Chem. Senses 24: 627–635, 1999

Confusing Tastes and Smells: How Odours can Influence the Perception of Sweet and Sour Tastes

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Abstract

This study investigated the relationship between perception of an odour when smelled and the taste of a solution to which the odour is added as a flavorant. In Experiment 1 (E1) sweetness, sourness, liking and intensity ratings were obtained for 20 odours. Taste ratings were then obtained for sucrose solutions to which the odours had been added as flavorants. Certain odours were found to enhance tasted sweetness while others suppressed it. The degree to which an odour smelled sweet was the best predictor of the taste ratings. These findings were extended in Experiment 2 (E2), which included a second tastant, citric acid, and employed four odours from E1. The most sweet smelling odour, caramel, was found to suppress the sourness of citric acid and, as in E1, to enhance the sweetness of sucrose. Again, odours with low sweetness suppressed the sweetness of tasted sucrose. The study demonstrated that the effects of odours on taste perception are not limited to sweetness enhancement and apply to sour as well as sweet tastes. The overall pattern of results is consistent with an explanation of the taste properties of odours in terms of prior flavour–taste associations.

Introduction

Perceptual confusion between the senses of smell and taste (Rozin, 1982) has been demonstrated by at least two types of finding. The first is the attribution of taste qualities to odours when sniffed and the second is the enhancement of taste intensities by odours. This study examines the link between these two observations.

The first finding, that taste qualities can be attributed to odours when sniffed, occurs when subjects are asked to evaluate the perceptual qualities of a set of odours on multiple dimensions. Subjects typically use such terms as 'sweet' or 'sour', even though the olfactory system contains no receptors equivalent to the oral receptors sensitive to such tastes (Harper *et al.*, 1968; Dravnieks, 1985; Voirol and Daget, 1986). The second finding is that of sweetness enhancement. In this case, certain odours, which in themselves possess no taste properties—thus, no sweetness which can be detected by oral receptors—are added as flavorants to a sweet solution such as sucrose, where they act to increase the perceived sweetness of the solution (Frank and Byram, 1988; Bingham *et al.*, 1990; Cliff and Noble, 1990; Frank *et al.*, 1993; Clark and Lawless, 1994; Schifferstein and Verlegh, 1996). The main aim of the first experiment reported here was to test whether the perceived sweetness of an odour when sniffed (orthonasal perception) predicts the degree to which, as a flavour (retronasal perception), it enhances the sweetness of a sucrose solution, thereby establishing a link between these two phenomena.

If certain odours can act to enhance the sweetness of sucrose, it is possible that other odours may act to suppress tasted sweetness. That is, they may reduce the perceived sweetness of a sucrose solution to which they are added as a flavorant. In fact such effects, termed sweetness suppression, have received little empirical attention (Frank *et al.*, 1991) and are examined in both experiments reported here. A further reason for wishing to study sweetness suppression comes from experiments on associative factors in the perception of taste properties in odours (Stevenson *et al.*, 1995). Among other findings, these have shown that, when a moderately sweet odour has been frequently sampled as a flavorant in a citric acid solution, it is subsequently perceived as being less sweet when sniffed. The present experiments asked whether the complementary effect could be obtained, whereby odours rated as low in sweetness would decrease the perceived sweetness of a sucrose solution to which they were added as flavorants and whether odours rated as sweet smelling might also suppress the sourness of citric acid (Experiment 2).

The results from experiments on associative factors have also suggested that one reason why taste properties are attributed to odours is because the odour has become associated with a particular taste when experienced retronasally at the same time as the taste (Stevenson *et al.*, 1998). In fact most previous studies of sweetness enhancement have employed flavours commonly experienced as foods or drinks. Experiment 1 investigated whether this might be important in the relationship between odour properties and taste judgements by including odours generally judged to be food- and non-food-like. If, as suspected, odour sweetness occurs because of an odour's previous history of co-occurrence with sweet tastes, then odour enhancement effects should be largely restricted to 'food-like' odours. The final issue, addressed only in Experiment 1, was whether the relationship between orthonasal perception of an odour and its effect as a flavorant in a sweet solution depends on the concentration of the odour. Evidence for increasing sweetness enhancement has been found when concentrations of peach (Cliff and Noble, 1990) and strawberry (Schifferstein and Verlegh, 1996) flavorants were increased. The aim here was to see whether such sensitivity to concentration would be found under the conditions employed in the present study.

Experiment 1

The basic design of this experiment was to select on the basis of pilot studies a set of stimuli which would provide five food-like and five non-food-like odours with sweetness and sourness ratings covering a large overall range. To investigate the effects of concentration a further two odours were included which had been used in our previous studies of associative factors, namely, lychee and water chestnut. In the main part of the experiment subjects were given four blocks of trials, in each of which they were asked to rate a set of odours when sniffed and then rate a set of sucrose solutions, sampled orally, to which these odours had been added as flavorants. The primary question addressed here was the degree to which the odour ratings obtained in the first part of each trial block predicted the ratings of flavoured solutions in the second.

