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Dynamic interaction of sweet and sour taste perceptions based on sucrose and citric acid



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Given the significance of dynamic taste perception, this study focused on sucrose and citric acid as research subjects to investigate quantitative principles governing the dynamic interactive responses between sweet and sour taste perception. Time-intensity experiments (30 assessors) revealed a logarithmic correlation between I_{\max} , AUC, and concentration, indicating that the sweetness of 2–10% sucrose and sourness of 0.006–0.024% citric acid exhibited mutual inhibition. Temporal dominance of sensations study (30 assessors) reveals that during the initial stage, the predominant attributes are sweetness and sourness, while in the later stage, salivation emerged as the dominant attribute across varying ratios of sweet-dominant, sour-dominant, and balanced sweet-sour sensations. At various sweet-to-sour ratios, dynamic liking (30 assessors) evaluation determined the optimal acceptance ratio of sweet-to-sour and elucidated the influential attributes of perceived preference along with their operational principles. The aforementioned research findings on the dynamic sweet-sour taste interaction patterns hold substantial implications for informing practical applications in the food industry.

Sweetness and sourness constituted two fundamental and indispensable taste modalities in the realm of food, and their intricate interplay exerted a profound impact on the overall flavor profile and subsequent consumer acceptance^{1,2}. By delving into the intricate nuances of this interactive response, food developers were able to exercise a heightened degree of precision in the formulation of recipes, thus enabling the crafting of culinary creations that aligned more closely with the preferences of consumers³.

Furthermore, the exploration of the interplay between sweetness and sourness served as a conduit for unraveling the intricate mechanisms underlying taste perception, propelling forward the progress of sensory science⁴. This endeavor not only augmented our understanding of the intricate workings of the human gustatory system but also harbored the potential to furnish novel insights and methodologies for addressing challenges such as taste disorders. By elucidating these intricate dynamics, we could also cultivate a deeper and more nuanced understanding of the subtle yet profound manner in which taste influences our culinary experiences.

Considering the significance of the interaction between sweet and sour tastes, a considerable number of studies have focused on the synergistic and antagonistic effects between sweet and sour taste perceptions. Pangborn

revealed that citric acid, within a concentration range of 0.007% to 0.073%, diminished the sweetness intensity of sucrose solutions varying from 0.5% to 20.0%, with a more pronounced effect on sweetness suppression observed at lower sucrose concentrations⁵. McBride compared the evaluations of sucrose/citric acid mixtures by two taste panels: experienced and novice assessors. The results showed good agreement between the panels, particularly in assessing total intensity, suggesting similar evaluation methods. However, experienced assessors exhibited less pronounced suppression of acidity by sweetness compared to novices, indicating that sensory panel experience may mitigate taste suppression⁶. Junge's group investigated sweet-sour interactions using sucrose, citric, and tartaric acids with participants from China ($n = 120$) and Denmark ($n = 139$). Results revealed no significant difference in sweetness suppression between acids, and sucrose similarly suppressed both acids' sourness⁷. In another study, Junge's group explored taste interactions in aqueous and cold-brewed coffee matrices using sucrose, citric acid, and tartaric acid. Two sub-studies with naive consumers ($n = 152$ for aqueous, $n = 115$ for coffee) revealed that sucrose's sweetness was suppressed by both acids in both matrices, while sourness suppression varied⁸. In these studies, the researchers merely discussed the

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trend-based variations in the intensities of both sweet and sour tastes when the sweetener and the sour agent coexisted, without delving into the specific quantitative principles underlying such observations.

Hence, in recent years, there has been a growing interest in studies that aim to quantify the trends in the interaction between sweet and sour tastes. Junge's work used a split-tongue gustometer to investigate three proposed mechanisms⁹. Two studies, utilizing low and high concentrations of sucrose and citric acid, found no significant difference in sweetness intensity between separate and mixed presentations, but significantly lower ratings with citric acid, suggesting a central mechanism for suppression. Our group's research¹⁰ found that citric acid increased the absolute threshold of sucrose (0.424–0.624%) and Weber fraction (20.5–33.0%). Conversely, sucrose increased the absolute threshold of citric acid (0.0057–0.0082%) and decreased its Weber fraction (17.96–9.53%). By fitting absolute threshold and Weber fraction variation equations, the sweet-sour taste sensory strength variation models were derived, and the interactive response to sweet-sour taste could be quantitatively calculated^{11,12}.

The aforementioned research findings elucidated the interaction trends and quantitative patterns of sweet and sour taste perceptions when sweeteners and acidulants coexisted. However, it is noteworthy that these studies primarily focused on the interplay of sweet and sour taste sensations under static evaluation conditions. It was universally acknowledged that human food intake constituted a dynamic and ever-changing process¹³. Consequently, compared to the investigation of static sweet and sour taste perceptions, exploring the interactive patterns of sweet and sour taste under dynamic evaluation conditions proved far more conducive to deepening our understanding of the perceptual mechanisms of taste, thereby unveiling how distinct taste components interplayed and influenced the overall flavor perception.

Jelinek and his colleagues were the first to propose the concept of dynamic response. Through subsequent refinements by researchers such as Moskowitz and Pangborn, the Time-Intensity (TI) evaluation method and associated instrumental system were established to investigate the temporal changes in the perceived intensity of individual taste substances over time¹⁴. For example, Freitas' group used TI to evaluate the sweetness and bitterness of sweeteners, such as sucralose, sweetener/saccharin mixtures, and aspartame, in different food items¹⁵. Sousa Lima utilized TI to study the differences between sweeteners, such as sucralose, acesulfame, sodium saccharin,

and sucrose³. Subsequently, based on the TI variation trend, the Pineau research group proposed the Temporal Dominance of Sensations (TDS) method to assess the dynamic characteristics of multiple taste attributes in foods as they evolve over time within the mouth¹⁶. Utilizing the TDS approach, Bommel, Santagiuliana, and their colleagues conducted explorations into the dynamic trends of different taste sensations, such as sweetness, sourness, and fattiness, within the oral cavity, using yogurt and cheese samples as their basis^{17,18}. Therefore, the current research on dynamic sensory perception revealed that systematic work has primarily focused on studying the independent dynamic intensity response trends of single taste modalities. Moreover, the investigation of dynamic responses following the combination of sweet and sour tastes had not been systematically undertaken.

Considering that elucidating the quantitative patterns of the interaction between sweet and sour taste perceptions over time could significantly contribute to our understanding of the dynamic processes underlying taste perception and reveal how different taste components interact and influence overall flavor, a comprehensive investigation was deemed necessary. Thus, a series of experiments were conducted in this study, using sucrose and citric acid as the subjects of investigation. In this study, we first utilized our self-established software, in conjunction with TI technology, to conduct an in-depth investigation into the variation patterns of sensory intensity observed when sucrose and citric acid were present in varying concentrations. Following this, we derived a refined quantitative mathematical model to describe these interactions. Subsequently, we employed the techniques of dynamic liking (DL) and TDS to investigate the patterns of taste perception variations under different intensities of sweet and sour taste experiences. Ultimately, we utilized the Temporal Drivers of Liking (TDL) technique to explore how sensory attributes influenced preference and their temporal variations during the perception process of sweet and sour tastes. The experimental design of this study was illustrated in Fig. 1.

