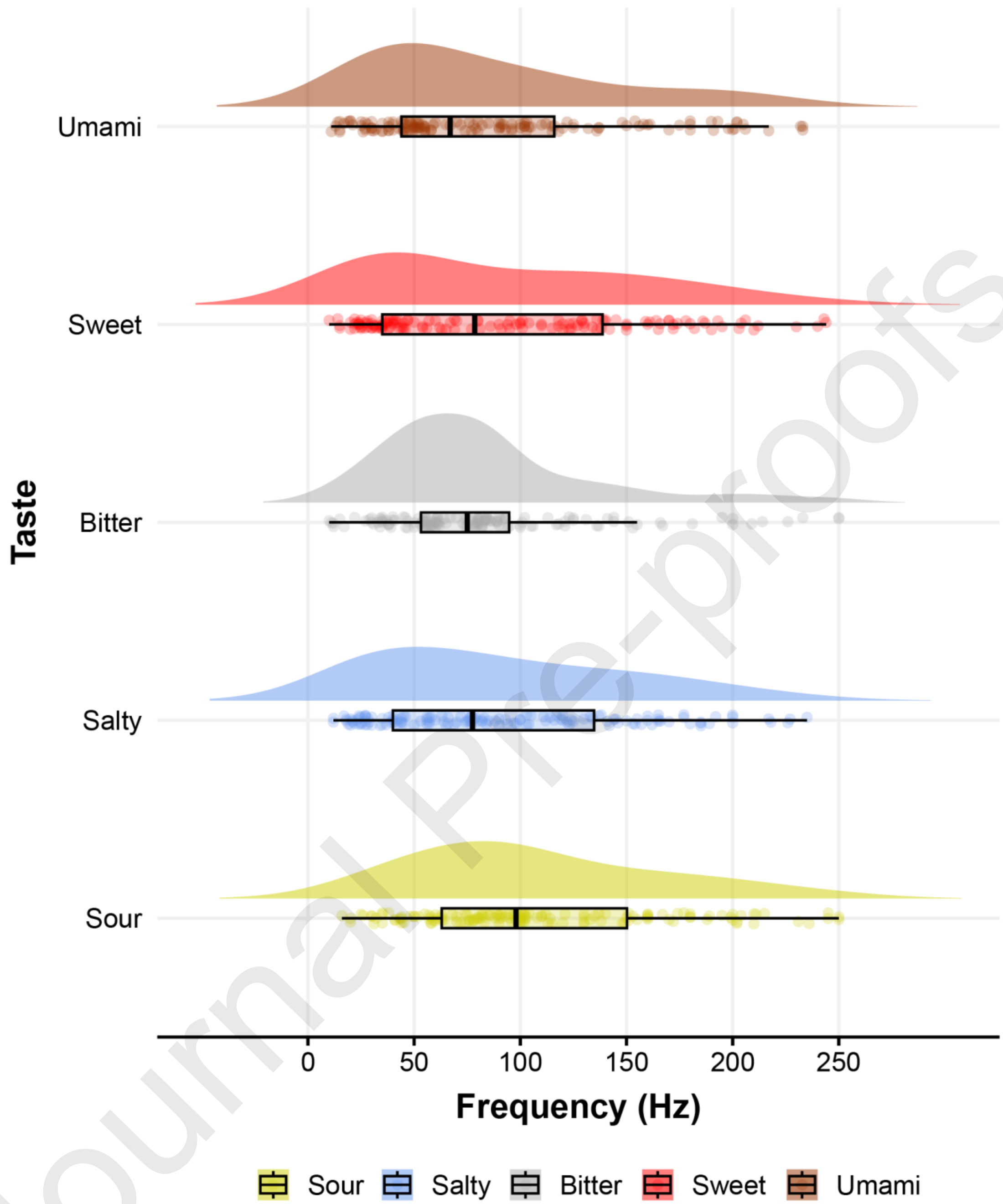
Overall, 86% of the basic taste samples were identified correctly. More specifically, the sweet samples were correctly identified 97% of the time, followed by the sour samples with 90%. Both the salty and bitter samples were correctly identified 85% of the time. Lastly, the umami samples were correctly identified 75% of the time.

