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Suppression of sourness: A comparative study involving mixtures of organic acids and sugars

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The degree of sourness suppression of perceptually equisour levels of citric, lactic, and malic acids by equal molar and weight amounts of sucrose, fructose, and glucose was determined in binary mixtures. Equisour acid levels were obtained by magnitude estimation. Mixture intensity ratings were collected on a categorical scale, using trained panelists. In general, equal sugar molarities and weights did not effect equivalent suppression. Instead, the perceived intensity of the sugars appeared to suppress sourness more systematically, implying that dominantly central neural mechanisms underlie suppression. This was confirmed when no significant differences were found between the suppressive abilities of sweetness-matched levels of sucrose, fructose, and an equiratio mixture of the two on citric acid sourness. The possibility of a separate receptor site/mechanism for glucose and a small peripheral component to suppression is also suggested.

Acids have many functions in food systems, including preserving, buffering, flavoring, and chelating. Acids are routinely used in the food industry as a means of lowering the pH of foods and beverages to enhance their shelf lives. Acidification of heat-sensitive, low-acid foods allows for commercial sterility with milder heat treatment (Sognefest, Hays, Wheaton, & Benjamin, 1948), thereby providing lower energy usage and overall cost reduction. However, the addition of commonly used food-grade organic acids alters the flavor of acidified foods, often rendering them unpalatable. As a result, only a few low-acid foods with the ability to tolerate such acid flavors have been successful candidates for acidification (McCarthy, Heil, Krugermann, & Desvignes, 1991).

Suppression or partial masking of sourness regularly occurs in complex food systems. It is well known that sweeteners constitute one of the most effective masking agents for sourness. Sweeteners are combined in the formulations of acidified foods to achieve optimum taste, while maintaining the desired pH. However, the most effective sweet masker(s) for a particular acid and the optimal level or range of the masker, given the acid concentration, are usually ascertained by a trial-and-error approach.

Mixture interactions have been variously examined in the literature, but the interaction of tastants with a view to achieving suppression of sourness has not received much attention. In studies involving interactions between sweet and sour tastants, citric acid and sucrose have primarily been used. Suprathreshold levels of citric acid have been shown to suppress sucrose sweetness (Pangborn, 1961). Sucrose was reported to suppress the perceived intensity of citric acid (McBride, 1989; McBride & Johnson, 1987). Schifferstein and Frijters (1991) reported that equisweet levels of aspartame, saccharin, fructose, and sucrose were equally effective in suppressing the perceived sourness of citric acid, whereas McBride and Finlay (1990) found that sucrose suppressed the sourness intensity of citric acid more effectively than did fructose. Mutually suppressing interactions between citric acid and the sweeteners aspartame and sucrose revealed that there was a greater suppression of sweetness by acid levels than of sourness by increasing sweetener levels (Bonnans & Noble, 1993).

The phenomenon of taste suppression, in general, depends on three main factors: (1) the type of suppressing taste substance, (2) the physical intensity of the suppressing component, and (3) the relative number of components that make up the mixtures (Kroeze, 1989). With respect to the physical intensity of the suppressing component, it has not been clearly established whether the weight, the molarity, or the perceived intensity of the suppressor is a significant determinant of the resulting suppression. Our goal in this study was to better understand the role played by each of these factors. A relationship between sourness suppression and sugar molarity would favor molecular mechanisms as being responsible for the suppression, whereas one with sugar weight might implicate physical effects, such as viscosity. On the other hand, a correspondence with perceived sugar sweetness would be indicative of neural effects (central/peripheral). Although the idea that suppression in sweet–sour mixtures is a perceptual phenomenon related

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to the perceived intensity of the masking agent has been explored (Schifferstein & Frijters, 1991), the work was limited to sourness suppression of citric acid alone, and the effects of the molarity or the weight of the masker were not concurrently examined.

Our objective was to determine the effects of the molarity, weight, and perceived sweetness intensity of three sugars on the perceived sourness intensity of three food-grade organic acids at perceptually equisour levels in a water-based model system. The results were confirmed by testing the effects of equisweet concentrations of two of the sugars on the sourness of one acid.

METHOD

Subjects

The subjects were selected on the basis of performance in a prescreening exercise that tested for sensitivity and reproducibility via a ranking test. Seventeen panelists (12 women and 5 men) qualified for participation. The subjects' ages ranged from 19 to 30 years. The subjects included staff and students at Oregon State University and residents from the local community. All were compensated for their participation.

Stimuli

Food-grade solutes were $>$ 99% pure, with the exception of lactic acid (calcium salt form), which was ~60% pure. The solutions were made in distilled water. Citric, lactic, and malic acids were used in the mixtures, and acid levels were selected by a sourness-matching exercise to be equisour with 0.00625 and 0.025 mol citric acid, designated *low* and *high*, respectively. The equisour acid levels were determined through trained panel evaluation using magnitude estimation (Stevens, 1956, 1957). The testing protocol followed Rubico (1993) and Moskowitz and Sidel (1971), wherein trained panelists evaluated sourness, using a reference modulus (0.00625 mol citric acid). Sourness-matched levels were determined from the power functions of the acids generated through magnitude estimation (Figure 1).