Results and discussion

Dynamic perception intensity of sucrose-citric acid mixtures

The TI results for sucrose at low (2%), medium (6%), and high (10%) concentrations, under the background of citric acid solutions of varying concentrations, were presented in Fig. 2. Meanwhile, the key characteristic parameters of the TI curve, which represent the dynamic changes in the

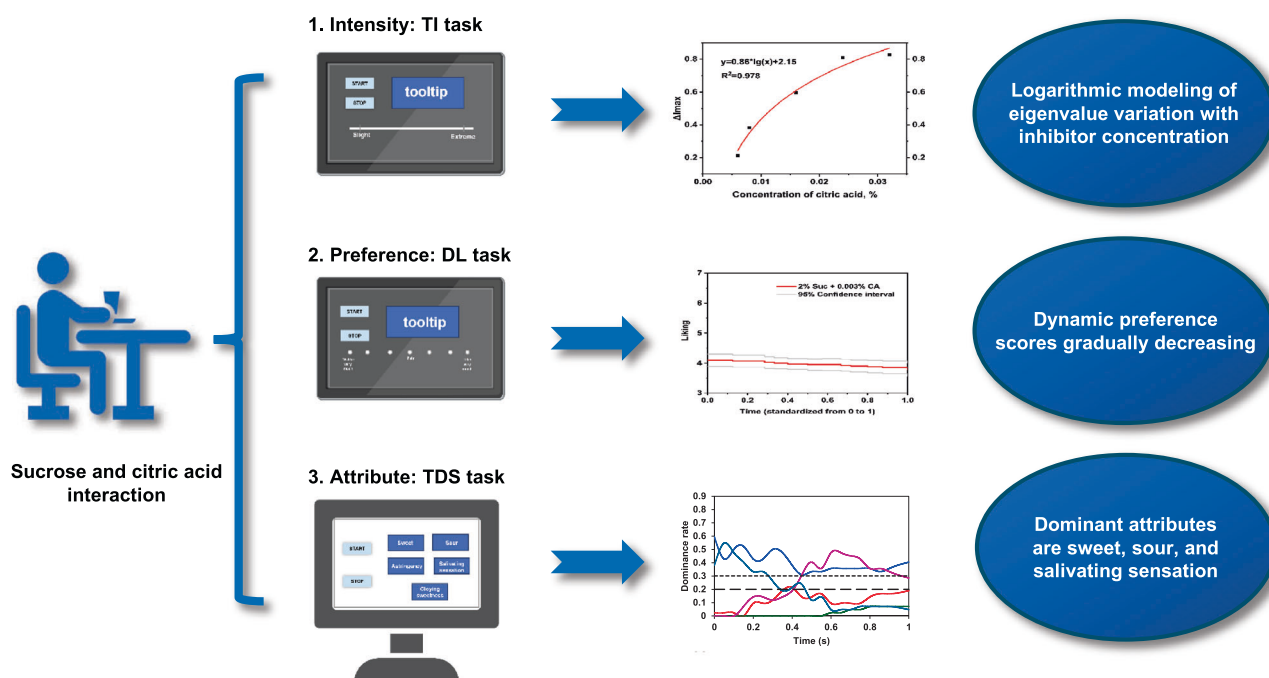


Fig. 1 | Flowchart of experimental design. Analysis of TI, DL, and TDS experiments on sucrose-citric acid mixtures revealed dynamic interactions in sweet-sour taste perception.

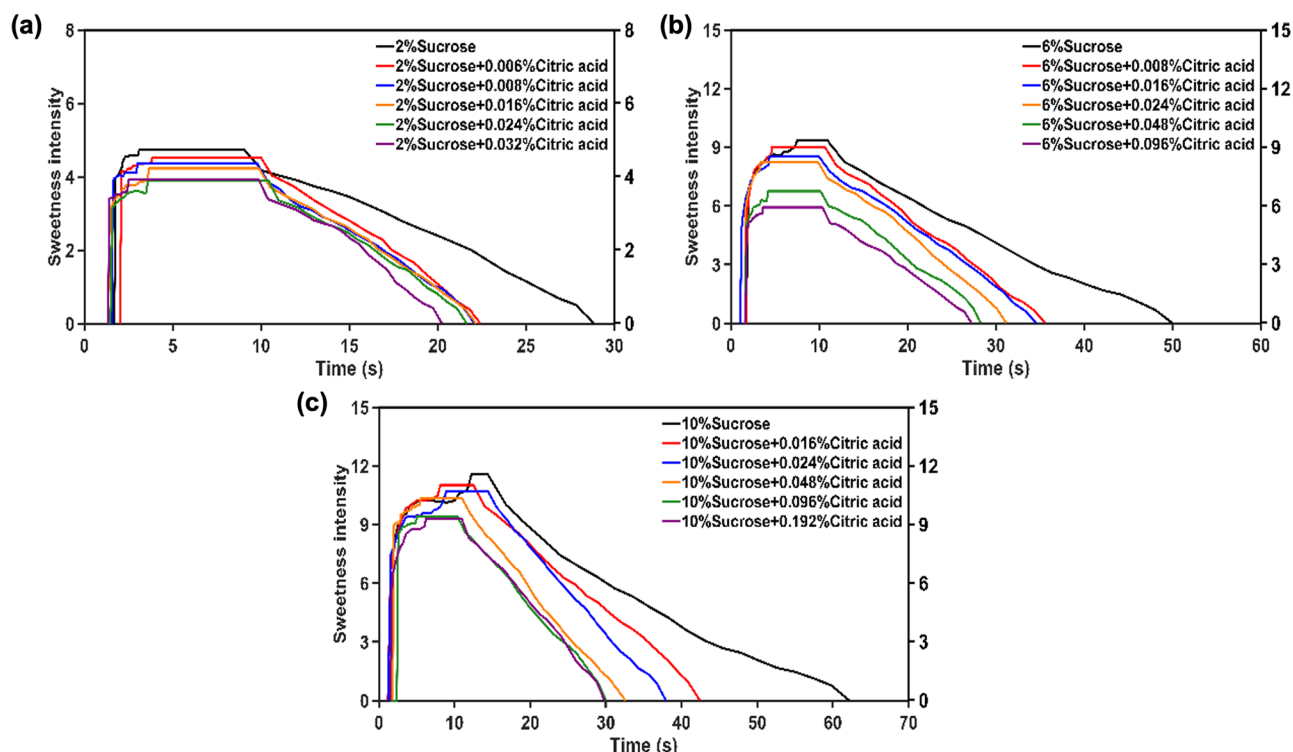


Fig. 2 | Average time-intensity curves for varying sweetness levels of sucrose under citric acid backgrounds. a 2% of sucrose; b 6% of sucrose; c 10% of sucrose.

Table 1 | Time-Intensity results for sucrose (2%, 6% and 10% of concentration) under different citric acid solutions