4.2. Frequency Associations

To obtain an overall perspective of the frequency data, Figure 1 presents a visualization of the raw data in the form of raincloud plots for the different basic tastes. The Gamma GLMM model comparison, based on the LRT and BIC revealed that M_2 (controlling for whether participants correctly identified basic taste sampled) was the best fitting and most parsimonious model (Table 1). The results of the M_2 model (Table 2) revealed that all the fixed effects estimates corresponding to the basic tastes, as well as the taste test fixed effect were statistically significant. The post hoc test based on M_2 revealed that the basic taste with the highest associated frequency was sourness, whereas umami and sweetness were the ones with the lowest associated frequency. Holm-corrected estimated marginal means revealed that the frequency associated with sourness (98.4 Hz, *SE* = 6.16, 95% CI = [82.5, 114.3]) was significantly higher than those associated with umami, (76.1 Hz, *SE* = 4.95, 95% CI = [63.4, 88.9]; z = 3.24, p = .012) and sweetness (77.3 Hz, *SE* = 6.03, 95% CI = [61.7, 92.8]; z = 2.99, p = .025). However, the frequency matched with sourness was not statistically significant compared to bitterness, (80.2 Hz, *SE* = 5.19, 95% CI = [66.8, 93.5]; z = 2.64, p = .067) and saltiness, (80.9 Hz, *SE* = 5.49, 95% CI = [66.7, 95.0]; z = 2.51, p = .085).

Figure 1

Raincloud Plot of Vibration Frequency Associations by Taste



325
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329 **Table 1**

330 *Model Comparison Results of Gamma GLMMs on Associated Frequency*

Model	Fixed effects	AIC	BIC	LRT			Marginal R^2
				d	X^2	*p*	
M_0		7,618.4	7,632.1				
M_1	Taste	7,608.6	7,640.6	4	17.82	.001	.27
M_2	Taste + Taste test	7,595.0	7,631.6	1	15.52	<.001	.39
M_3	Taste + Taste test + Age + Gender	7,594.9	7,640.6	1	4.10	.128	.48

Note. The table presents the sequential results of the model comparison analysis of the Gamma GLMMs on frequency. LRT = likelihood information test; AIC = Akaike Information Criterion; BIC = Bayesian Information Criterion.

Table 2

Results of Gamma GLMMs on Frequency

	M_1	M_2	M_3
Fixed effects			
$Intercept_{Sour}$	108.7	86.3	47.6
	[97.61, 119.79]	[72.46, 100.14]	[11.95, 83.25]
	(<.001)	(<.001)	(.009)
$Taste_{Salty}$	-18.65	-17.54	-17.22
	[-32.25, -5.04]	[-30.81, -4.26]	[-30.44, -3.99]
	(.007)	(.010)	(.011)
$Taste_{Bitter}$	-22.96	-18.25	-18.07
	[-36.32, -9.59]	[-31.51, -4.99]	[-31.28, -4.87]
	(.001)	(.007)	(.007)
$Taste_{Sweet}$	-18.97	-21.12	-21.22
	[-32.59, -5.35]	[-34.42, -7.82]	[-34.45, -7.99]

	(.006)	(.002)	(.002)
$Taste_{Umami}$	-26.8	-22.29	-22.58
	[-39.95, -13.66]	[-35.32, -9.27]	[-35.53, -9.63]
	(<.001)	(.001)	(.001)
Taste test		24.22	23.92
		[14.36, 34.08]	[14.14, 33.70]
		(<.001)	(<.001)
Age			1.34
			[0.15, 2.54]
			(.028)
$Gender_{Male}$			3.83
			[-7.74, 15.40]
			(.516)
Random effects			
σ2	0.37	0.36	0.36

Participants	72	72	72
Observations	713	713	713

Note. The table presents the results of all the GLMMs with frequency as dependent variable. The values for each variable correspond, from top to bottom to its coefficient estimate, 95% confidence interval in square brackets, and *p*-value in parentheses.