Method

Subjects

Thirty-one subjects (mean age 25.2 years), 15 male and 16 female, all students at Macquarie University, were paid for participating in one experimental session. No subject reported having a cold or other respiratory tract infection in the week prior to testing.

Stimuli

Twenty experimental odours and three context-setting odours were used in the experiment. Table 1 illustrates names, concentrations and sources of all odorants. Pilot studies were used to establish approximately equal intensities between odours and to identify if any odour had an actual taste (odours were sampled by mouth with the nose pinched). Maltol was found to taste bitter. Context-setting tastes (0.6 M sucrose and 0.023 M citric acid; Univar) and odours were primarily included to ensure a similar judgemental context within each block of tests.

Table 1 Name, concentration and source of odours used in Experiment 1

Odour	Concentration/s (g/l)	Source
(1) Strawberry	1.00	Quest
(2) Maracuja	1.00	Quest
(3) Maltol	6.08	Dragoco
(4) Mango	16.70	Queen
(5) Caramel	1.60	Dragoco
(6) Damascone	0.08	Dragoco
(7) Cedryl acetate	0.10	Dragoco
(8) Acetyl methyl carbinol	0.12	Dragoco
(9) Angelica oil	0.03	Dragoco
(10) Eucalyptol	0.10	Fluka
(11) Lychee	0.06, 0.12, 0.24, 0.96, 3.84	Quest
(12) Water chestnut	0.04, 0.08, 0.16, 0.64, 2.56	Quest
(13) Snow milk	1.60	Quest
(14) Malt vinegar	[a]	Cornwell
(15) Orange	1.00	Quest

Odours 1-5 formed the 'Food' set, 6-10 the 'Non-food' set, 11 the five 'Lychee concentration series' and 12 the five 'Water chestnut concentration series'. Odours 13-14 were the context set and 15 was used for practice.

[a]Equal mixture of distilled water and vinegar by volume.

In addition to water chestnut and lychee, five odours were selected as food related and five as non-food related. Those classified as non-food included at least one flavour used in wine (damascone), but when sampled out of context this flavour is not readily identifiable. The tasted solutions consisted of the 20 experimental odours (at the same concentrations) in 0.3 M sucrose and 0.3 M sucrose alone (Univar).

Odours were presented in 250 ml polypropylene wash bottles which were stoppered after use. Odour bottles were replenished with the odorant every morning preceding testing. Tastes and odours were presented in transparent 22 ml disposable sample cups (10 ml samples of each solution). All stimuli were presented at 22°C.

Procedure

Subjects were given four consecutive blocks of tests, the order of which was counterbalanced using the Williams square (Edwards, 1968). Each block consisted of a smelling phase and then a tasting phase. The smelling phase started by the subject sniffing the two context-setting odours (a 'sour' and a 'sweet' smell) and then a practice odour—orange—was smelled and rated. Five target odours were then smelled and rated in counterbalanced order. Following this, the tasting phase began. Two context-setting tastes were sampled (0.023 M citric acid and 0.6 M sucrose) and then 0.3 M sucrose was tasted and rated. Then the five odours smelt in the first part of the block were sampled this time as flavorants in 0.3 M sucrose. Each of these was tasted, expectorated and then rated, in counterbalanced order.

The procedure of alternating periods of tasting and smelling was adopted to reduce adaptation and fatigue. Overall four blocks were completed in which subjects sampled a set of five lychee odours/flavours in sucrose, varying in concentration, a set of five water chestnut odours/flavours in sucrose, varying in concentration, five 'food' odours/flavours in sucrose and five 'non-food' odours/flavours in sucrose.

At the start of the experiment, subjects were instructed in the use of the rating scales. For odours, these consisted of four 15.3 cm visual analogue scales in the following order: Liking/Disliking (anchors: Dislike extremely and Like extremely, with the centre point marked Indifference); Overall Intensity; Sourness; and Sweetness (anchors: None, Extremely strong). All ratings reported in the text/figures were converted to a 100-point scale. Three questions followed: 'Before today, had you EVER smelt a SIMILAR odour to this before?', available responses: Yes, Unsure, No; 'Before today, had you EVER smelt THIS odour before?', available responses: Yes, Unsure, No; and 'Would you describe this odour as being food (or drink) like?', available responses: Food (or drink) like, Unsure, Not like a food (or drink). The only difference in the ratings scales used for tastes and odours was that the three final questions described above were omitted. This rating procedure was modelled on that used by Stevenson *et al.* (Stevenson *et al.*, 1995).