Concentration of sucrose, %	Concentration of citric acid, %	I_{\max}^*	T_{\max}^*	T_{start}	T_{dec}	T_{end}^*	AUC*
2%	0	4.76 ± 0.09^a	4.62 ± 0.90^a	1.82 ± 0.13^a	10.04 ± 0.85^a	29.96 ± 1.73^a	90.73 ± 6.78^a
	0.006	4.55 ± 0.09^a	5.23 ± 0.93^a	2.13 ± 0.13^a	10.79 ± 0.86^a	23.44 ± 1.53^b	69.76 ± 4.67^{ab}
	0.008	4.38 ± 0.08^a	4.61 ± 0.93^a	1.69 ± 0.13^a	10.94 ± 0.89^a	22.69 ± 1.16^b	65.70 ± 3.63^b
	0.016	4.18 ± 0.10^b	5.07 ± 0.95^a	1.56 ± 0.14^a	10.65 ± 0.79^a	22.23 ± 1.20^b	62.13 ± 3.97^b
	0.024	3.97 ± 0.11^b	4.97 ± 0.94^a	1.64 ± 0.16^a	11.21 ± 0.90^a	21.64 ± 0.96^b	57.95 ± 3.5^b
	0.032	3.94 ± 0.09^b	3.63 ± 0.76^a	1.53 ± 0.18^a	10.66 ± 0.75^a	20.60 ± 0.79^b	56.85 ± 2.88^b
6%	0	9.38 ± 0.07^a	9.45 ± 0.93^a	1.88 ± 0.16^a	12.16 ± 0.94^a	53.16 ± 3.72^a	262.08 ± 17.71^a
	0.008	9.03 ± 0.12^{ab}	6.6 ± 1.06^{ab}	1.84 ± 0.15^a	11.62 ± 0.90^a	40.78 ± 4.61^{ab}	205.44 ± 18.25^{ab}
	0.016	8.55 ± 0.12^b	6.57 ± 1.15^{ab}	1.38 ± 0.18^a	11.42 ± 1.02^a	36.17 ± 2.10^b	186.33 ± 9.76^b
	0.024	8.27 ± 0.17^b	4.74 ± 0.86^b	1.69 ± 0.11^a	11.54 ± 1.19^a	33.58 ± 2.60^b	174.13 ± 12.69^{bc}
	0.048	6.88 ± 0.28^c	5.24 ± 0.77^b	1.79 ± 0.16^a	11.34 ± 0.91^a	30.62 ± 2.58^b	134.93 ± 12.20^c
	0.096	6.08 ± 0.28^c	4.53 ± 0.68^b	1.85 ± 0.16^a	11.64 ± 0.96^a	29.33 ± 2.31^b	117.31 ± 10.94^c
10%	0	11.58 ± 0.14^a	12.26 ± 0.19^a	1.97 ± 0.19^a	14.51 ± 0.37^a	68.80 ± 7.20^a	379.61 ± 28.45^a
	0.016	11.05 ± 0.16^{ab}	9.70 ± 0.90^{ab}	1.44 ± 0.16^a	13.37 ± 0.87^a	44.83 ± 2.92^{ab}	298.35 ± 17.95^{ab}
	0.024	10.65 ± 0.14^{bc}	10.18 ± 0.86^{ab}	1.44 ± 0.13^a	14.61 ± 0.51^a	39.95 ± 2.28^b	260.48 ± 13.69^{bc}
	0.048	10.33 ± 0.14^c	6.79 ± 0.99^b	1.92 ± 0.11^a	11.58 ± 0.88^a	33.93 ± 2.32^{bc}	214.68 ± 11.50^c
	0.096	9.45 ± 0.19^d	7.45 ± 1.10^b	1.62 ± 0.14^a	11.61 ± 0.94^a	31.09 ± 1.69^c	187.30 ± 12.93^c
	0.192	9.34 ± 0.20^d	8.66 ± 1.07^b	1.65 ± 0.14^a	12.34 ± 1.12^a	31.10 ± 1.89^{bc}	183.75 ± 12.04^c

*Indicate that the samples were significantly different.

Different letters in the same line indicate significant differences between samples by Duncan's test ($p < 0.05$).

perceived intensity of sucrose's sweetness over time, were listed in Table 1. As shown in Fig. 2, it was observed that citric acid at various concentrations consistently inhibited the perception of sucrose's sweetness, with the degree of inhibition demonstrating a positive correlation to the concentration of citric acid. Furthermore, the addition of citric acid significantly reduced the duration of the sweet sensation and accelerated the rate of its decline.

As evident from Table 1, with the increment in citric acid concentration, significant differences were observed in the I_{\max} , T_{\max} , T_{end} , and AUC of the TI curves for sucrose at low, medium, and high concentrations. This indicated that citric acid could effectively reduce the maximum intensity of sucrose's sweetness, decrease the time to reach maximum intensity, and the overall duration of the sweet sensation, ultimately leading to a decrease in the overall perception of sweetness in the oral cavity.

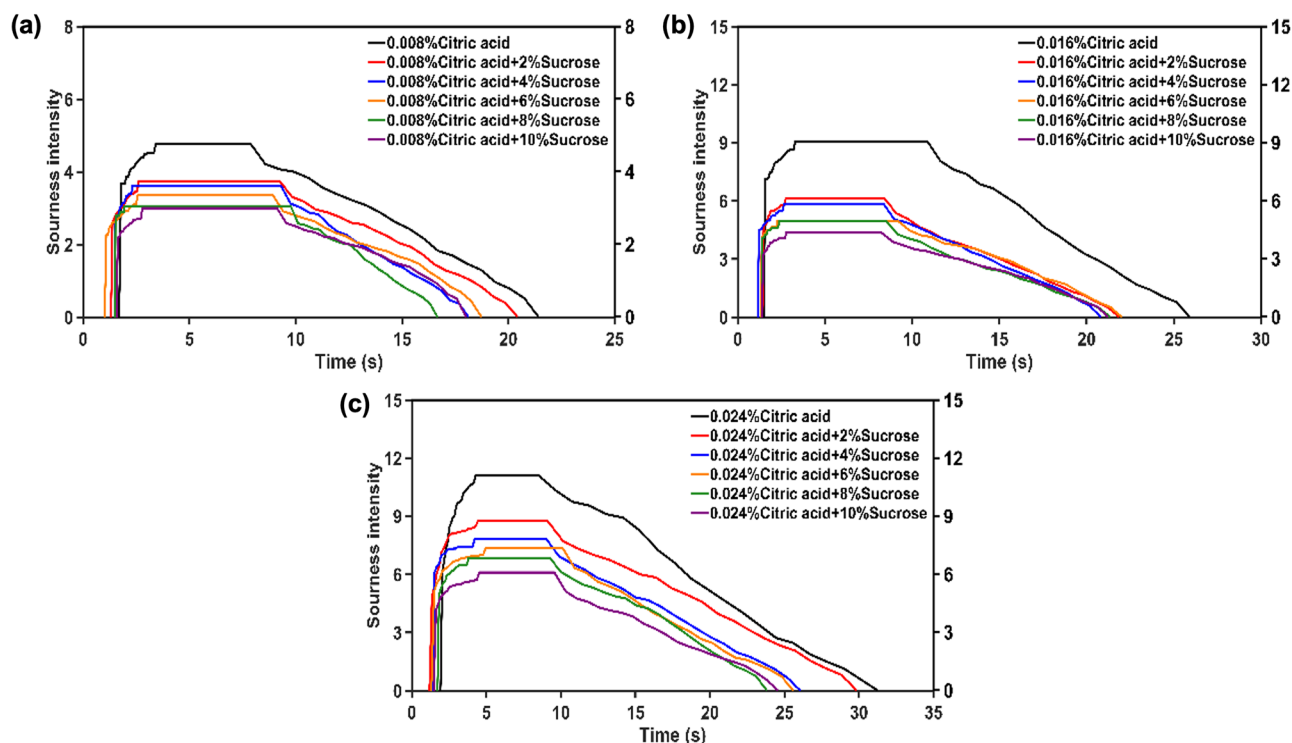


Fig. 3 | Average time-intensity curves for varying sourness levels of citric acid under sucrose backgrounds. a 0.008% of citric acid; **b** 0.016% of citric acid; **c** 0.024% of citric acid.

Table 2 | Time-Intensity results for citric acid (0.008%, 0.016% and 0.024% of concentration) under different sucrose solutions