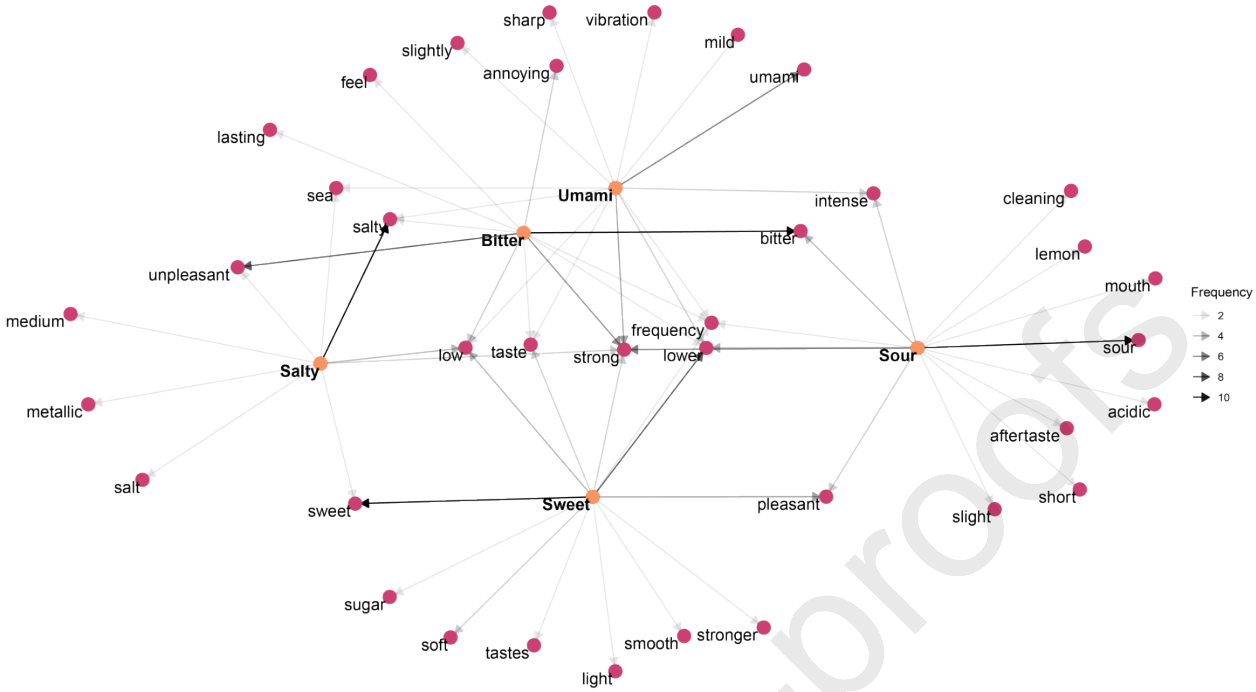
4.3. Text Analysis

Considering the relationship between the different tastes, the word frequency graph of the free text responses revealed that participants justified matching sweet and sour with specific frequencies based on both intensity and pleasantness (Figure 2). In comparison, salty, bitter, and umami were associated with strength and unpleasantness. Here it is worth noting that individuals tend to confound strength with bitterness, as exemplified by the case of coffee (Dijksterhuis, 1998; Van Doorn et al., 2014), which may lead to a negative connotation of the word strength. At the individual taste level, several responses to the matching of the sour samples included the word mouth ($n = 12$). A closer look into these responses revealed that they mainly referred to mouthfeel ($n = 7$). These comments included descriptions of the sour samples as cleaning ($n = 2$), rough ($n = 1$), coating ($n = 1$), vibrant ($n = 1$), sharp ($n = 1$), tingly ($n = 1$). In the case of sweetness, responses including the words soft and smooth were common. A closer look at the responses containing the word soft ($n = 7$) for the sweet taste showed that they mainly related to a soft taste, although it could also refer to mouthfeel ($n = 1$) and a direct association between the soft taste and a soft frequency ($n = 1$). As per the responses containing