The sweeteners used were sucrose, fructose, and glucose. Sweetener levels were designated *low* and *high*, corresponding to 0.0625 and 0.25 mol on a molar basis and 11.25 and 45 g/L on a weight basis. The molar values were selected on the basis of literature values and pilot testing. The listed weight levels were selected because the sugars glucose and fructose fortuitously have identical formula weights and molecular weights, thereby allowing a reduction in the total number of samples to be tested. Sucrose has a different formula weight and molecular weight; therefore, for the purposes of experimental design and analysis, it was treated as two sweeteners (i.e., sucrose equimolar and sucrose equiweight). A sugar-free acid control was simultaneously tested at every level of each acid. All the stimulus concentrations are presented in Table 1. This resulted in a factorial plus control experimental design [(3 acids × 2 acid levels × 4 sweeteners × 2 sweetener levels) + acid control]. In addition, evaluation of all *48 + control* treatment combinations was conducted in duplicate, providing two replications.

The results from the work above were confirmed using two sugars (sucrose and fructose) and one acid (citric). Sweetness matching was performed on sucrose, fructose, and a 1:1 equiratio mixture of the two. Equiratio sugar mixtures were prepared on the basis of a procedure described by Frijters and Oude Ophuis (1983). Three sweetness-matched levels obtained from the sugar power functions (Figure 2) were used to test the effect of equisweet sugar concentrations on the suppression of citric acid sourness. The sugar levels selected from the plots were equisweet with 0.0313, 0.0625, and 0.125 mol sucrose. The concentration of citric acid in all the mixtures was fixed at 0.00625 mol.

Procedure

The solutions were prepared 12–14 h before testing and were stored overnight at 4º C. Prior to serving, solutions were allowed to equilibrate to room temperature (21º to 22ºC). Approximately 30 ml of each sample was presented in 85-ml plastic cups, and the cups were coded with three-digit random numbers. Up to five samples were served in a set, and no more than four sets were presented each day. The serving order of samples was randomized within an acid type and level, with each sample being evaluated twice. The stimuli were sampled by the sip-and-spit method. This part of the study used category scaling, where subjects rate the intensities of stimuli by assigning them values on a limited, typically numerical scale (Meilgaard, Civille, & Carr, 1991). Direct scaling of this type has its basis in the scaling developed by Thurstone, whose law of comparative judgment pointed out that the degree to which the psychological impressions of any two stimuli in a set overlap (i.e., the amount of con-

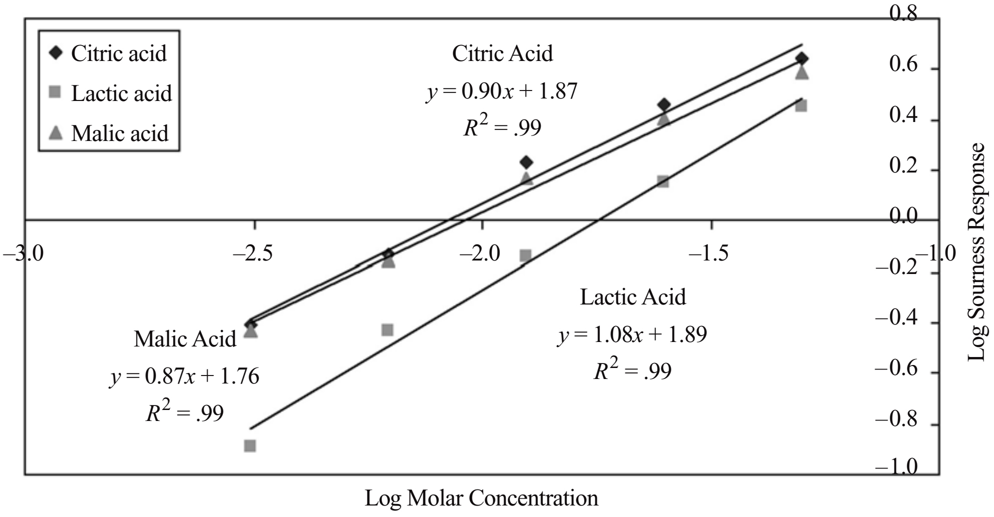


Figure 1. Power functions of acid sourness. Each data point represents the mean of 51 values (17 panelists × 3 replications).

