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An Empirical Test of Olsson's Interaction Model Using Mixtures of Tastants

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Abstract

In 1994, Olsson published a model predicting the intensity and quality of an odor mixture percept on the basis of the intensities of the unmixed components. Whether this model can also be used for mixtures of dissimilar tasting substances was investigated for sucrose/citric acid mixtures.

The identification data revealed asymmetrical mixture suppression, which does not support the model. The intensity responses were in accordance with the definitions employed for level independence and hypo-additivity. However, the intensity judgements suggest deviations from symmetry and exhibited compromise, which violates two other principles. A comparison with previously published data shows that these violations probably occur for other mixture types, too. It is concluded that the Olsson interaction model cannot describe interactions in mixtures of dissimilar tasting components accurately. **Chem Senses 21: 283–291, 1996.**

Introduction

Most of the models describing interactions among tastants or among odorants try to predict the perceived intensity of the mixture. The qualitative characteristics of the mixture percept are usually not incorporated in the model. In taste research, qualitative differences between stimulus components have been incorporated in mixture models implicitly by constructing separate models for similar and for dissimilar tasting substances. Models for similar tasting substances assume that the mixture components are 'peripherally dependent' or 'compete for receptor sites'. Examples are Beidler's (1971) Mixture Equation (De Graaf and Frijters, 1986), the Substitution Model (Moskowitz, 1974) and the Equiratio Mixture Model (Frijters and Oude Ophuis, 1983; Schifferstein, 1995, 1996). Mixtures of dissimilar tasting components generally exhibit suppression of the component intensities (e.g. Pangborn, 1960). These interactions are—at least partly—due to central suppression mechanisms (Kroeze, 1983; Kroeze and Bartoshuk, 1985). Rules have been proposed to predict mixture intensity from the intensities of its unmixed components (e.g. McBride, 1989). However, a model predicting mixture total intensity from the sum of the specific intensities of the components within the mixture yields more accurate predictions (Schifferstein and Frijters, 1993). All current mixture models for dissimilar tasting substances lack a detailed account of the mixture suppression mechanism.

In odor mixture research, the qualitative similarity among component sensations was originally incorporated in the Berglund *et al.* (1973) Vector Summation Model. In this model, the intensities of the sensations elicited by the mixture and its unmixed components are represented by the lengths of three vectors in a psychological space. The angle α between the sensations elicited by the unmixed substances A and B, reflects the difference in quality between the two

sensations. According to the model, the mixture percept equals the resultant of the two vectors representing the sensations for the unmixed components. The model is given by:

$$R_{AB} = (R_A^2 + R_B^2 + 2R_AR_B\cos\alpha)^{1/2} \quad (1)$$

where R_{AB} is the intensity response to the mixture, and R_A and R_B are the responses to the components presented separately.

However, the empirical estimate for α in the Vector Summation Model is not a satisfying measure of the degree of qualitative dissimilarity between two odorants. It deviates from 0° when a substance is mixed with itself (Moskowitz and Barbe, 1977), it is affected by the form of the psychophysical functions of the components (Bartoshuk, 1975), the empirical estimate for $\cos\alpha$ may turn out to be smaller than -1 or larger than $+1$ (Laffort and Dravnieks, 1982) and all empirical α-values reported for odorants lie in the restricted range between 95° and 135° (Cain, 1975; Berglund *et al.*, 1976; Laing and Willcox, 1983; Laing *et al.*, 1984; Berglund and Olsson, 1993c). The good predictive validity of the Vector Summation model has made it the starting point for a number of extended odor interaction models (Patte and Laffort, 1979; Laffort and Dravnieks, 1982; Laffort *et al.*, 1989). In these models, however, the interaction parameter is no longer related to the degree of qualitative similarity among the mixture components.