the word smooth in the sweet taste ($n = 12$), they also mainly referred to smooth taste, although it also referred to mouthfeel ($n = 1$), and a direct association between smooth taste and a soft frequency ($n = 3$). Regarding the word medium in for the salty taste, these comments ($n = 5$) related to the selection of an intermediate frequency due to intermediate valence ($n = 3$) and arousal ($n = 1$). In the case of the word sharp with the umami taste, these comments described the sample as not having a sharp taste.

When it comes to the sentiment analysis using the basic taste sampled as fixed effect, the results revealed a significant effect on valence, $F(4, 638) = 36.03$, $p < .001$, $\eta_p^2 = .18$. All the tastes significantly differed from each other in terms of valence ($p < .001$), with three exceptions, namely sour–salty ($p = .941$), sour–umami ($p = .830$), and salty–umami ($p = .998$). Furthermore, there was a significant effect of taste on arousal, $F(4, 638) = 23.14$, $p < .001$, $\eta_p^2 = .13$. All the tastes significantly differed from each other in terms of arousal ($p < .05$), with three exceptions, namely sour–bitter ($p = .134$), salty–umami ($p = .734$), and sweet–umami ($p = .140$). Figure 3 presents boxplots of the sentiment data for each basic taste.

Figure 2

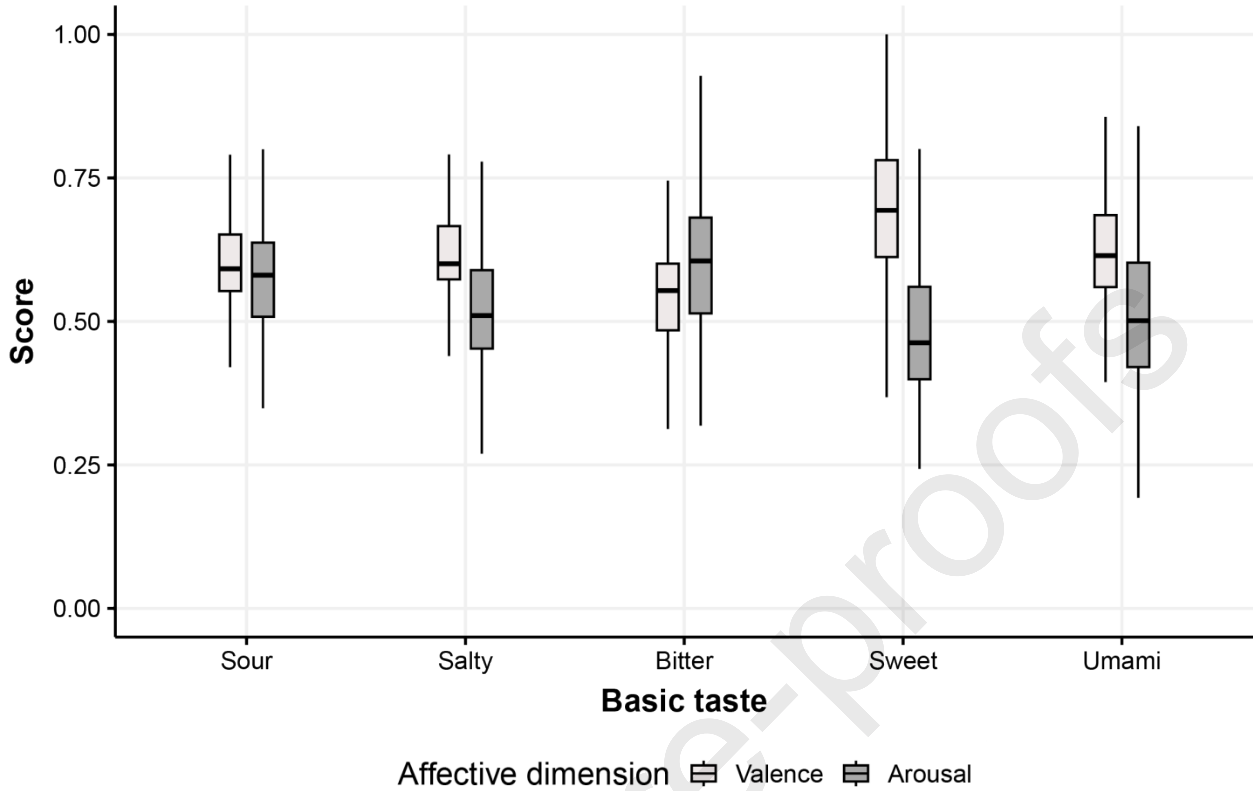
Word Frequency Graph of Free Text Responses