Table 1
Stimulus Concentrations

Sugar	Molarity (in mol)	Weight (in grams/liter)	Acid	Molarity (in mol)	Weight (in grams/liter)
Low glucose (Em/Ew)	0.0625	11.25	low citric	0.00625	1.2
Low fructose (Em/Ew)	0.0625	11.25	low malic	0.0068	0.9112
Low sucrose (Em)	0.0625	21.375	low lactic	0.0142	2.166102
Low sucrose (Ew)	0.03289	11.25	high citric	0.025	4.8
High glucose (Em/Ew)	0.25	45	high malic	0.0288	3.8592
High fructose (Em/Ew)	0.25	45	high lactic	0.06283	9.58408
High sucrose (Em)	0.25	85.5			
High sucrose (Ew)	0.13158	45			

Note—Em, equimolar; Ew, equiweight.

fusion between the stimuli) is enough information for one to infer the psychological distances among the various stimuli (Riskey, 1988). Upon tasting the samples, the panelists rated the sweetness and sourness intensities of the mixture solutions on a 16-point intensity scale (0 = *none*, 3 = *mild*, 7 = *mild to moderate*, 11 = *moderate*, and 15 = *moderate to high*). The panelists were trained in the use of the scale with the help of references and training exercises conducted prior to testing. The sourness references made with citric acid were as follows: sour 3 (0.00313 mol), sour 7 (0.00625 mol), sour 11 (0.0125 mol), and sour 15 (0.025 mol). The sweetness references were made with fructose at the following levels: sweet 3 (0.0625 mol), sweet 7 (0.125 mol), sweet 11 (0.25 mol), and sweet 15 (0.5 mol). The panelists were encouraged to thoroughly rinse their mouths with water between samples. The subjects were also asked to refrain from smoking, eating, or drinking anything for at least a half hour before testing. The pH of all the controls and binary mixture solutions was recorded prior to testing.

Data Analysis

Sessions were separated by acid type (citric, malic, or lactic) and level (low or high), giving a total of six sessions. The data were analyzed using a mixed-model analysis of variance within session, with Tukey's honest significant difference as the post hoc means separation procedure. Analyses were conducted using SPSS Version 8.0 (1997). Model effects were treatment (sugar name and level; fixed effect), panelist (random effect), and the interaction of panelist and treatment (random effect).

For the confirmation, the analysis was conducted within a sweetness-matched sugar level obtained from the sugar sweetness functions in Figure 2.

RESULTS

The Effect of Equiweight and Equimolar Sugar Concentrations and the Effect of Perceived Sweetness of the Sugars at Equiweight Levels

Mean sourness and sweetness intensity ratings for all the mixtures are presented in Table 2. From this point on, *sourness suppression*, or *the degree of suppression*, will refer to a reduction in the sourness rating for a mixture solution, as compared with the sourness rating for the corresponding acid-only control.

Trends within acids and across sugars. From the values in Table 2, it can be seen that for the three acid mixtures at low and high acid levels, sourness suppression was significant for the mixtures with equimolar fructose, as well as equiweight sucrose, at the high sugar level ($p < .05$). In addition, mixtures of low- and high-level malic acid with equimolar sucrose at the low sugar level were found to show significantly more sourness suppression ($p < .05$), as compared with the low sugar level mixtures

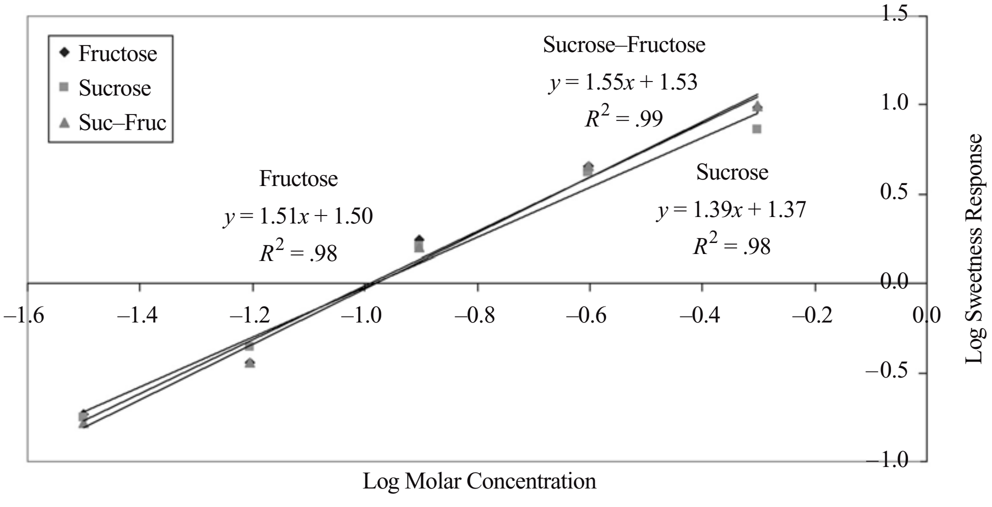


Figure 2. Power functions of sugar sweetness. Each data point represents the mean of 51 values (17 panelists × 3 replications).