Concentration of citric acid, %	Concentration of sucrose, %	I_{\max}^*	T_{\max}	T_{start}	T_{dec}	T_{end}^*	AUC*
0.008%	0	4.78 ± 0.09^a	4.09 ± 0.6^a	1.93 ± 0.18^a	9.15 ± 0.89^a	22.24 ± 1.29^a	66.68 ± 3.74^a
	2	3.79 ± 0.13^b	3.25 ± 0.44^a	1.47 ± 0.14^a	10.08 ± 0.7^a	20.71 ± 0.72^a	52.81 ± 2.76^{ab}
	4	3.67 ± 0.13^{bc}	2.63 ± 0.28^a	1.57 ± 0.11^a	10.02 ± 0.64^a	18.44 ± 0.72^{ab}	46.19 ± 1.66^b
	6	3.40 ± 0.1^{bc}	2.90 ± 0.31^a	1.30 ± 0.15^a	9.81 ± 0.74^a	19.05 ± 0.74^{ab}	44.72 ± 1.96^{bc}
	8	3.14 ± 0.15^c	2.13 ± 0.19^a	1.68 ± 0.18^a	10.41 ± 0.63^a	16.94 ± 0.65^b	38.38 ± 1.83^c
	10	3.03 ± 0.07^c	3.02 ± 0.28^a	1.80 ± 0.18^a	10.01 ± 0.71^a	18.30 ± 0.66^{ab}	38.42 ± 1.46^c
0.016%	0	9.09 ± 0.08^a	4.15 ± 0.68^a	1.56 ± 0.09^a	11.36 ± 0.62^a	27.88 ± 2.25^a	159.99 ± 11.96^a
	2	6.20 ± 0.17^b	3.71 ± 0.75^a	1.51 ± 0.10^a	9.82 ± 0.94^a	22.56 ± 1.30^a	88.51 ± 5.27^b
	4	5.69 ± 0.15^b	3.96 ± 0.77^a	1.32 ± 0.15^a	10.85 ± 0.81^a	21.80 ± 1.31^a	83.51 ± 5.24^b
	6	5.01 ± 0.14^c	2.48 ± 0.21^a	1.53 ± 0.17^a	10.28 ± 0.77^a	22.70 ± 1.18^a	78.84 ± 4.47^b
	8	4.87 ± 0.15^{cd}	3.15 ± 0.68^a	1.37 ± 0.12^a	10.31 ± 0.89^a	20.62 ± 1.02^a	67.28 ± 4.31^b
	10	4.41 ± 0.12^d	3.65 ± 0.69^a	1.53 ± 0.14^a	9.11 ± 0.70^a	21.83 ± 1.12^a	62.71 ± 2.58^b
0.024%	0	11.13 ± 0.09^a	4.92 ± 0.6^a	2.12 ± 0.16^a	9.33 ± 0.76^a	33.15 ± 2.38^a	207.79 ± 14.52^a
	2	8.77 ± 0.11^b	6.27 ± 0.96^a	1.44 ± 0.17^a	10.34 ± 0.88^a	31.07 ± 1.84^a	164.39 ± 8.32^b
	4	7.84 ± 0.14^c	6.01 ± 0.96^a	1.55 ± 0.16^a	10.52 ± 0.97^a	26.97 ± 1.54^a	133.67 ± 7.43^{bc}
	6	7.37 ± 0.13^c	6.43 ± 0.89^a	1.58 ± 0.15^a	11.04 ± 0.74^a	26.55 ± 1.59^a	118.52 ± 5.53^c
	8	6.86 ± 0.14^d	4.90 ± 0.76^a	1.94 ± 0.16^a	10.29 ± 0.8^a	24.62 ± 1.59^a	108.66 ± 7.01^c
	10	6.13 ± 0.11^e	6.10 ± 0.94^a	1.71 ± 0.15^a	10.58 ± 0.8^a	25.71 ± 1.66^a	96.89 ± 6.05^c

* Indicate that the samples were significantly different.

Different letters in the same line indicate significant differences between samples by Duncan's test ($p < 0.05$).

The TI results for citric acid at low (0.008%), medium (0.016%), and high (0.024%) concentrations, under the background of sucrose solutions of varying concentrations, were presented in Fig. 3. Meanwhile, the key characteristic parameters of the TI curve, which represent the dynamic changes in the perceived intensity of citric acid's sourness over time, were

listed in Table 2. As shown in Fig. 3, it was observed that as the concentration of sucrose increased, the perceived intensity of citric acid's sourness decreased significantly. A comparison with Fig. 2 revealed that the suppression of citric acid's sourness by sucrose was substantially greater than the inhibition of sucrose's sweetness by citric acid, indicating an

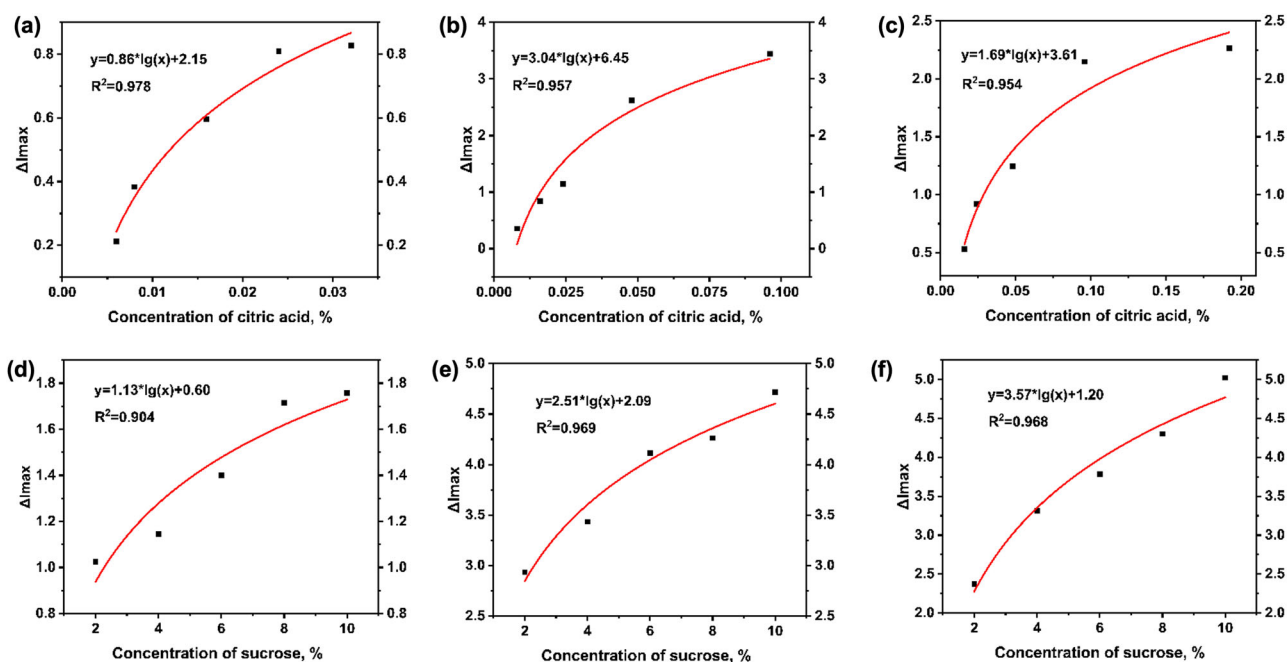


Fig. 4 | Relationship between target taste substance's ΔI_{\max} and corresponding background taste substance's concentration. a 2% of sucrose under varying concentrations of citric acid; **b** 6% of sucrose under varying concentrations of citric acid; **c** 10% of sucrose under varying concentrations of citric acid; **d** 0.008% of citric acid

under varying concentrations of sucrose; **e** 0.016% of citric acid under varying concentrations of sucrose; **f** 0.024% of citric acid under varying concentrations of sucrose.

asymmetrical inhibitory effect between the two taste sensations. This suggested that sweetness dominated in this interaction. From a biological perspective, the adaptive advantage of sweetness perception may contribute to its stronger inhibitory effect in competition with other tastes^{19,20}.

As evident from Table 2, under the background of sucrose solutions of varying concentrations, significant changes were observed in the I_{\max} , T_{end} , and AUC of the TI curve for low-concentration citric acid (0.008%). These parameters exhibited a gradual decrease as the concentration of sucrose increased. However, when the concentration of citric acid rose to moderate levels (0.016% and 0.024%), the increase in sucrose concentration only significantly reduced I_{\max} and AUC. These results indicated that, in pure sucrose-citric acid model solutions, sucrose could markedly decrease both the maximum intensity of citric acid's sourness and the overall perception of sourness in the oral cavity.