Olsson's (1994) interaction model for odor quality and intensity is a unique model in that it predicts both the qualitative and the quantitative characteristics of a mixture percept on the basis of the intensities of the unmixed components. The present study investigates whether this model can also be used for mixtures of dissimilar tasting substances. The present paper thereby follows the recent trend in chemosensory psychophysical research in which mixture models developed for the sense of taste are tested in research on smell perception and vice versa (e.g. Bartoshuk, 1975; Frijters, 1987; Berglund and Olsson, 1993c; Schifferstein and Frijters, 1993; Sühnel, 1993). The present experiment was designed to replicate Olsson's (1994) *n*-butanol/pyridine mixture experiment using sucrose/citric acid mixtures.

Methods and materials

Subjects

Twenty-four paid volunteers, 11 men and 13 women, ranging in age from 18 to 31 years (median age 23 years), participated. Most subjects were students of the Agricultural University and had little or no experience with psychophysical scaling tasks. They were naive with respect to the substances used and the purpose of the study.

Stimuli

The stimuli were solutions of sucrose (Merck 7653), citric acid (Merck 244) and mixtures of these substances in demineralized water. The sucrose concentrations were 0.00, 0.125, 0.25, 0.50 and 1.00 M. The citric acid concentrations were 0.0, 1.25, 2.5, 5.0 and 10.0 mM. The mixtures were constructed on the basis of a full factorial mixing design: Each of the sucrose concentrations was mixed with each of the citric acid concentrations. Solutions were prepared at least 24 h before tasting and were stored in a dark, refrigerated room at 4°C for no longer than 6 days.

Procedure

Subjects were instructed to judge the quality and the intensity of each stimulus on one response form. First, they identified the stimulus by circling one of four response alternatives. They marked an A when they thought the sample contained only a sweetener, they marked a B when they thought the sample contained only acid, they circled AB when they thought both sweetener and acid were present or they circled O when they thought the sample was water. After judging the quality of the sample, subjects judged the perceived total intensity by the method of free modulus magnitude estimation. The subjects were asked to assign a number to the intensity of the first sample. When judging the other samples, the ratio between the numeric response for the previous sample and the current one was supposed to reflect the intensity ratio between these samples. They were allowed to use all positive numbers. The subjects were instructed to include every quality they perceived in the total intensity judgement. The hedonic values of the stimuli were to be disregarded.

The first 14 trials of the first session were practice trials used to familiarize the subjects with the tastes elicited by the unmixed substances. During these trials, subjects were presented with samples of unmixed sucrose, unmixed citric acid and water. No mixtures were presented. Water and the two lower concentrations of each substance were presented twice. The two higher concentration levels of each substance were presented once. The identity of these 14 stimuli was already indicated on the response form. Subjects were instructed to focus attention on the quality of the samples presented, because they had to be able to recognize the taste

qualities in the remainder of the experiment. During the practice trials, subjects judged perceived intensity only.

The subjects were requested to rinse their mouths thoroughly with demineralized water after each stimulus. The stimuli were presented at room temperature (20°C) in polystyrene medicine cups. Each cup contained about 10 ml of solution. The time interval between stimuli was 40 s. The order in which the 25 different stimuli were presented was randomized and differed between and within subjects. During the first session (70 min), the 14 practice trials and three stimulus sets (3 × 25 = 75 stimuli) were evaluated. During the second session (60 min), just the three experimental stimulus sets were presented. The two sessions were separated by 1 or 2 days.

Data analysis

For each of the 25 stimuli, the proportion of cases (n = 144) in which it was identified as a solution of a sweetener P(A), unmixed acid P(B), a mixture P(AB) or water P(O) was calculated. Individual estimates of perceived total intensity were obtained by calculating the arithmetic mean of each subject's six estimates for each stimulus. The individual scales were divided by the idiosyncratic arithmetic means before pooling the data arithmetically to obtain the group scale. The intensity responses of one subject were discarded because he had not followed the task instructions when assigning numbers to the samples.

Results and discussion

Unmixed components

The identification of the majority of the unmixed stimuli was good [P(correct) > 0.90], except for 0.125 M sucrose. This sample was erroneously identified as water in 21% of the cases. The psychophysical functions for perceived total intensity were described accurately by power functions with exponents 0.60 (R^2 = 0.994) and 0.92 (R^2 = 0.990) for citric acid and sucrose, respectively.