Note. The graph shows the occurrence frequency ($n > 2$) of words in the free text responses to the question "In a few words, explain why you selected this frequency" for each basic taste (indicated as nodes in yellow). The underlying analysis for the graph was based on the responses to the 10 samples tasted by each of the 72 participants. The graph comprises 93 unique word occurrences for all the tastes. The opaqueness of the arrows indicates the occurrence frequency of each word connected to each basic taste.

Figure 3

Boxplot of Extracted Valence and Arousal Levels of Free Text Responses Explaining Participants' Justifications Behind Taste–Vibration Matchings



5. Discussion

In the present study, we set out to uncover crossmodal correspondences between vibrotactile frequency and basic tastes. To this end, we conducted an experiment in which participants tasted different aqueous basic taste solution and searched for the frequency (delivered through a consumer-grade subwoofer wristband) that they most strongly associated with each basic taste sample. The results revealed that the taste with the highest associated frequencies was sourness (~ 98 Hz), whereas the tastes with the lowest associated frequencies were sweetness and umami (~ 77 Hz). In addition, the results revealed that correctly identifying the basic taste being sampled significantly influenced the frequency associated with it.

As expected, the results revealed some parallels with crossmodal correspondences between basic tastes and pitch. Similar to basic taste–pitch associations (Wang et al., 2015, 2016), sourness was associated with higher frequencies than the other tastes. Furthermore, the correspondences found here seemed to be partly driven by shared affective evocations. In this regard, another parallel with basic taste–pitch associations relates to the different influence of valence and arousal depending on the basic taste. As Wang et al. (2015) found, in study on associations between soundtracks and basic tastes, those involving sweet and bitter tastes were partly mediated by valence, whereas those involving sour tastes were in part mediated by arousal, which seems to be the case with the correspondences studied here.

In the present study, sourness was associated with the highest frequencies. Participants commonly cited associating the sour samples with specific frequencies based on the intensity of either or both stimuli. In addition, the sentiment analysis of the free text revealed that the responses related to the sour samples presented a higher level of arousal than the other tastes, except bitterness. Nevertheless, it is worth noticing that the valence of the text responses surrounding sourness was in the mid-levels, lower than sweetness but higher than bitterness, and not significantly different from saltiness or umami. Unlike the case of valence, past literature has found a more consistent positive relationship between the frequency of vibrotactile feedback and arousal (Hasegawa et al., 2019; Seifi & MacLean, 2013; Soares, 2023; Wilson & Brewster, 2017; Yoo et al., 2015). For example, in a recent study using pure vibrotactile stimuli, Soares (2023) found that higher frequencies are significantly associated with higher levels of arousal. Hence, it is possible that people associated sourness with higher vibrotactile frequencies because of their high arousal evocations.