After subjects had read the instructions, the experimenter carefully reiterated their content. Crucially, all subjects were explicitly told that, with respect to sweetness and sourness judgements of odours, '. . . sweetness and sourness are two qualities that an odour might possess. It might possess BOTH, NEITHER, ONE or THE OTHER quality. . .'. The option of using zero ratings was carefully stressed. Subjects were then shown how to smell the odours. They were then informed that they could take as long as they wished to smell each odour (average time ~5 s), before handing it back to the experimenter and completing the rating scales. A minimum time of 45 s separated subsequent odour presentations.

Subjects were given a new set of instructions after completing the smelling phase of the first test block. These repeated the original instructions for using the scales and informed subjects that solutions were to be gently swilled and then expectorated. As with smelling the odours, no time limit was set on the swilling phase, but subjects generally expectorated after ~4 s. Ratings were made immediately after expectoration. Subjects then completed at least one water rinse (more if they desired) and at least 45 s separated subsequent samples. Subjects were also given a 5 min break after completing their second block of tests, during which they were provided with plain crackers and more mineral water.

Results

Sweetness taste enhancement and suppression

Figure 1a–d illustrates the sweetness ratings for the various odour–sucrose combinations, relative to sucrose alone. An ANOVA was conducted on each figure's data to compare the mean sweetness of plain sucrose (collapsed across all four ratings taken of plain sucrose) and the flavoured sucrose solutions. All reported results are significant at the 5% level unless otherwise stated—a format adopted throughout this paper.

For the food-like odours, there was a significant F, indicating differences between the various sweetness ratings [$F(5,150) = 12.06$; see Figure 1a]. Paired t-tests revealed that caramel [$t(30) = 3.70$], strawberry [$t(30) = 3.51$] and maracuja [$t(30) = 2.80$] significantly enhanced the sweetness of sucrose when contrasted with plain sucrose, whilst maltol significantly suppressed it [$t(30) = 3.55$]. Mango exerted no significant effect. The F for the non-food-like odours was also significant [$F(5,150) = 3.74$; see Figure 1b]. Paired t-tests revealed that damascone [$t(30) = 2.41$], angelica oil [$t(30) = 2.36$] and cedryl acetate [$t(30) = 1.67$; not significant in this case] suppressed sweetness ratings when contrasted with plain sucrose. Acetyl methyl carbamol and eucalyptol exerted no significant effect on sweetness ratings. For the lychee series there were also significant differences between solutions [$F(5,150) = 3.12$; see Figure 1c]. Paired t-tests revealed that the lowest concentration of lychee significantly enhanced sweetness when contrasted with plain sucrose [$t(30) = 4.26$; LY 1 on Figure 1c]. There was some indication that the three strongest concentrations also acted to enhance sweetness (ts respectively 1.75, 1.72 and 1.65; see LY3–5 on Figure 1c), though not significantly. However, the second weakest solution exerted no significant effect (LY 2 on Figure 1c). Finally, there were no significant differences between solutions for the water chestnut series (see Figure 1d).

Which odour quality best predicts taste enhancement?

To determine the best predictor of an odour's ability to enhance the sweetness of sucrose, a regression analysis was conducted. The mean tasted sweetness of the odour–sucrose mixtures formed the dependent variable and the mean smelled characteristics of each odour (sweetness, sourness, liking, overall intensity) formed the independent variables. Maltol was excluded from this analysis because of its large studentized residual.

The best solution is illustrated in Table 2, along with the associated regression coefficients (B) and significance tests (t). This solution explained 60% of the variance (adjusted multiple R^2) and the multiple R for regression was