Quantitative model establishment of dynamic interaction for sweet and sour taste

Upon analyzing the data presented in Tables 1 and 2, it was evident that, in the coexistence of sucrose and citric acid, they markedly influenced each other's I_{\max} and AUC values. The parameter I_{\max} represented the maximum perceptual intensity elicited by a gustatory stimulus, whereas AUC encapsulated the cumulative perceptual response throughout the entire duration of the stimulus. The systematic variations observed in these parameters reveal that sweet and sour tastes were not isolated entities; instead, they engaged in a sophisticated interaction. Consequently, we designated I_{\max} and AUC as the covarying psychophysical parameters that characterize the interactive responses between sweet and sour tastes.

To further elucidate the relationship between I_{\max} and the corresponding concentrations of sucrose and citric acid, scatter plots were constructed (as shown in Fig. 4), utilizing the background concentrations of sucrose and citric acid as the X axis and ΔI_{\max} (calculated as the difference between I_{\max} when sucrose or citric acid was present in isolation and I_{\max} in the presence of the respective background) as the Y axis. As depicted in Fig. 4, where (a–c) represented the quantified results of ΔI_{\max} for sucrose, while (d–f) showcased the same for citric acid, it was evident that after fitting, the ΔI_{\max} values for both sucrose and citric acid exhibited a well logarithmic

relationship with their respective background concentrations. Notably, the correlation coefficients for these relationships were all above 0.9. The specific equations and parameters were listed in Table 3. Furthermore, the relationship curves between ΔAUC (calculated as the difference between AUC when sucrose or citric acid was present in isolation and AUC in the presence of the respective background) and the corresponding changes in sucrose and citric acid were established using an analogous method, as illustrated in Fig. 5. Concurrently, the corresponding fitting equations and parameters were presented in Table 4. Similar to the quantitative model observed for ΔI_{\max} , a well logarithmic relationship was evident between ΔAUC and the corresponding concentrations of sucrose and citric acid.

When sucrose and citric acid were present in combination, the equations provided in Tables 3 and 4 enabled the computation of both the maximum perceived intensities of sweetness and sourness, as well as the cumulative perception intensities of these tastes throughout their dynamic interplay. More specifically, the dynamic interactive quantification model established in this study not only elucidated the intricate interactions between sweetness and sourness in terms of their intensities but also permitted an accurate quantification of the resultant perceptual intensities in humans following their interaction.

These results contribute to the advancement of research endeavors by offering a dynamic interactive quantification model that helps clarify the complex interactions between sweetness and sourness in taste mixtures. By enabling the computation of maximum perceived intensities and cumulative perception intensities, the model provides a method for more accurately quantifying the perceptual outcomes of taste interactions in humans. This approach could potentially enhance the understanding of taste perception mechanisms and offer a framework that might be useful for further research in sensory science. Additionally, it could support efforts to optimize flavor profiles in product development, particularly in industries related to food and beverages, by providing insights into how different tastes interact dynamically.

DL results of sucrose-citric acid mixtures

Based on the previous experimental results^{11,12} and JAR analysis technique^{21,22}, a total of nine different concentration combinations of

Table 3 | Equation parameters of the fitted logarithm curve between ΔI_{\max} and background taste substances

Target taste substance	Background taste substance	Fitted Curves			
		Fitted Equation	Equation parameters		R^2
			a	b	
Sucrose (2%)	Citric acid	$\Delta I_{\max} = a \times \log_{10}(C_{tsb}) + b$	0.86	2.15	0.978
Sucrose (6%)			3.04	6.45	0.957
Sucrose (10%)			1.69	3.61	0.954
Citric acid (0.008%)	Sucrose		1.13	0.60	0.904
Citric acid (0.016%)			2.51	2.09	0.969
Citric acid (0.024%)			3.57	1.20	0.968

C_{tsb} means the concentration of background taste substance.

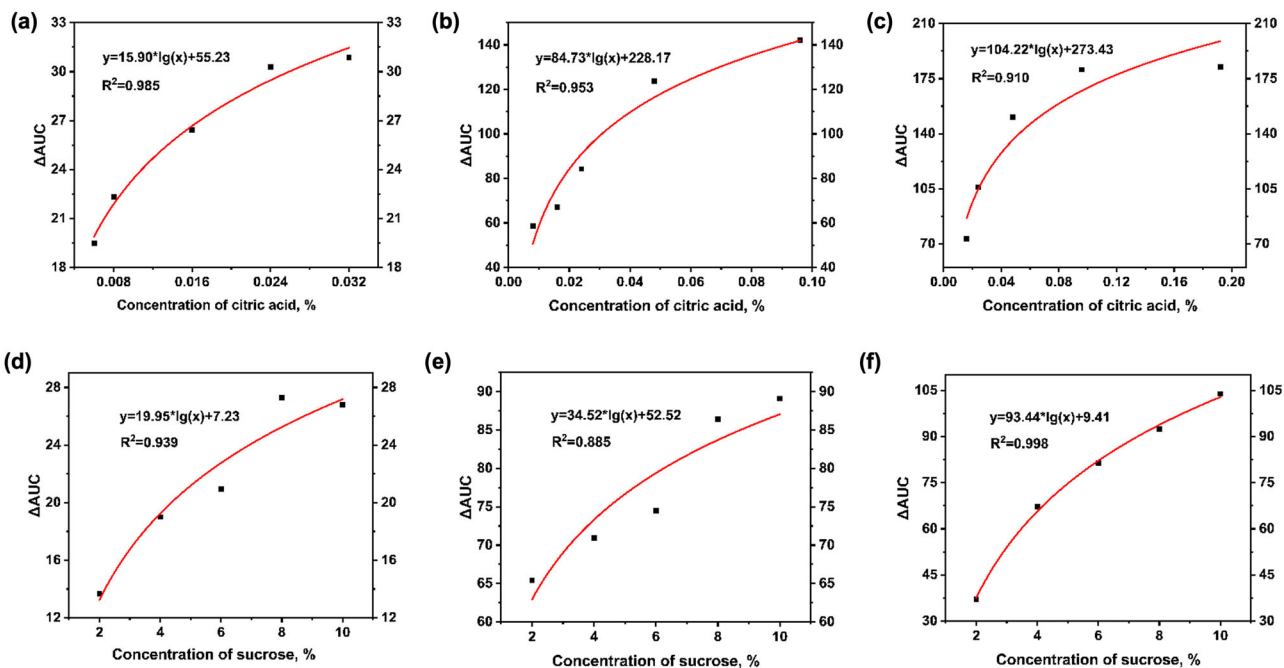


Fig. 5 | Relationship between target taste substance’s ΔAUC and the corresponding background taste substance’s concentration. **a** 2% of sucrose under varying concentrations of citric acid; **b** 6% of sucrose under varying concentrations of citric acid; **c** 10% of sucrose under varying concentrations of citric acid; **d** 0.008% of citric acid under varying concentrations of sucrose; **e** 0.016% of citric acid under varying concentrations of sucrose; **f** 0.024% of citric acid under varying concentrations of sucrose.

Table 4 | Equation parameters of the fitted logarithm curve between ΔAUC and background taste substances

Target taste substance	Background taste substance	Fitted Curves			
		Fitted Equation	Equation parameters		R^2
			a	b	
Sucrose (2%)	Citric acid	$\Delta AUC = a \times \log_{10}(C_{tsb}) + b$	15.90	55.23	0.985
Sucrose (6%)			84.73	228.17	0.953
Sucrose (10%)			104.22	273.43	0.910
Citric acid (0.008%)	Sucrose		19.95	7.23	0.939
Citric acid (0.016%)			34.52	52.52	0.885
Citric acid (0.024%)			93.44	9.41	0.998

C_{tsb} means the concentration of background taste substance.