Mixture quality

The probability of identifying a mixture as unmixed sweetener (A), unmixed acid (B), sweetener/acid mixture (AB) or water (O) is given as a function of the relative component intensity (τ) in Figure 1. The τ-ratio provides information on the relative intensities of the two substances when presented separately. The average responses to the unmixed components (R_A and R_B) are used as measures of perceived intensity:

$$\tau = R_A/(R_A + R_B). \quad (2)$$

On several occasions, the mixture is mistakenly identified as either sweetener or acid. Similar to the results on butanol/pyridine mixtures (Olsson, 1994), the probability of identifying a mixture as A or B increases as the target component intensity increases relative to the other component. With an increasing proportion of sucrose, P(A) increases. An analogous trend is found when the relative citric acid level increases. The probability that a mixture is identified as AB is largest when P(A) = P(B). The mixture with the lowest sucrose and acid levels is sometimes identified as water.

The present results deviate from Olsson's results in several respects. First of all, the value of P(AB) in most cases exceeds 0.5, whereas in Olsson's experiment P(AB) ≤ 0.4. This finding indicates that the sweet and sour sensations elicited by the sucrose/citric acid mixture are more distinct and easier to recognize than the sensations forming the olfactory mixture percept in Olsson's study. Secondly, the maximum of the curve is not found at τ = 0.5, but for τ ≈ 0.4. This outcome suggests that mixture suppression is not symmetrical for the sucrose/citric acid mixtures. Sweet appears to be the dominant component in the mixture percept when the total intensity of the unmixed sweetener equals the total intensity of the unmixed acid.

Mixture intensity

Four principles have been used by Berglund and Olsson (1993a, b), and Olsson (1994) to characterize odor-intensity

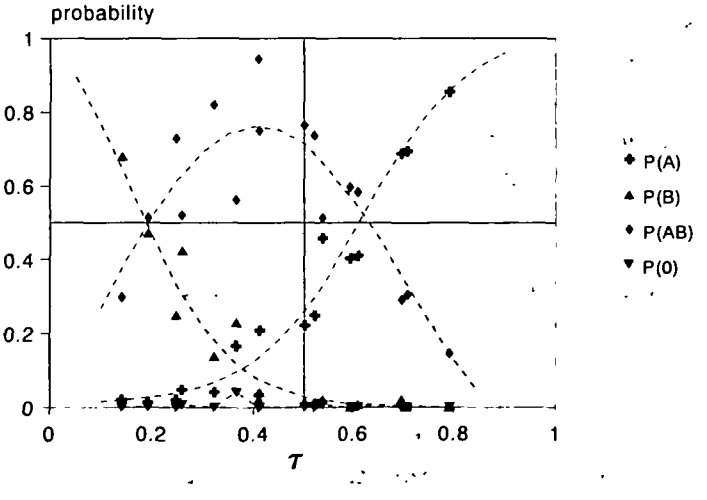

Figure 1 The proportion of cases in which a sucrose/citric acid mixture was identified as unmixed sweetener [P(A)], unmixed acid [P(B)], a mixture [P(AB)] or water [P(O)] as a function of the relative component intensity τ (= $R_A/R_A + R_B$). The curves were estimated by polynomial or logistic regression and are of no theoretical importance.