Table 2
Mean Sourness and Sweetness Intensity Ratings for Control (No-Sugar) and Binary Acid–Sugar Mixtures at Low and High Sugar and Acid Levels

	Citric Acid Mixtures		Lactic Acid Mixtures		Malic Acid Mixtures	
Sugar Level and Type	Mean Sourness	Mean Sweetness	Mean Sourness	Mean Sweetness	Mean Sourness	Mean Sweetness
			Low Acid Level			
Control	8.53_{a}	0.97_{f}	7.97_{a}	0.85_{f}	8.12_{ab}	0.97_{g}
Low fructose	7.88_{a}	3.38_{de}	7.50_{a}	3.00_{e}	8.56_{a}	2.74_{e}
Low glucose	8.35_{a}	1.18_{f}	8.32_{a}	1.50_{f}	8.50_{a}	1.21_{fg}
Low sucrose (Em)	6.79_{ab}	4.85_{cd}	7.03_{ab}	4.32_{d}	7.06_{bc}	4.59_{d}
Low sucrose (Ew)	7.50_{a}	2.18_{ef}	7.38_{ab}	1.82_{f}	7.88_{ab}	2.26_{ef}
High fructose	5.53_{b}	10.32_{ab}	5.21_{cd}	9.26_{b}	5.38_{d}	10.21_{b}
High glucose	7.88_{a}	5.18_{c}	7.12_{ab}	3.26_{de}	8.06_{ab}	3.97_{d}
High sucrose (Em)	5.06_{b}	11.85_{a}	4.06_{d}	11.88_{a}	3.74_{e}	12.62_{a}
High sucrose (Ew)	5.71_{b}	9.12_{b}	6.09_{bc}	7.85_{c}	5.85_{cd}	7.44_{c}
			High Acid Level			
Control	12.38_{a}	0.68_{f}	11.18_{ab}	0.91_{d}	11.32_{ab}	0.82_{e}
Low fructose	11.97_{a}	2.15_{de}	10.53_{abcd}	1.56_{d}	11.62_{a}	1.79_{de}
Low glucose	11.82_{ab}	1.09_{f}	11.65_{a}	1.18_{d}	11.79_{a}	1.56_{e}
Low sucrose (Em)	11.32_{ab}	3.50_{c}	10.09_{bcd}	3.03_{c}	9.91_{bc}	3.74_{c}
Low sucrose (Ew)	11.62_{ab}	1.44_{ef}	10.97_{abc}	1.65_{d}	10.74_{ab}	2.03_{de}
High fructose	9.91_{c}	7.24_{b}	9.76_{cd}	6.35_{b}	8.56_{cd}	9.18_{b}
High glucose	11.97_{a}	3.18_{cd}	10.82_{abc}	2.68_{c}	10.50_{ab}	3.06_{cd}
High sucrose (Em)	9.32_{c}	9.85_{a}	7.62_{e}	10.26_{a}	7.44_{d}	11.12_{a}
High sucrose (Ew)	10.53_{bc}	6.88_{b}	9.38_{d}	6.38_{b}	8.82_{cd}	7.97_{b}

Note—Means with different alphabetic subscripts within a column and acid level are significantly different at $p \leq .05$; means are across 17 panelists and 2 replications. Scale values correspond to 0 = *none*, 3 = *mild*, 7 = *mild to moderate*, 11 = *moderate*, and 15 = *moderate to high*. Em, equimolar; Ew, equiweight.

with fructose and glucose. Also, an interesting anomaly, albeit nonsignificant ($p > .05$), was noted in low sugar level mixtures of glucose with lactic and malic acids at both acid levels and of fructose with malic acid at both acid levels, where the sugar–acid mixture was perceived to have a higher sourness than the corresponding acid control.

The pH of all the mixture solutions was dictated by the pH of the acid type and level present in the mixture, and so the pH of the low citric acid control and the corresponding mixtures was 2.63 ± 0.01, whereas that of the high-acid control and the mixtures was 2.45 ± 0.01. The pH of the lactic acid controls and mixtures at the low and high acid levels was 3.45 ± 0.01 and 3.39 ± 0.01, respectively, whereas that of the malic acid controls and mixtures was 2.82 ± 0.01 and 2.54 ± 0.01 at low and high acid levels, respectively.

Trends within sugars and across acids. Figures 3A–3F show degree of sourness suppression as a function of perceived sweetness of sugars at equiweight levels. From a comparison of glucose–acid mixtures shown in Figures 3A and 3B versus Figures 3C and 3D (fructose–acid mixtures) and Figures 3E and 3F (sucrose–acid mixtures), it appears that the glucose–acid mixtures behaved differently than did the acid mixtures with the other sugars. The glucose was perceived to impart some sweet taste, but it did not show much corresponding sourness suppression (degree of suppression not exceeding 1 at the levels examined). The acid–sugar mixtures of fructose and sucrose showed marginally higher suppression in the mild sweetness intensity range and substantially higher suppression in the mild-to-moderate sweetness intensity range.