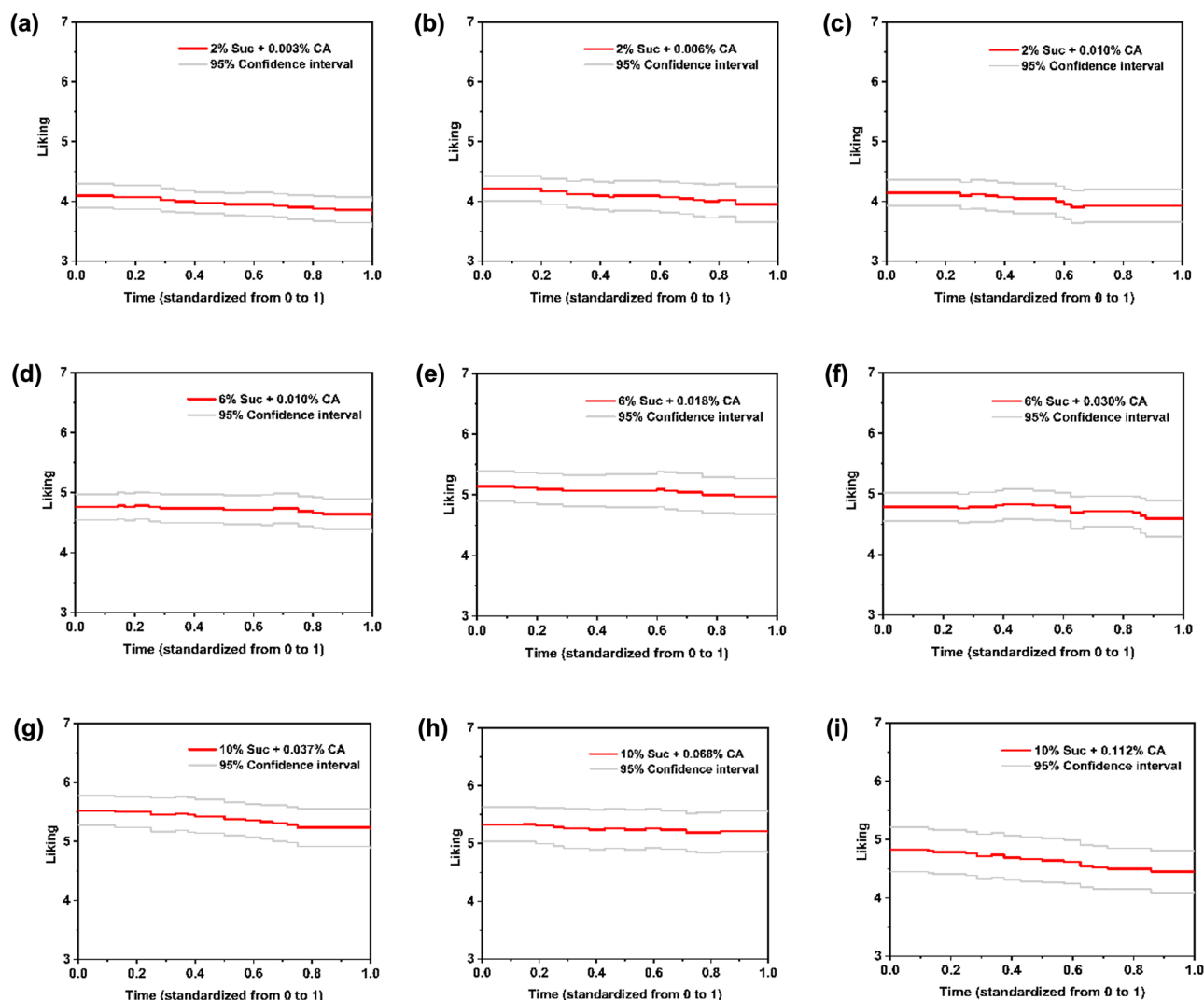


Fig. 6 | Dynamic liking standard curves for sucrose-citric acid mixtures. **a** 2% of sucrose and 0.003% of citric acid; **b** 2% of sucrose and 0.006% of citric acid; **c** 2% of sucrose and 0.003% of citric acid; **d** 6% of sucrose and 0.010% of citric acid; **e** 6% of sucrose and 0.018% of citric acid; **f** 6% of sucrose and 0.030% of citric acid; **g** 10% of sucrose and 0.037% of citric acid; **h** 10% of sucrose and 0.068% of citric acid; **i** 10% of sucrose and 0.112% of citric acid.

sucrose-citric acid mixed solutions were designed. Simultaneously, the self-established evaluation software in our laboratory was utilized to perform DL assessments on the aforementioned sucrose-citric acid mixed solutions, with the results presented in Fig. 6. Specifically, Fig. 6a–c, d–f, g–i presented the DL curves for sensory panels' perceptions of predominantly sweet, optimally balanced sweet-sour, and predominantly sour, respectively, within the context of 2%, 6%, and 10% sucrose sweetness levels.

In Fig. 6, the sensory panels' liking ratings ranged from 1 to 7, where 1 indicated strong dislike and 7 indicated strong like. By examining the preference rating curves, trends in preference variation over time could be observed. Initially, it was observed that the overall trend for all samples was a gradual decline over time, with preference ratings converging towards the neutral descriptor, namely 'moderate' (rated as 4). Consequently, the disparity in preference among the samples progressively diminished. This phenomenon was analogous to the findings reported by Delarue and Loesch²³, primarily attributed to an increase in inter-individual preference variability leading to more neutral evaluation outcomes. Secondly, under the backgrounds of low, medium, and high concentrations of sucrose, the DL rating was the highest when the sensory panels perceived the taste as optimally balanced sweet-sour, with a more gentle fluctuation in preference levels than the other two perceptions. Lastly, under the background of low

sucrose concentration, the sensory panel demonstrated a preference for the sucrose-citric acid mixture with predominantly sour perception. Under medium and high sucrose concentrations, overall preference ratings reached their zenith. Conversely, under the background of high sucrose concentration, the sensory panel preferred the sucrose-citric acid mixture with predominantly sweet perception.

Temporal dominance of sensations results from sucrose-citric acid mixtures

The standardized dynamic dominant attribute test results for the sucrose-citric acid mixtures of different concentrations were depicted in Supplementary Fig. 1. This figure elucidated the dynamic shifts in six sensory attributes (sweet, sour, astringency, salivating sensation, and cloying sweetness) throughout the entire sensory perception process. Remarkably, among all the sucrose-citric acid mixtures analyzed, only three attributes—sweetness, salivating sensation, and sourness—demonstrated dominance rates exceeding the significance threshold. Further analysis revealed that, at the initial phase of ingestion, the dominant attributes were primarily sweetness and sourness. As time progressed, particularly in the later stages of swallowing, salivating sensation emerged as a new dominant attribute, characterizing the aftertaste.

Table 5 | Temporal dominance of sensations results of sucrose-citric acid mixtures under varying concentration

Sucrose-citric acid mixture	Total time*	Sweet*	Sour*	Astringency*	Salivating sensation	Cloying sweetness*
2% Sucrose + 0.003% Citric acid	38.1 ± 1.99 ^{ab}	17.69 ± 1.9 ^a	5.02 ± 1.24 ^d	6.48 ± 1.57 ^{ab}	7.33 ± 1.79 ^a	1.57 ± 0.67 ^b
2% Sucrose + 0.006% Citric acid	33.12 ± 1.65 ^b	12.19 ± 1.35 ^{bc}	6.69 ± 0.95 ^{cd}	4.69 ± 0.99 ^b	9.02 ± 1.7 ^a	0.52 ± 0.31 ^b
2% Sucrose + 0.010% Citric acid	40.62 ± 2.55 ^{ab}	7.81 ± 1.5 ^{cd}	10.79 ± 1.38 ^{ab}	10 ± 2.22 ^a	11.07 ± 2.07 ^a	0.95 ± 0.66 ^b
6% Sucrose + 0.010% Citric acid	39.79 ± 2.98 ^{ab}	16.9 ± 1.77 ^{ab}	4.79 ± 1.1 ^d	3.14 ± 1.38 ^b	12.07 ± 2.33 ^a	2.88 ± 1.02 ^{ab}
6% Sucrose + 0.018% Citric acid	37.71 ± 1.75 ^{ab}	16.31 ± 1.73 ^{ab}	7.74 ± 0.86 ^{bcd}	3.33 ± 0.89 ^b	8.4 ± 2.12 ^a	1.93 ± 0.74 ^{ab}
6% Sucrose + 0.030% Citric acid	40.48 ± 3.59 ^{ab}	9.21 ± 1.68 ^{cd}	11.43 ± 1.42 ^{ab}	7.21 ± 2.02 ^{ab}	11.52 ± 2.53 ^a	1.1 ± 0.57 ^b
10% Sucrose + 0.037% Citric acid	42.12 ± 3.53 ^a	18.26 ± 2.18 ^a	5.76 ± 0.63 ^{cd}	6 ± 1.89 ^{ab}	7.9 ± 1.35 ^a	4.19 ± 1.37 ^a
10% Sucrose + 0.068% Citric acid	41.83 ± 3.15 ^{ab}	14.67 ± 2.27 ^{ab}	9.29 ± 1.02 ^{bc}	6.64 ± 1.74 ^{ab}	8.88 ± 1.85 ^a	2.36 ± 0.93 ^{ab}
10% Sucrose + 0.112% Citric acid	39.71 ± 2.71 ^{ab}	6.6 ± 1.11 ^d	14.02 ± 1.94 ^d	4.88 ± 1.39 ^b	13.64 ± 2.6 ^a	0.57 ± 0.25 ^b