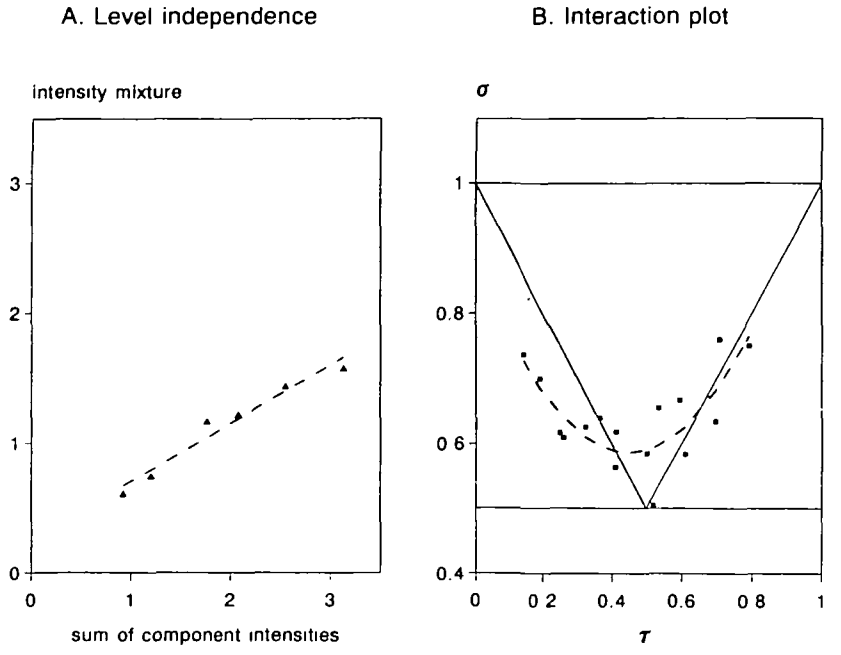

Figure 2 Characterization of the intensity interaction between sucrose and citric acid. Panel A shows the test of level independence The response to a mixture (R_{AB}) is plotted as a function of the sum of the responses to the unmixed components ($R_A + R_B$) for components with approximately equal intensities ($R_A \approx R_B$, $0.40 < \tau < 0.60$). Panel B shows an interaction plot, where the degree of additivity ($\sigma = R_{AB}/R_A + R_B$) is plotted as a function of the relative component intensity ($\tau = R_A/R_A + R_B$) The horizontal lines represent complete additivity ($\sigma = 1$) and the arithmetic mean of the component perceived intensities ($\sigma = 0\ 5$), respectively The V-shaped line represents the case where mixture intensity equals that of the strongest component. The dotted lines show results of regression analyses.

interaction: level independence, hypo-additivity, symmetry and compromise. Below, we investigate the validity of these principles for the interaction between citric acid and sucrose.

Level independence implies that the degree of mixture interaction is the same for combinations of two strong components and for two weak components, as long as their τ-values are equal. Apart from τ, Patte and Laffort (1979) use σ (the degree of arithmetic additivity) to characterize mixture interactions. To calculate σ, the response to a mixture (R_{AB}) is divided by the sum of the responses to the unmixed components:

$$\sigma = R_{AB}/(R_A + R_B) \quad (3)$$

If sucrose/citric acid mixtures show level independence, R_{AB} and $R_A + R_B$ should be related by a straight line through the origin. Level independence was tested for pairs of approximately equi-intense components: Only mixtures with τ-values between 0.4 and 0.6 were included ($n = 6$). For these substance combinations, the stronger component is at most 50% more intense than the weaker. Linear regression analysis yielded $R_{AB} = 0.25 + 0.45\ (R_A + R_B)$. The intercept did not differ significantly from zero (two-tailed test, $t = 2.29$, $P > 0.05$). Linear regression through the origin yielded $R_{AB} = 0.56\ (R_A + R_B)$. Given the good fit of this regression equation ($R^2 = 0.990$), we can conclude that the principle of level independence holds for sucrose/citric acid mixtures (Figure 2A).

According to the second principle, hypo-additivity, the sum of the perceived intensities of the components exceeds the perceived intensity of the mixture: $R_{AB} < R_A + R_B$. In Figure 2B the degree of additivity (σ) is given as a function of the relative component intensity (τ). The upper and lower horizontal lines represent complete additivity ($R_{AB} = R_A + R_B$) and the arithmetic mean of the component perceived intensities [$R_{AB} = (R_A + R_B)/2$], respectively. The V-shaped line represents the case where the perceived taste-intensity of the mixture equals that of the strongest taste component. The data exhibit hypo-additivity ($\sigma < 1$).