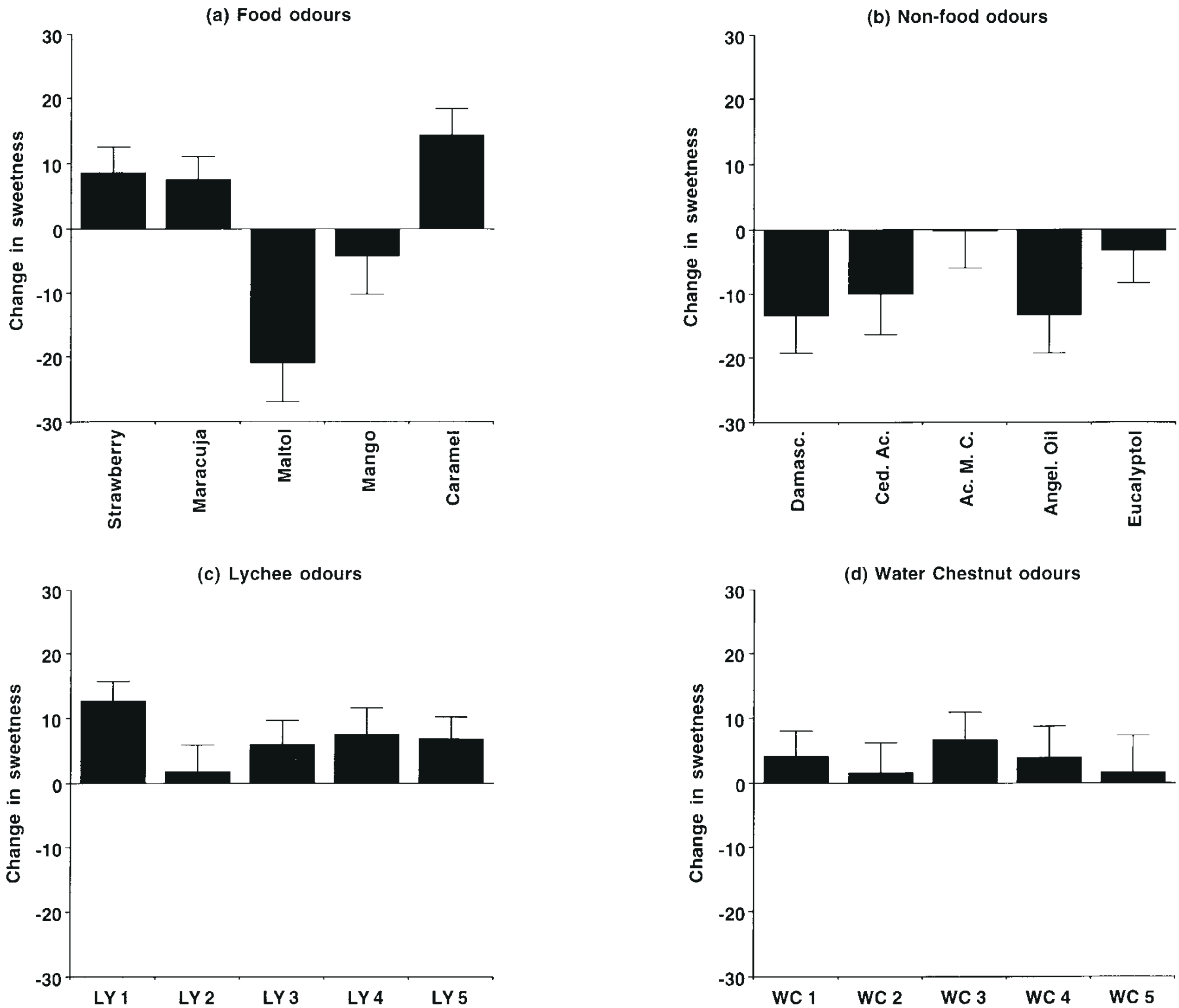

Figure 1 **(a)** Mean sweetness ratings for the food odour–sucrose combinations less than for sucrose alone, with SEMs (note that maltol was excluded from the regression analysis due to its bitter taste). Positive values indicate enhancement and negative, suppression. **(b)** Mean sweetness ratings for the non-food odour–sucrose combinations less than for sucrose alone, with SEMs. **(c)** Mean sweetness ratings for the lychee (LY) odour–sucrose combinations less than for sucrose alone, with SEMs. **(d)** Mean sweetness ratings for the water chestnut (WC) odour–sucrose combinations less than for sucrose alone, with SEMs.

Table 2 Regression analysis for Experiment 1

Variable	Tasted sweetness (*r*)	Odour intensity (*r*)	Tolerance	*B*	*t*	Sr^2
Odour intensity	–0.02		0.72	–0.36	2.98*	0.25
Odour sweetness	0.67	0.53	0.72	0.44	5.40*	0.83

The dependent variable was tasted sweetness: the independent variables entered into the model were odour: intensity, sweetness, sourness and liking. The best solution involved two variables, odour sweetness and intensity.

*$P < 0.05$.

significantly different from zero [$F(2,16) = 14.57$]. The solution involved two variables, odour sweetness and odour intensity. Both significantly contributed to the model, with odour sweetness the most important predictor based on ranking by the squared semi-partial correlation coefficient (see Table 2). Although odour sweetness was significantly correlated with the dependent variable, tasted sweetness, intensity was not. However, intensity was significantly correlated with the residuals from the prediction of tasted sweetness scores from odour sweetness ($r = -0.51$), suggesting that odour overall intensity was acting as a suppressor variable (Howell, 1992). Thus, removing variations in odour intensity allows odour sweetness to explain more of the variation in tasted sweetness.

To check the validity of this solution all the adjusted multiple R^2 and sums of squares were calculated for all the possible models (15 in total). The highest adjusted multiple R^2 was provided by odour sweetness, odour liking and odour overall intensity (61.5% of the variance explained). However, this did not differ significantly from the simpler solution reached by the forward stepwise method. Repeated use of the same odorant at different concentrations (namely lychee and water chestnut) did not unduly influence the regression model, as the best solution was still odour sweetness and odour overall intensity, when the three intermediate concentrations of lychee and water chestnut were omitted.