The Effect of Equisweet Sugar Concentrations

Within the three perceptually sweetness-matched levels, the sweetness ratings for the sugar types were not significantly different, demonstrating the success of the sweetness matching (Figure 4). The corresponding sourness ratings for the mixtures were similarly not significantly different from each other but were significantly different from the acid-only and sugar-only controls at all three equisweet levels (Figure 4).

DISCUSSION

Across acid types and levels, it was found that equiweight and equimolar levels of the sugars effected unequal amounts of sourness suppression in terms of a decrease in perceived sourness intensity ratings. If the suppression at either the equiweight or the equimolar sugar level had been equivalent across the acids, physical sugar parameters or molecular mechanisms would be the likely cause of such suppression. However, the results imply that neither completely explains the observed suppression. Although a sugar concentration effect is undeniable (because it is linked to sugar weight, sugar molarity, and perceived sweetness), in the context of our stated objectives, sugar weight or sugar molarity alone did not account for the suppression seen.

To better examine the effect of the perceived intensity of the masking agent on the target taste, the three sugars were selected for the property of being ranked in their perceived sweetness intensitiy at equal weight levels. Shallenberger (1993) averaged the findings of several taste studies to show that on a weight basis, when sucrose has a

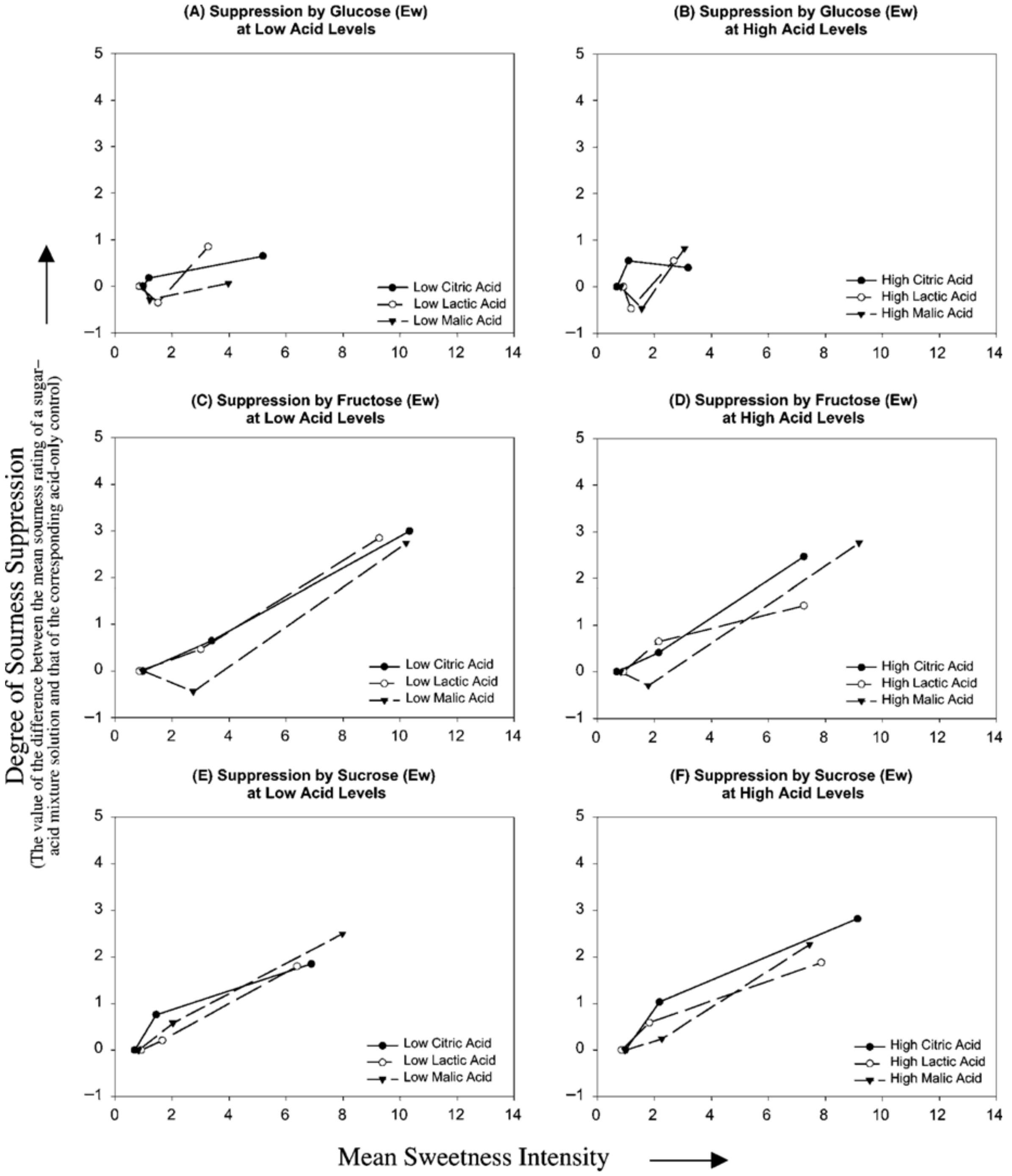


Figure 3. Degree of sourness suppression as a function of sweetness by equiweight (Ew) sugars across acid types.

relative sweetness of 100, the average relative sweetness of D-glucose is 64, whereas that of D-fructose is 120.5, making fructose the sweetest of the three. On the other hand, on a molar basis, sucrose is the sweetest of the three.