* Indicate that the samples were significantly different.

Different letters in the same line indicate significant differences between samples by Duncan's test ($p < 0.05$).

A significance analysis was conducted on the temporal dominance of sensations' data of sucrose-citric acid mixtures under varying concentration conditions, with the results presented in Table 5. Initially, it was observed that increasing concentrations of citric acid and sucrose had little impact on the overall perception duration of dynamic dominant sensations, indicating that the duration of dominant sensations remained relatively stable throughout the tasting process. Secondly, it was observed that the intensity of sweetness perception was more profoundly influenced by variations in citric acid concentration under low sucrose concentration conditions. Thirdly, our findings indicated that the dominant duration of the salivating sensation remained unaffected by alterations in both citric acid and sucrose concentrations, highlighting the relative independence of salivating sensation perception from the intensities of sweetness and sourness. Lastly, a notable trend emerged wherein the dominant duration of cloying sweetness exhibited a positive correlation with increasing sucrose concentrations, while demonstrating a negative correlation with rising citric acid concentrations.

Our findings on the dominance transition from sweetness/sourness to salivating sensation in sucrose-citric acid aqueous solutions differed from observations in coffee, where sweet-to-flavor dominance shifts occur with delayed transitions²⁴. This discrepancy might stem from matrix complexity: in simple aqueous systems, physicochemical interactions (e.g., taste masking, salivary dilution) drive post-swallow salivation dominance, whereas in heterogeneous systems (e.g., coffee), delayed tastant release or flavor-taste binding might prolong flavor dominance. Notably, our findings and Monteleone's work both indicated the critical role of temporal dynamics in sensory dominance, suggesting that oral processing mechanisms (e.g., shear forces, saliva interaction) modulate attribute transitions, though their specific drivers depend on matrix rheology and compositional synergy.

The correlation analysis result between the durations of dominant attributes and the total duration in sucrose-citric acid mixtures is shown in Supplementary Fig. 2. As depicted in the figure, the attributes of sweetness, astringency, and salivating sensation exhibited a statistically significant positive correlation with the total duration of the temporal dominance of sensations test. Conversely, sourness demonstrated no discernible influence on the overall duration. Furthermore, a notable negative correlation was observed between sweetness and sourness, indicating that as the perception of sourness diminishes, the perception of sweetness intensifies, suggesting a reciprocal inhibitory relationship between the two sensory attributes. Additionally, the correlations between cloying sweetness and other sensory attributes were generally weak, indicating that cloying sweetness is relatively independent of and less influenced by other sensory attributes.

TDL results of sucrose-citric acid mixtures

The analysis of TDL was a methodology that combined dynamic dominant sensations testing with DL testing, enabling an in-depth comprehension of how sensory attributes influenced liking and its temporal evolution during

sample perception²⁵. The CLWD value, calculated through this methodology, signified an individual's liking perceived during the dominance of a specific sensory attribute, reflecting the positive or negative driving impact of that attribute on liking. The TDL results of sucrose-citric acid mixtures of varying concentrations were listed in Table 6.

Under the background of low sucrose concentration (2%), the astringency attribute exhibited a significant reduction in liking, implying its contribution to a negative sensory experience. This result was similar to the Rudge²⁶ and Zhao's²⁷ studies, which both highlighted the negative impact of astringency on sensory perception. Meanwhile, an imbalance in the intensity of taste attributes between sucrose and citric acid led to a notable positive influence of sweetness and sourness attributes on DL. Conversely, when the intensities of these taste attributes were relatively balanced, the positive effect of sweetness and sourness descriptors was not statistically significant. These findings underscore the critical role of the balance between sweetness and sourness intensities in eliciting positive sensory evaluations during taste perception. Lastly, under this concentration condition, the impact of the sweet cloying attribute on DL was not statistically significant.

Under the background of medium sucrose concentration (6%), the following observations were made. Firstly, a significant reduction in liking was observed among certain assessors due to the perception of sweet cloying. This finding suggested that when the intensity of sweetness became relatively high, assessors might perceive excessive sweetness, leading to discomfort and subsequently negatively influencing overall sensory preference. This observation aligned with the findings of Akemura and Xu^{28,29}, who also reported that excessive sweetness could diminish preference, highlighting the importance of balancing sweetness intensity to optimize sensory appeal. Secondly, it was found that increasing the concentration of citric acid mitigated the negative effects associated with excessive sweetness. Finally, the negative influence of the salivating sensation became significant in the presence of medium to high concentrations of citric acid, suggesting that under certain specific sweetness-to-sourness ratios, the perception of salivating sensation may elicit a negative sensory experience.

Under the background of high sucrose concentration (10%), it was observed that even when the intensity of sourness surpassed that of sweetness, a notable perception of sweet cloying persisted among a subset of assessors, leading to a detrimental effect on liking. This observation underscored that the emergence of sweet cloying was not solely contingent upon the sweet-to-sour ratio but was also intimately linked to the duration of these sensory attributes. Particularly during the initial phases of sample evaluation, despite the prevalence of sourness, the inhibitory effect of sourness progressively waned over time. This, in turn, led to an overpowering intensity of sweetness that might have induced discomfort among the assessors. Consequently, strategies such as prolonging the duration of the acidulant or opting for sweeteners with shorter sweetness durations could effectively mitigate the adverse influence of sweet cloying on liking. These results have practical implications for food and beverage product

Table 6 | Temporal drivers of liking results of sucrose-citric acid mixtures under varying concentration

Concentration of sucrose	Sensations	Concentration of citric acid					
		0.003%		0.006%		0.010%	
		n	CLWD	n	CLWD	n	CLWD
2%	Sweet	42	0.19***	41	0.11	32	0.19***
	Sour	25	0.29***	33	0.11	41	0.21***
	Astringency	22	-0.09	24	0.04	24	-0.12**
	Salivating sensation	20	-0.07	28	-0.10**	32	-0.12
	Cloying sweetness	6	-0.23	3	-0.21	3	-0.55
6%		0.010%		0.018%		0.030%	
		n	CLWD	n	n	CLWD	n
	Sweet	42	0.14**	41	42	0.14**	41
	Sour	28	0.30***	39	28	0.30***	39
	Astringency	14	0.11	17	14	0.11	17
	Salivating sensation	30	-0.06	22	30	-0.06	22
	Cloying sweetness	8	-0.17**	7	8	-0.17**	7
10%		0.037%		0.068%		0.112%	
		n	CLWD	n	n	CLWD	n
	Sweet	42	0.26***	40	42	0.26***	40
	Sour	39	0.52***	38	39	0.52***	38
	Astringency	19	0.140	19	19	0.140	19
	Salivating sensation	29	-0.10	27	29	-0.10	27
	Cloying sweetness	13	-0.22**	6	13	-0.22**	6

Significance level: *10%, **5%, ***1%.

development, where optimizing sweetness and acidity balance is critical. By selecting appropriate sweeteners or adjusting the duration of sensory attributes, manufacturers can enhance consumer preference and satisfaction. For instance, in beverages or confectionery, using sweeteners with shorter sweetness durations or incorporating acidulants that extend the perception of acidity could reduce the perception of excessive sweetness, leading to more balanced and enjoyable sensory experiences. This approach not only improves product appeal but also aligns with consumer preferences for natural and balanced flavors.