Qualities relationship to concentration

The following ANOVAs examined how the various qualities measured here changed as a function of lychee and water chestnut concentration—both when tasted in sucrose solution and when smelled as an odour. Interestingly the magnitude of changes in overall intensity for the odours appeared to exceed that for changes in sweetness and sourness, suggesting that the latter qualities may be somewhat insensitive to changes in concentration.

When sniffed, lychee odour intensity increased as a function of concentration [$F(4,120) = 14.68$], as did odour sourness [$F(4,120) = 4.62$]. Odour sweetness ratings showed no significant change across concentration, nor did odour liking. When tasted as lychee-flavoured sucrose solutions, rated intensity increased with lychee concentration [$F(4,120) = 6.60$]. Tasted sweetness did change across concentration, with the lowest concentration having the highest sweetness rating [$F(4,120) = 2.47$]. Sourness ratings increased across concentration [$F(4,120) = 3.46$]. Liking ratings did not change across concentration.

Water chestnut odour intensity increased with concentration [$F(4,120) = 15.14$], as did odour sourness [$F(4,120) = 3.96$]. Odour sweetness initially decreased, then increased again as a function of concentration, but with no overall pattern [$F(4,120) = 3.32$]. Liking changed significantly across concentration, tending to decrease [$F(4,120) = 2.78$]. Intensity ratings of the water chestnut-flavoured sucrose solutions increased with concentration [$F(4,120) = 6.51$], as did sourness ratings [$F(4,120) = 4.44$]. There was no significant change in sweetness ratings. Liking ratings progressively decreased as water chestnut concentration increased [$F(4,120) = 4.56$].

'Food/non-food' judgements and familiarity ratings

The food/non-food judgements broadly agreed with the preselected categories. The food odours were judged to be 'food', with the exception of mango, which was judged to be a non-food. Food/non-food judgements for lychee and water chestnut, at all concentration steps, revealed a median judgement of 'Unsure'. The non-food odours were judged to be non-foods, with the exception of acetyl methyl carbamol, where the median response was 'Unsure'. Interestingly, mean odour sweetness ratings were significantly correlated with the sum of food/non-food ratings for each odour (Spearman's $\rho = 0.74$). That is, the more an odour was deemed to be a food, the higher the sweetness rating it tended to receive. Finally, subjects claimed to be broadly familiar with all the odours presented during the experiment.

Discussion

The degree to which an odour smells sweet was found to be a good predictor of the degree to which that same odour will enhance or suppress the sweetness of sucrose. Sweetness taste enhancement was found with caramel, maracuja, strawberry and lychee (at the lowest concentration step) and sweetness taste suppression with angelica oil and damascone. There were also some indications that the higher concentrations of lychee enhanced sweetness and that cedryl acetate suppressed it. With respect to concentration, the smelled sweetness and sourness of lychee and water chestnut odours changed very little as concentration increased, even when quite large changes in perceived intensity occurred. Thus, over the concentration range explored here, the taste-like qualities of these two odours remained quite stable.

Finally, whether an odour was judged as a food or a non-food was significantly related to the degree to which it was perceived to smell sweet. One odour producing variable judgements as to whether it was food-like was acetyl methyl carbamol. Fourteen subjects judged it to be a food, often spontaneously telling the experimenter that it was 'butter menthol', a brand of Australian cough lozenge. It is of interest that these subjects judged the smell to be significantly sweeter (mean 54.4) than did the nine subjects who were unsure (mean 23.7) or the eight who thought it a non-food odour [mean 17.8; $F(2,28) = 8.35$]. This post-hoc analysis is consistent with the claim that associative factors are important in odour judgements.

Experiment 2

As noted earlier, there has been very limited evidence for sweetness suppression by odours (Frank *et al.*, 1991) and few data bearing on whether enhancement and suppression occur when tastants other than sucrose are used. Therefore a second experiment was conducted to check the main sweetness enhancement and suppression effects of Experiment 1 and to see if enhancement and suppression effects could be observed for a second tastant, namely citric acid. Experiment 2 used four odours selected from those employed in Experiment 1. This more limited set was used so that replications of each trial could be conducted without excessive taste or olfactory adaptation.

Method

Subjects

Twenty-eight Sydney University students participated in this experiment as part of their course requirements. Subjects were randomly allocated to one of two groups, Smelling then Tasting (SM/TS) or Tasting then Smelling (TS/SM). Group SM/TS consisted of 14 subjects, nine female and five male, with a mean age of 19.1 years. Group TS/SM also consisted of 14 subjects, ten female and four male, with a mean age of 18.7 years. No subject reported having a cold or other respiratory tract infection in the week prior to testing.

Stimuli

The odours were lychee at the lowest concentration used in Experiment 1, caramel, angelica oil and cedryl acetate (concentrations as for Experiment 1). The tasted solutions consisted of 0.3 M sucrose alone and with the four odours added as flavours, and 0.0075 M citric acid alone and with the four odours added as flavours. Odours and tastes were presented as in Experiment 1.