The frequencies associated with sweetness (together with umami) were the lowest and significantly different from sourness. The results of the text analysis revealed that participants seemed to match sweetness with a frequency that produced positively valenced sensations. Participants often stated they matched the pleasant, sweet taste with a pleasant frequency. In addition, as the sentiment analysis revealed, the valence of the responses related to the sweet samples was the highest and significantly different from all the other tastes suggesting that the participants matched sweetness with a frequency that triggered positive valence. The findings of previous research on the pleasantness of vibrotactile feedback, and more specifically the effect of frequency, are not entirely consistent. However, recent studies in the human–computer interaction (HCI) literature have found that vibrations at low frequencies generate the most pleasant sensations. For instance, Israr and Abnousi (2018) designed a wearable device that delivered tactile strokes on the forearm and found that strokes at low frequencies (20 Hz) were the most pleasant, whereas those at higher frequencies (250 Hz) felt unpleasant. Furthermore, Shim and Tan (2020) developed a display capable of delivering custom-made and naturalistic vibrotactile feedback on the palm of the hand and found that low frequency signals (≤ 20) at different levels of arousal (e.g., simulating a bathtub water jet and bubbles) were the most pleasant ones. These results suggest that sweetness may be associated to lower frequency vibrations based on the positive affect evoked by both dimensions. However, it is worth noting that the clearly negatively valenced bitter taste was not consistently associated with any particular frequency. Here, it is important to consider that the range of frequencies that individuals find pleasant may be highly idiosyncratic, which may be a reason behind the inconsistent findings in past research.

Even though our results suggest that the associations of sweetness and sourness to vibrotactile frequencies are related to valence and arousal, respectively, it is also possible that these correspondences may emerge from a lexical account. When it comes to sweetness, for instance, participants used the tactile descriptors smooth ($n = 12$) and soft ($n = 7$) to match the sweet samples to specific vibrotactile frequencies. Individuals tend to use the word smooth to refer to sweet tastes (Burke, 2014), and low frequencies (≤ 20 Hz) are often perceived as smooth (Israr & Abnousi, 2018). This suggests that sweetness and lower vibrotactile frequencies may be matched together due to the use of the same terms to describe the sensory experiences of both dimensions.

In light of the lexical account, when it comes to sourness, participants used various tactile descriptors, namely cleaning ($n = 2$), rough ($n = 1$), coating ($n = 1$), vibrant ($n = 1$), sharp ($n = 1$), tingly (n = 1), to match the sour taste to specific frequencies. However, in this case, these terms were used specifically to describe the mouthfeel triggered by the sour solutions. As Spence (2023) noted, it is possible that the use of tactile terms to refer to basic tastes are descriptions of physical sensations felt in the mouth rather than metaphorical portrayals. For instance, Riofrio-Grijalva et al. (2020) investigated the tactile sensations resulting from the different basic tastes and found that sourness is described as rough and sharp, whereas sweetness is described as smooth, velvety, and silky. Indeed, sourness can produce contracting sensations in the oral cavity that can cause tingling sensations (Agorastos et al., 2023; Klosse, 2014). It is possible that sour taste sensations cause the mouth to vibrate at a specific range of frequencies, similar to the effects of Szechuan pepper. The tingling and numbing sensations in the lips and tongue when eating or being in contact with Szechuan pepper are produced by vibrations at around 50 Hz, the range of tactile RA1 afferent fibers (Hagura et al., 2013).