As can be seen from the mean values in Table 2, at equimolar sugar levels, sucrose mixtures were found to be the sweetest, and the glucose mixtures were the least sweet. Thus, the order of perceived sweetness intensities of the individual sugars, as predicted by Shallenberger (1993), was also observed in mixtures of the same sugars with the three acids at two levels each; this order of perceived sweetness was translated into a corresponding suppression of sourness, with sucrose suppressing more than fructose, which in turn suppressed more than glucose.

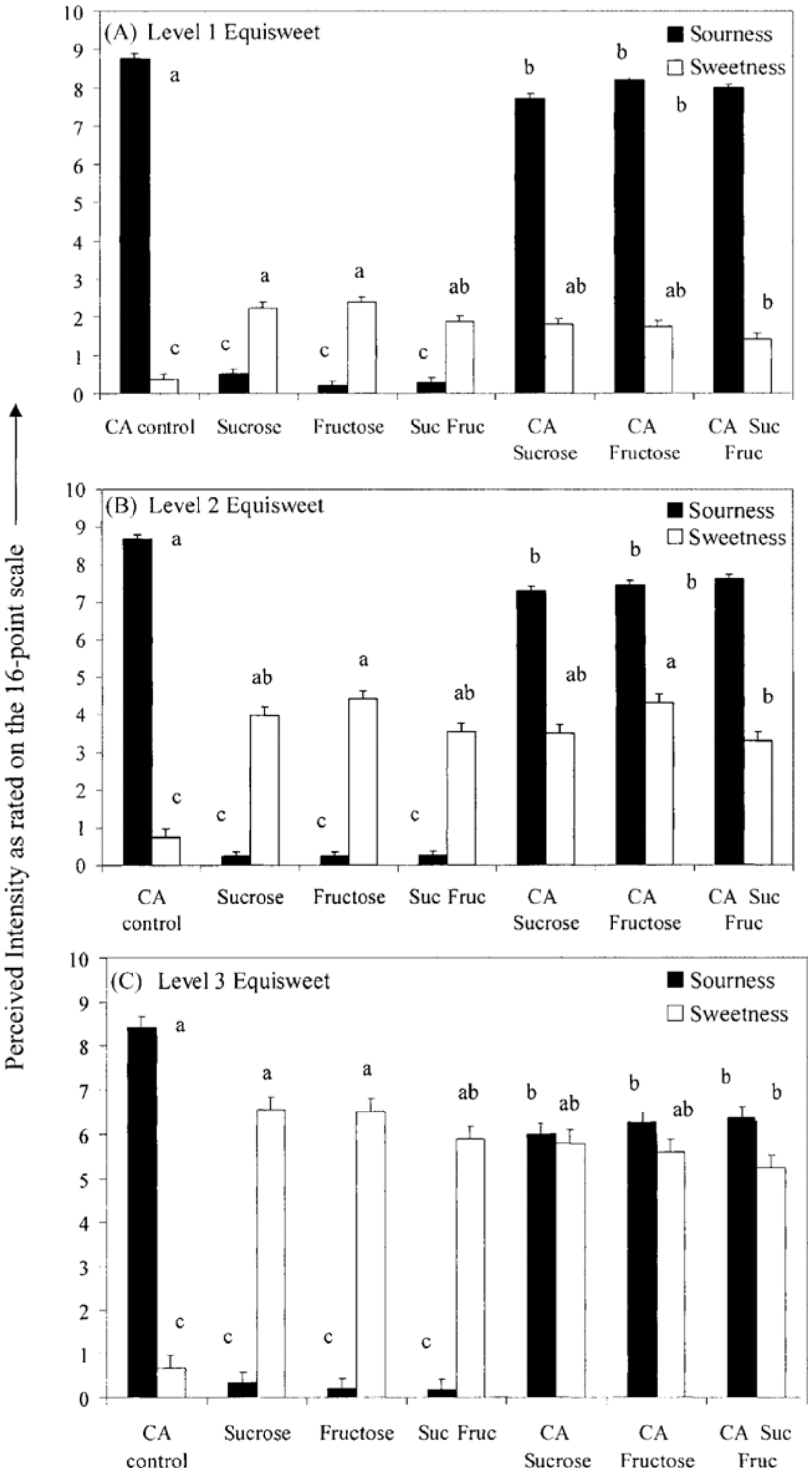
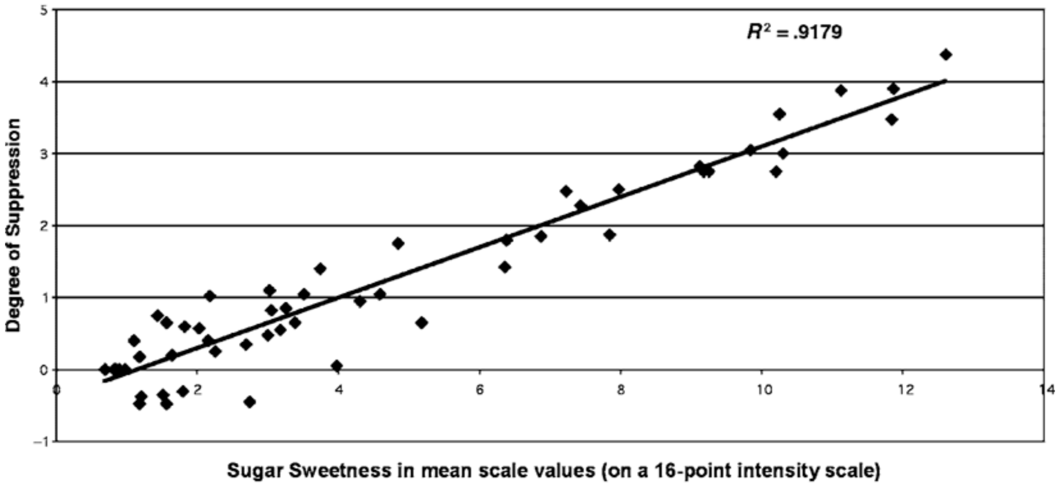