Procedure

The experiment contained two discrete phases. In the tasting phase subjects sampled a solution, expectorated it, rated it on the same scales used for tasting in Experiment 1, chewed some bread and then rinsed with water, before proceeding to the next stimulus. Over a ten-trial block, subjects sampled the four flavorants in sucrose, sucrose alone, the four flavorants in citric acid and citric acid alone. These stimuli were then repeated in a different sequence in a second ten-trial block. Presentation order within each block was determined using the Williams square. As before, a minimum interval of 45 s separated subsequent tastings. Unlike Experiment 1, testing in this experiment took place in groups, of 1–4 subjects. As no context-setting tastants were used in this experiment, the written instructions were modified so as to advise subjects to be cautious in their use of the extreme ends of the scale.

The odour phase of the experiment contained two counterbalanced five-trial blocks, each containing the four odours and a water blank. Odours were sniffed for as long as the subject required and were then rated on the four scales and three questions as in Experiment 1. Subjects were instructed not to smell the odour again once they started to complete the scales and to be cautious in using the extreme end of the scales.

Whether the smelling phase preceded the tasting phase or vice versa depended upon the group that the subject was allocated to. Counterbalancing presentation order was included here so as to check whether or not it influenced rating behaviour. Subjects were unaware that there was a second component to the experiment during the first phase.

Results

The key findings here are that caramel suppressed the sourness of citric acid and enhanced the sweetness of sucrose, and that angelica oil suppressed the sweetness of sucrose. There were no effects of presentation order on any analysis, i.e. whether sniffing preceded tasting or vice versa did not appear to influence odour or taste ratings.

Sniffed odour sourness ratings are shown in Figure 2a. An ANOVA on these data revealed that ratings of sourness significantly differed between stimuli [main effect of Stimulus type, $F(4,104) = 19.67$]. Comparison by paired t-tests of water with each odour revealed that lychee [$t(27) = 2.90$], cedryl acetate [$t(27) = 5.17$] and angelica oil [$t(27) = 5.93$] were rated as sourer smelling whereas caramel was rated as less sour than water, though not significantly so ($t < 1$). Figure 2b shows ratings of tasted sourness for the four flavorants in citric acid compared with citric acid alone. An ANOVA on these data (including citric acid alone) revealed significant difference in sourness ratings between stimuli [main effect of Stimulus type, $F(4,104) = 3.55$]. Paired t-tests revealed a significant difference between sourness ratings for citric acid alone and for citric acid with caramel [$t(27) = 2.20$], but not for citric acid with any other flavour (all ts < 1).

Odour sweetness ratings are shown in Figure 2c. An ANOVA on these data revealed significant differences in sweetness ratings between odours [main effect of Stimulus type, $F(4,104) = 66.62$]. Paired t-tests between sweetness ratings of water and sweetness ratings of the odours revealed that all smelled significantly sweeter [lychee, $t(27) = 6.78$; caramel, $t(27) = 21.75$; cedryl acetate, $t(27) = 4.07$; and angelica oil, $t(27) = 3.97$]. Ratings of tasted sweetness are shown in Figure 2d. An ANOVA on these data (including plain sucrose) revealed significant differences between flavours [main effect of Stimulus type, $F(4,104) = 8.74$]. Paired t-tests against plain sucrose revealed that caramel enhanced sweetness [$t(27) = 2.76$] and angelica oil suppressed it [$t(27) = 2.95$]. There was some indication that cedryl acetate had a suppressive effect [$t(27) = 1.30$], though this failed to reach significance. Lychee exerted no significant effect.

Discussion

Experiment 2 found that the sweet-smelling odour caramel can both enhance the sweetness of sucrose and suppress the sourness of citric acid. Lychee, which was used at the concentration producing enhancement in Experiment 1, failed to significantly enhance the sweetness of sucrose here. We can offer no obvious explanation as to why this should be so, other than to note that the procedural changes may have resulted in reduced power to detect an effect. Experiment 2