Another important result of our study lies in the effect of the correct identification of the basic tastes. Individuals generally make mistakes identifying some basic tastes like umami and bitterness (Rousmans, 2000). Especially when an actual tastant is absent, people may rely on their own semantic networks related to the different basic tastes, which may include specific flavors/odors given that they co-occur with specific foodstuffs in the environment, either naturally (e.g., strawberries are associated with sweetness because they are naturally sweet) or artificially (e.g., vanilla is associated with sweetness, although vanilla beans are actually naturally bitter, due to its common use in desserts; Spence, 2022). Hence, in the absence of an actual tastant, people may more strongly rely on these semantic networks, which are confounded with odors, and therefore form crossmodal correspondences based on different mechanisms of features. In a similar vein, the confusion of bitterness and sourness may have also biased the frequencies associated with each taste, as the perception of the tastant might have been in conflict with the semantic network related to the taste they thought they had.

Furthermore, based on our results, more than one mechanism may be at play in the formation of associations between vibrotactile frequencies and basic tastes, which may depend on the specific stimuli involved (e.g., sweet vs. sour). For instance, as our results suggest, associations with sweetness may depend more on valence, whereas the associations with sourness may depend more on arousal and a lexical account. As the body of literature has shown thus far, the different theoretical accounts of crossmodal correspondences should not be seen as mutually exclusive, but they may all hold some explanatory power as to their mechanisms (Spence, 2011, 2020). For instance, Barbosa Escobar et al., (2023a) found that more than one underlying mechanisms (i.e., affective vs. semantic) may be at play in the context of associations between visual textures and temperature. In addition, the influence of each mechanism may depend on the specific stimuli as in Wang et al. (2015).

The present findings have potential practical implications concerning the enhancement of eating experiences and the promotion of healthier eating habits. First, it is important to consider that future studies should test the effect of the correspondences found here on taste expectations and perception. If specific vibrotactile cues can significantly influence taste expectations in the corresponding direction, they may be used to prime people to think about a specific taste, and hence make food choices accordingly. For example, specific frequencies may be used to drive people's attention to sour foods. Moreover, the associations found here may potentially be used to convey specific sweet, sour, and umami taste sensations through crossmodal effects and consequently enhance eating experiences, and improve the taste of healthier foods, such as those with reduced sugar content, as evidenced by tactics using sound–taste crossmodal influences in products with varying levels of sugar (Guedes, Prada, et al., 2023). Another potential application may relate to the use of vibrations timed to chewing movements to influence tactile sensations in the mouth and consequently enhance eating experiences. In a recent study with a similar approach, in the HCI space, Kleinberger et al. (2023) developed a mobile app with different audio modes to alter chewing sounds and used it in an experiment in which participants were tasked to eating sour cream and onion Pringles. The latter authors found that amplifying eating sounds improved the crispiness, saltiness, sourness, and flavor intensity perception of the chips.

The associations found here are especially applicable in people's increasingly digital experiences in everyday life and the pervasive use of wearable technologies, which are already transforming the customer experience (Hoyer et al., 2020). Wearable technologies refer to compact electronic devices that can be worn as external accessories (e.g., glasses, watches) or be embedded in clothing or even directly in the body (e.g., implanted, adhered). These devices can track and exchange information on the go, and, through cloud access, make informed decisions (John Dian et al., 2020; Niknejad et al., 2020). The market for wearable technologies has experienced rapid growth in the last decades (Grand View Research, 2022), which potentially widens the reach of tactile technology leveraging the correspondences studied here. Here, it is worth considering that the vibrotactile stimulation provided by the wearables could influence taste judgements by increasing the wearer's attention or by increasing the perceived intensity of the food.