Figure 4. Sourness and sweetness ratings at Equisweet Levels 1, 2, and 3. CA, citric acid.

With sugars on an equiweight basis, fructose mixtures were the sweetest and the glucose mixtures were the least sweet at the low acid level, as was expected. But at the high acid level, there were no significant differences ($p > .05$) between the sweetness ratings of the fructose and the sucrose mixtures. These results are in accordance with Cardello, Hunt, and Mann (1979), who similarly observed that fructose, which has a sweetening advantage over su-

(a) Impact of Sugar Sweetness on Degree of Sourness Suppression



(b) Impact of Sugar Molarity on Suppression of Sourness

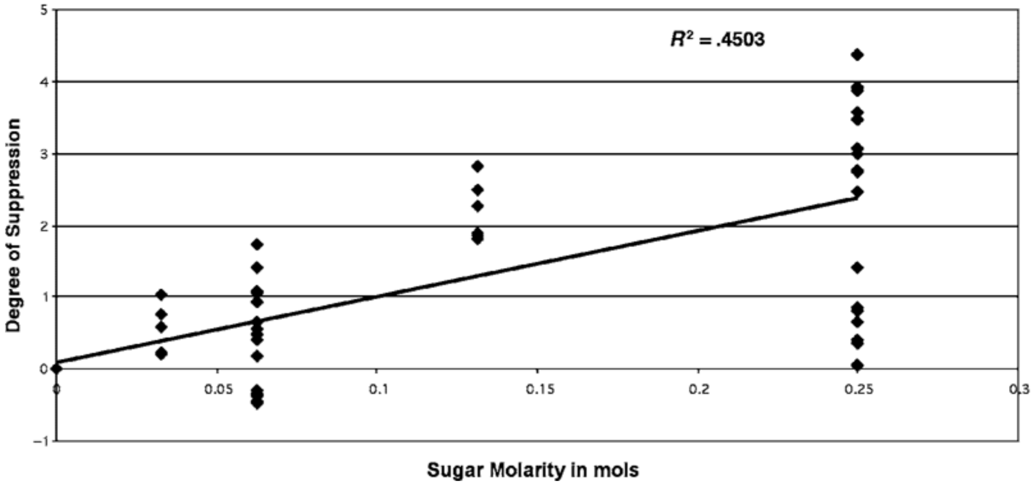


Figure 5. Degree of sourness suppression versus sugar sweetness, sugar molarity, and sugar weight across all the acid and sugar mixture data.

crose in model distilled water solutions, as well as in low acid media at low sugar concentrations, loses this advantage in highly acidic solutions. Thus, at the high acid level, fructose and sucrose mixtures with all three acids were found to be similar in their sweetness ratings and similar in terms of the corresponding sourness ratings ($p > .05$). Consequently, although it seemed likely that the perceived sweetness intensities of sucrose and fructose determined the extent of sourness suppression, this needed to be confirmed by directly examining the effect of equisweet sugar concentrations on suppression.