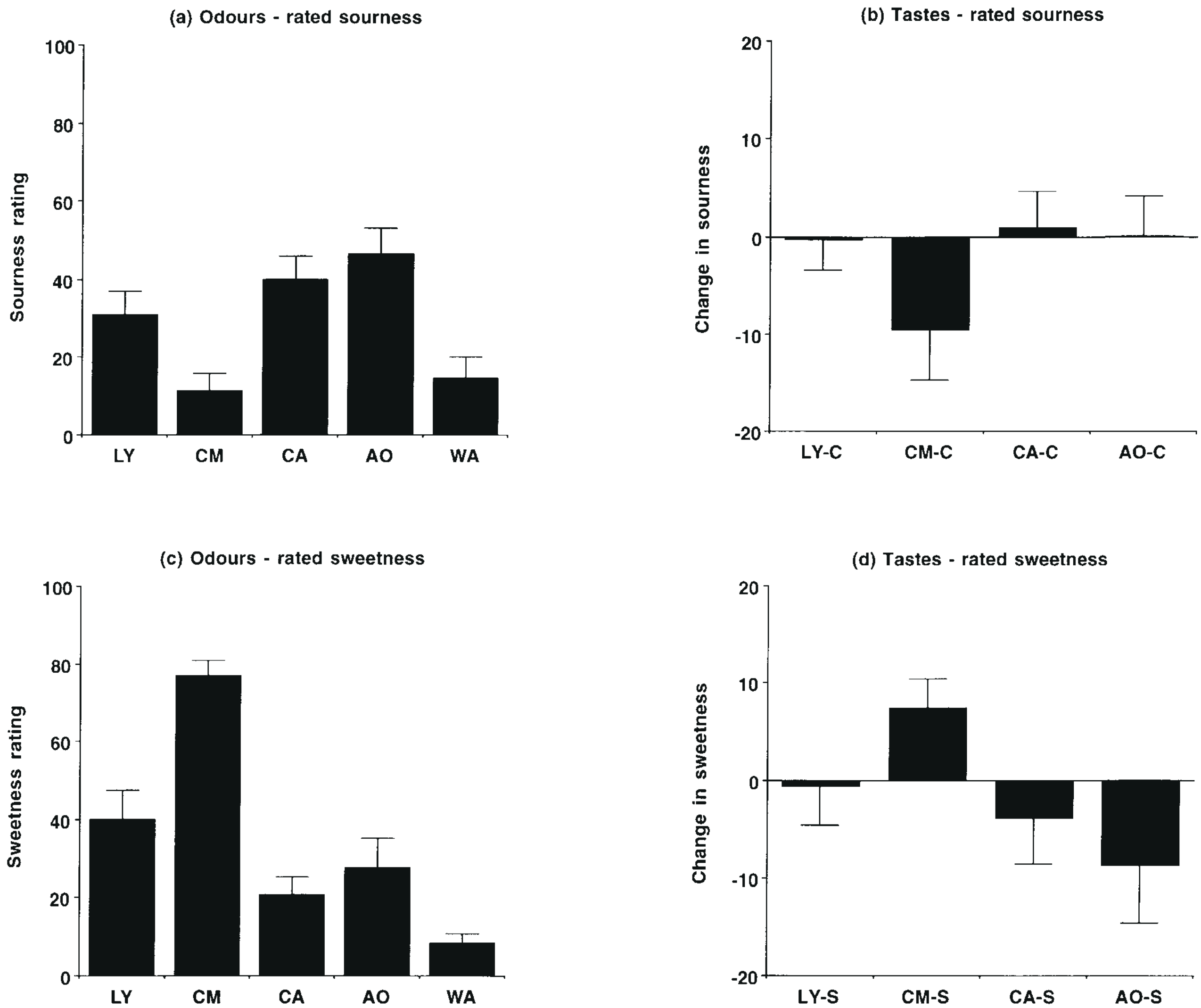

Figure 2 **(a)** Mean ratings of odour sourness for the four odorants and water when sniffed, with SEMs. LY, lychee; CM, caramel; CA, cedryl acetate; AO, angelica oil; WA, water. **(b)** Mean ratings of tasted sourness for the four flavorants in citric acid less than for citric acid alone, with SEMs. Positive values indicate enhancement and negative, suppression. The suffix -C indicates that odours were sampled in citric acid solution. **(c)** Mean ratings of odour sweetness for the four odorants and water when sniffed, with SEMs. **(d)** Mean ratings of tasted sweetness for the four flavorants in sucrose less than for sucrose alone, with SEMs. Positive values indicate enhancement and negative, suppression. The suffix -S indicates that odours were sampled in sucrose solution.

also found evidence of the sweetness suppression effect observed in Experiment 1. When angelica oil was mixed with sucrose it significantly reduced its sweetness when compared with sucrose alone, whilst cedryl acetate produced a similar effect, although it failed to reach significance (as in Experiment 1). Neither angelica oil nor cedryl acetate enhanced the sourness of citric acid, although in each case, mean sourness ratings were in the expected direction. It seems that angelica oil was sufficiently sour-smelling to suppress the sweetness of the sucrose solution, but not enough to enhance the sourness of the citric acid.

General discussion

These results have several implications for understanding the way in which tastes and odours interact in the mouth to produce taste enhancement and suppression effects. A number of different types of explanation for such interactions may be distinguished. One way in which they vary is the degree to which they appeal to psychological processes. They are discussed here in order of increasing involvement of such processes.