Methods

Preparation of sucrose-citric acid mixtures

Sucrose and citric acid were purchased from Shanghai Aladdin Biochemical Technology Co., Ltd. In the TI assessment section, the concentrations of sucrose-citric acid mixtures were listed in Supplementary Tables 1 and 2. The DL and TDS assessments' samples were listed in Supplementary Table 3. All the solutions were prepared using ultrapure water, with a resistivity of 18.2 MΩ-cm, by using the Millipore system. Before the sensory analysis, all the samples were kept at 20 °C.

Sensory panel

The sensory panel comprised 30 selected assessors (15 males and 15 females, aged between 20 and 35 years), selected in accordance with the Chinese national standard GB/T 16291.1-2012: Sensory analysis - General guidance for the selection, training, and monitoring of assessors - Part 1: Selected assessors. Each participant was apprised of the study's objectives and underwent a comprehensive two-week training program (conducted once daily), which encompassed the following aspects:

- (1) Sensory evaluation terminology training: This included instruction on terms such as intensity, dynamic, and liking, to ensure a common language among assessors.
- (2) Basic taste sensation discrimination: All participants were required to achieve perfect scores in distinguishing various taste sensations.

- (3) TI, TDS, and DL method training: Assessors were trained in TI, TDS, and DL methods to enhance their sensory evaluation skills.
- (4) Taste intensity evaluation accuracy: The relative error in evaluating the taste intensity of the same concentration was expected to be less than 10%, ensuring high precision in measurements.

Furthermore, all assessors were instructed to abstain from smoking and eating for at least half an hour prior to each sensory evaluation experiment to minimize potential interferences.

The above selecting and training experiments were obtained ethical approval from the Ethics Committee of Zhejiang Gongshang University (23134701). All participants provided written informed consent prior to participation, with explicit information about data confidentiality and voluntary withdrawal rights.

TI assessment

The assessors were instructed to rinse their mouths prior to the commencement of the formal experiment. Subsequently, they were required to taste reference samples categorized as 'slight' and 'extreme' for the purpose of taste correction pertaining to sweetness and sourness. The sample testing was executed utilizing the 'SugarRuler module' integrated within the EasySensory Evaluation software, which was self-developed by our laboratory.

Upon the initiation of the test, each assessor consumed 10 mL of the sample in a single instance to ensure comprehensive contact between the sample and the oral cavity. After a duration of 10 seconds, the software's screen displayed the instruction 'Please swallow', prompting the assessors to ingest the entire sample. It was imperative for the assessors to swallow all samples while maintaining an unaltered internal state of their mouths and refraining from swallowing saliva. Throughout this process, the assessors were tasked with continuously moving or clicking the cursor in accordance with the perceived taste intensity until it subsided entirely.

The software was configured to collect intensity data at a frequency of 0.01 seconds and store this information on the computer. A mandatory rest period of at least 2 minutes was enforced between each sample to ensure the accuracy and reliability of the sensory evaluations.

Taste attributes determination for the temporal dominance of sensations assessment

In the Temporal Dominance of Sensations assessment, the evaluation of individual attributes was not carried out in isolation. Instead, it necessitated the ongoing selection of predominant attribute descriptors from a multitude of attributes throughout the entire evaluation process. Hence, the development of an attribute list that was both exhaustive and succinct emerged as a pivotal task³⁰.

In this study, a panel of 12 expert sensory assessors was assembled to form an attribute term evaluation panel. Initially, a series of samples with different concentration combinations of sucrose, citric acid, and their mixtures were provided. These samples encompassed a range of sweet and sour intensities, including those that were predominantly sour, predominantly sweet, moderately balanced, as well as low, medium, and high concentrations of sucrose and citric acid. Subsequently, each assessor assessed the aforementioned samples and provided corresponding sensory attribute terms. Ultimately, the team leader of the evaluation panel facilitated a discussion and selection process to finalize the attribute terms for the sensory evaluation. The attribute terms and their definitions obtained in this study for the sucrose-citric acid mixture were presented as follows.

- (1) Sweet: A fundamental taste sensation was generated by the dilute aqueous solutions of natural or artificial substances, such as sucrose or aspartame.
- (2) Sour: A fundamental taste sensation was elicited by the dilute aqueous solutions of acidic substances, such as citric acid, tartaric acid, and others.
- (3) Astringency: The chemical stimulation induced a contraction of the tongue or the surface of the oral cavity, leading to a sensation characterized by roughness, dryness, and shrinkage, accompanied by the pulling or wrinkling of the skin.
- (4) Salivating sensation: The mouthfeel or taste of food stimulated the secretion of saliva, resulting in a sensation of increased moisture in the mouth and on the tongue.
- (5) Cloying sweetness: a sensation of discomfort induced by the excessive intensity of sweetness.

DL and temporal dominance of sensations assessments

Understanding that qualitative-quantitative testing could potentially exert an influence on preference assessments, the same sample was rigorously subjected to a preference evaluation prior to undergoing quantitative analysis³¹. The detailed methodology was outlined as follows.

In the initial stage, the DL assessment was conducted utilizing the 'SugarPreference module' integrated within the EasySensory Evaluation software. During this assessment, the panelist was instructed to take a 10 mL aliquot of the sample into their mouth, retain it for a duration of 10 seconds, and subsequently swallow it. Throughout this entire process, continuous evaluation of sample preference was undertaken, extending until all sensory perceptions had dissipated post-ingestion.

In the second stage, the TDS assessment was administered, adhering to a protocol analogous to the DL assessment, utilizing the 'SensoMaker module' integrated within the EasySensory Evaluation software. Specifically, the panelist was instructed to identify and select the predominant sensory attributes immediately upon ingesting the sample, and to continue this process until all sensations had completely dissipated.

Data analysis

Compared with other sensory evaluation techniques, TI curves were distinguished by the abundant information they contain within individual curves, as well as by the substantial inter-panelist variability and intra-individual consistency observed. In light of these characteristics, the present

study adopted the methodology proposed by Liu³² for processing TI data. This involved generating mean curves for visual comparison of different samples. Utilizing MATLAB, key parameters of the TI curves were extracted to provide a quantitative characterization of the curves. Subsequently, analysis of variance was conducted to rigorously analyze the effects of both panelists and samples on the sensory perceptions measured.

Data analyses for DL and TDS were conducted using XLSTAT and MATLAB. Subsequently, the TDL approach was employed to systematically investigate the influence of dominant sensory attributes on the DL scores obtained throughout the sensory evaluation³³.

Ethical approval

This study obtained ethical approval from the Ethics Committee of Zhejiang Gongshang University (23134701). All participants provided written informed consent before participation, with explicit information about data confidentiality and voluntary withdrawal rights.

Statement confirmation

All the participants provided written informed consent to take part in this study.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Author contributions

Y.M.: investigation, formal analysis, sensory analysis, and writing-original draft. Z.Z., L.L.: investigation, formal analysis, and sensory analysis. X.Y., Y.Q., Z.Q., Y.C.: investigation. X.Z., J.S.: methodology and conceptualization. and writing a review. S.T., G.J.: conceptualization, writing, review, editing, and supervision.

Competing interests

The authors declare no competing interests.

Additional information

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