The results from the confirmatory study showed perceived sweetness intensities of sucrose and fructose to be the main determinant of sourness suppression of citric acid. At all three sweetness-matched levels examined, the resulting suppression in the acid–sugar mixtures was not significantly different irrespective of sugar type (i.e., sucrose, fructose, or an equisweet mixture of the two; Figure 3). Given that only perceived sweetness, and not sugar concentration, is equivalent at equisweet levels and that equisweet sugar levels produced equivalent suppression in sugar–citric-acid mixtures, it appears that sourness suppression is mostly perceptual and a result of higher order processing at the brain level, as opposed to the peripheral level. These findings demonstrate that central processing mechanisms may be largely responsible for the observed behavior, where *central* refers to levels higher than the nucleus of the solitary tract (Norgren & Leonard, 1973).

With respect to glucose mixtures across acid types and levels, glucose contributed sweetness mostly at the high sugar level. But the corresponding sourness ratings did not reflect this, since they remained largely unchanged from the sourness rating of the no-sugar control. A comparison of the suppressive ability of the three sweeteners as a function of their perceived sweetness across acid types and levels shows that glucose (Figures 3A and 3B) appears to behave differently than fructose (Figures 3C and 3D) and sucrose (Figures 3E and 3F) in the range of concentrations examined. With two out of three acids, glucose mixtures (Figures 3A and 3B) showed a trend of initial sourness enhancement, followed by marginal sourness suppression in mixtures. Fructose mixtures (Figures 3C and 3D) showed initial sourness enhancement only with malic acid and suppression with citric and lactic acids. Sucrose mixtures showed sourness suppression with all three acids. On the basis of the observed response patterns, in general, glucose appears to be a less effective suppressor of sourness, as compared with sucrose or fructose, in a low range of perceived sweetness. To confirm this, more data would be needed in the region of higher perceived sweetness values for glucose. However, a distinct response pattern to the same acids and differential efficacy as a suppressor, as compared with sucrose and fructose in a similar range of perceived sweetness, points toward separate receptors/receptor mechanisms for the different sugars and, thereby, a peripheral component to suppression.

Work with quinine–sucrose mixtures (Lawless, 1979, 1982) has also shown the possible existence of a peripheral component to mixture suppression, in addition to the central. Thus, in contrast to Schifferstein and Frijters (1991), who deemed mixture suppression to be a purely perceptual phenomenon and who found it unlikely that it could be accounted for by receptor events, we believe suppression to have both receptor-related and perceptual components. This supports Kroeze's (1989) idea that the phenomenon of mixture suppression should be viewed as a continuum with central and peripheral components, as opposed to one or the other.

In terms of conceptual process models from the realm of integration psychophysics, it has been hypothesized that since homogenous mixtures of fructose–sucrose and fructose–glucose have a sweetness that, at higher concentrations, exceeds that of the individual components, these mixtures follow a separate-sites model. The separate-sites model implies that the two components of the mixture are transduced independently at separate receptor sites (McBride, 1989). Further evidence to support independent receptor sites/mechanisms for the transduction of glucose and fructose has come from the isolation of fructose nontasting and glucose nontasting variants from natural populations of adult and larval fruitflies (*Drosophila melanogaster*) and from the identification of potential human glucose nontasters by elevated glucose thresholds (Kennedy, Eylam, Poskanzer, & Saikku, 1997). Another psychophysical study has suggested different receptor cell mechanisms for furanose and pyranose monosaccharides on the basis of human and fruit fly (*Drosophila adiastola*) response functions. Our results also suggest a mechanism for the pyranose-furanose disaccharide sucrose similar to that of furanose monosaccharides (Armstrong et al., 1998). Our findings on sourness suppression appear to corroborate the findings from the aforementioned studies and support the proposed existence of a separate receptor/mechanism for glucose from the receptor(s)/mechanism for fructose and sucrose.

It remains to be seen whether the findings from this work using model solutions will be supported in more complex systems. In some cases, as in a study of the perception of sweet–acid mixtures in gels (Barylko-Pikielna, Matuszewska, & Radzanowska, 1999), this has been supported. It was found that the general rules of behavior observed for the mixtures in water solutions were also followed in gels, with an additional effect of the nature of the gelling agent. More work of this type could eventually lead us away from the current approach, based on trial and error, to determining the ranges for mixture components in real products.

In conclusion, sourness suppression is not mediated by the molarity or weight of the sugar in the binary mixture solutions of the sugars and acids examined. For the sugars sucrose and fructose, the perceived intensity of the masker and, thereby, central neural mechanisms appear to be largely responsible for the observed suppression. The regression equations from overall scatterplots of the degree of sourness suppression versus the perceived sugar sweetness, sugar molarity, and sugar weight confirm the relationship between sourness suppression and perceived sweetness (Figure 5). The data also support the existence of a receptor/mechanism for glucose separate from that for fructose and sucrose and, thereby, a peripheral component to suppression.

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