5.1. Limitations and Future Directions

Several limitations in the present study should be noted. First, the strength of each participant's association could not be determined. Future studies can directly ask participants about their confidence level behind each pair of vibration frequency–taste association, as a metacognitive analysis can provide insights into the level of consensual agreement across participants (Wang et al., 2021). A further limitation lies in the use of only one concentration level for the different taste solutions used. It is possible that varying taste intensities may influence the associated frequencies. Nevertheless, this may be especially relevant for associations involving a high arousal basic taste such as bitterness, like the case of color–taste associations and different levels of bitterness intensity (Sugimori & Kawasaki, 2022). Future studies should test the robustness of the correspondences found here with multiple concentrations of basic taste solutions or measure each individual's perceived intensity of the stimuli. In addition, studies could use different types of basic taste stimuli (e.g., solid gel or solid tastants). A potential limitation of the present study lies in the presentation of the samples. Even though two replicates of each basic taste were used, and they were all fully randomized, carryover effects could have been present. Future studies could use other presentation methods such as a Latin square design in order to further reduce experimental error. Another limitation is that the only parameter of the vibrotactile feedback that participants could manipulate was frequency (within the low frequency range since outside it is imperceptible to humans), as the amplitude (i.e., intensity) of the vibrations could also influence the associations uncovered. That being said, keeping the amplitude constant allowed for a cleaner experimental design and a less complicated task for participants. Future studies should explore the influence of amplitude in these correspondences narrowing the basic tastes and frequencies studied in order to keep the design and task manageable for participants.

An additional limitation relates to the delivery of the vibrotactile feedback, as the perception of the vibrations and hence their associations may differ depending on where the vibrations are felt. Here, we adopted an approach with a relatively high ecological validity, as we used a consumer-grade device in the form of a wristband, a common format used in smartwatches and fitness trackers. However, in the future, the use of devices that deliver vibrotactile feedback in different parts of the body can be explored. For example, the use of bone-conduction headphones (Koizumi et al., 2011) and smart textiles (Singh et al., 2020) may be an interesting and versatile opportunity.

6. Conclusion

Our findings provide evidence for the existence of a novel set of crossmodal correspondences, namely between basic tastes and the frequency of tactile vibrations. These findings suggest that these associations may be based, to different extents, on affective and semantic mechanisms. At the same time, the semantic mechanism may have underpinnings on mouthfeel sensations. The present study thus contributes to the literature on crossmodal correspondences by studying the understudied dimension related to tactile vibrations. Furthermore, our study raises the question whether the connection between gustation and touch is stronger than previously thought at a physical level. From a practical perspective, the findings derived here may inform future research and the development of novel smart devices to enhance multisensory eating experiences and promote healthier eating habits.

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Credit Author Statement

Francisco Barbosa Escobar: Conceptualization, Methodology, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization. **Qian Janice Wang**: Conceptualization, Methodology, Writing - Review & Editing, Supervision, Funding acquisition.

Declaration of Interest Statement

None.

Highlights

- Crossmodal correspondences between tactile vibrations and basic tastes were studied.
- Sourness was most strongly associated with vibrations around 98 Hz.
- Sweetness and umami were most strongly associated with vibrations around 77 Hz.
- Correctly identifying the basic taste had a significant influence on the associated frequency.

Crossmodal Correspondences Between Tactile Vibrations and Basic Tastes

Methods

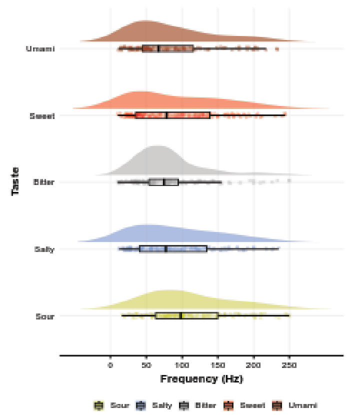
Participants searched for a vibrotactile frequency that they intuitively associated with the different basic tastes.

N = 72

Taste stimuli (aqueous solutions):
5 basic tastes (sweet, sour, salty, bitter, umami) × 2 replicates

Vibrotactile stimuli:
Delivered through sub-woofer wrtistband (10–250 Hz)

Results



Estimated Marginal Means:

Sour: *M* = 98.41, *SE* = 6.16

Salty: *M* = 80.87, *SE* = 5.49

Bitter: *M* = 80.16, *SE* = 5.19

Sweet: *M* = 77.29, *SE* = 6.03

Umami: *M* = 76.12, *SE* = 4.95