The most basic issue is whether a finding that sweetness ratings for a sucrose solution containing some tasteless flavour are higher than for the equivalent unflavoured solution represents a valid perceptual phenomenon or a measurement artifact. The latter is implied by, for example, appeal to the process of 'dumping' (Clark and Lawless, 1994). When subjects are restricted to ratings along very general dimensions, like 'sweetness' and 'sourness' in the present experiments, they are unable to express directly the perceptual experience provided, say, by a strawberry–sucrose solution containing an element of 'fruitiness'. By default, this is expressed as an additional element of 'sweetness'. However, when additional scales are provided which include 'fruitiness', subjects are no longer forced to increase their sweetness rating of such a solution. The prediction from this, and from related suggestions (Frank *et al.*, 1993), is that the sweetness enhancement effect should decrease as the number of appropriate rating scales is increased and this has been confirmed in a number of studies (Clark and Lawless, 1994); although see Polet *et al.* (Polet *et al.*, 1999). However, the present results indicate that not all flavour–taste interactions can be explained in such a manner. Three findings are especially relevant. First, dumping is asymmetrical, in that it may account for an increase in reported sweetness but not for a decrease, as found with some flavours in both Experiments 1 and 2. Second, inappropriate measurement cannot readily account for the ability of some flavours—as for caramel in Experiment 2—both to increase sweetness ratings of a sucrose solution and decrease sourness ratings of a citric acid solution. Third, it offers no explanation for why two disparate qualities, namely fruitiness (for strawberry, maracuja and lychee) and caramelness (for caramel), should both be dumped into just sweetness ratings.

A second type of explanation would accept that flavour-induced changes in taste ratings represent valid perceptual effects, but would propose that they arise from physiological events within the mouth. This kind of account would need to propose that the presence in the mouth of certain flavours, which cannot directly stimulate taste receptors for sweetness, can nonetheless modulate the sensitivity of such receptors. Two of our findings are problematic for this account. First, the relationship between odour sweetness and tasted sweetness ratings found in Experiment 1. This forces a physiological account into the unlikely presumption that the chemical properties of any stimulus which provokes a 'sweetness' response in the olfactory receptors are exactly those properties which allow the stimulus to modulate oral taste receptors in the same way. The second arises from the finding in Experiment 2 that such interactions occur for sourness as well as sweetness. In general, these tend to act antagonistically at a perceptual level (Schifferstein and Frijters, 1990; Stevenson and Prescott, 1997), as in the finding here that caramel enhanced tasted sweetness but suppressed tasted sourness. Consequently, a physiological account would need to assume for any flavour that affected perception of these qualities an inverse relationship between the way its chemistry affected sweet and sour receptors in the mouth.

In terms of increasing involvement of psychological processes, the next type of explanation appeals to interactions at a perceptual level where oral and nasal sensory inputs are integrated, and assumes that these interactions are of an unchanging kind. In general terms this account proposes that olfactory sensations possess inherent perceptual qualities, some corresponding to sweetness. Ingestion of a sucrose solution containing a sweet flavour would produce the perception of sweetness based on two sources, taste sensations and retronasal olfactory sensations, with the result that the flavoured solution is perceived as sweeter than unflavoured sucrose. Although Schifferstein and Verlegh (1996) do not express their account of sweetness enhancement in the terms used here, their appeal to 'subjective similarity' between flavours and tastes would seem to make them examples of this kind of explanation.

The final type of general account considered here shares the same assumptions as the previous one, except that the perceptual properties of olfactory stimulation, and thus the way they interact with taste perception, is assumed to be influenced by individual experience and does not display a fixed relationship. More direct and systematic evidence on this issue comes from the experiments providing the background to the present study, which varied the co-occurrence of relatively unfamiliar flavours like lychee and water chestnut with sweet or sour tastes. Without exception these have found that sucrose-paired flavours subsequently smell sweeter and citric acid-paired flavours smell sourer (Stevenson *et al.*, 1995, 1998) (R.J. Stevenson *et al.*, submitted for publication; R.A. Boakes *et al.*, submitted for publication).

In conclusion, the results from this study indicate that the widespread use of the term 'sweet' when describing certain odours and sweetness enhancement by flavours are closely related effects. The overall pattern of results is consistent with the last of the types of explanation for flavour–taste interactions discussed above. This proposes that sweetness enhancement and suppression are not measurement artifacts, but that they arise from summation and subtractive processes at a perceptual, as opposed to a physiological, level. These processes allow modification of the input from taste receptors by olfactory input with related perceptual qualities, such as sweetness and sourness. These properties are not necessarily fixed in value, but may be modified by experience.

Acknowledgements

The authors would particularly like to thank Roger Turner, from Dragoco, and Quest International for their assistance and for supplying many of the odours. This research was partly supported by the University of Sydney/CSIRO Collaborative Research Grant scheme and an Australian Research Council Large Grant to R.A.B.

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Accepted June 2, 1999