According to Berglund and Olsson's (1993a, b) definition of symmetry, combinations of components with τ-values equi-distant from 0.5 should form mixtures with the same degree of additivity. When $\tau = 0$ or $\tau = 1$, σ equals 1 by definition. For all the other τ-values, $\sigma < 1$. Given the pattern in Figure 2B, we assumed that testing for symmetry was equivalent to determining whether the data deviated from a symmetrical curve with a minimum near $\tau = 0.5$. A

second order polynomial was estimated to determine at which τ-value σ was minimal. The τ-value found (0.45) deviates slightly from the value expected for symmetry (0.50). Predictions of a third order polynomial were not significantly better than those of the second order polynomial ($P > 0.50$).

The fourth principle concerns the possibility that a mixture may be weaker than the strongest of its components. This principle is referred to as compromise (e.g. Cain and Drexler, 1974). In Figure 2B, the mixtures below the V-shaped line fit the definition of compromise: 63% of the observations lie below this line. This implies that for most sucrose/citric acid mixtures, the act of physical addition gave rise to a perceptual intensity reduction. Interestingly, every mixture with the highest sucrose level exhibited compromise.

It should be noted that the definitions for the four interaction principles used above, are typical for studies using total intensity judgements only. Other investigators have used other definitions for principles carrying the same name. For example, when additivity is defined as the case where the response to the mixture (R_{AB}) equals the sum of responses to the unmixed substances ($R_A + R_B$), virtually all mixtures exhibit hypo-additivity. This hypo-additivity results from compression in the psychophysical functions of the mixture components (Bartoshuk, 1975). De Graaf and Frijters (1988) have referred to this definition of additivity as 'apparent additivity'. According to these authors 'the nature *and* magnitude of the taste interaction between substances must be compared with the nature *and* magnitude of the apparent taste interactions within substances' (p. 527) to determine the sensory interactions in the mixture. The apparent within-substance interactions are assessed by comparing the sum of two responses (e.g. $R_A + R_{2A}$) to the response to a hypothetical mixture of the substance mixed with itself (R_{3A}). For uniformity, the term 'hypo-additivity' in the remainder of this paper refers to the definition used by Berglund and Olsson. The expression 'mixture suppression' is used for De Graaf and Frijters' definition.

Due to the common finding of hypo-additivity (e.g. Pfaffmann *et al.*, 1971), the definition of symmetry for intensity judgements mostly reduces to determining whether σ is minimal for equi-intense components. This rule concurs with the predictions of several interaction models [e.g. the Vector Summation model (Berglund *et al.*, 1973), the Dominant Component rule (e.g. McBride, 1989), and the U-model (Patte and Laffort, 1979)]. In taste mixture research, however, the evaluation of symmetry usually involves qualitative information: symmetrical suppression refers to the case where components suppress each other's specific intensities to the same degree (e.g. Schifferstein and Frijters, 1993). For example, in a mixture composed of a sucrose level and a citric acid level that produce equi-intense sensations when unmixed, the sourness should equal the sweetness intensity. The discrepancies in definitions explain why the current total intensity data approximate symmetry ($\sigma = 0.45$), whereas the identification data clearly deviate from symmetry ($\sigma \approx 0.4$).

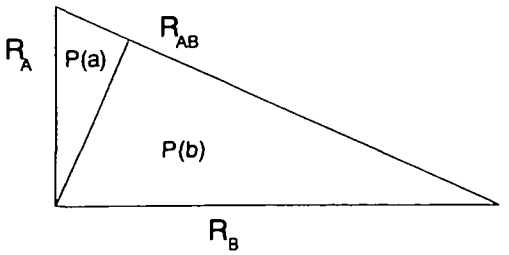

Figure 3 Graphical presentation of Olsson's (1994) interaction model. For an explanation, see text.

Olsson's interaction model

On the basis of his empirical findings, Olsson (1994) designed an interaction model comprising rules for both qualitative and quantitative odor interaction. He found that the principles of level independence, hypo-additivity and symmetry were valid for odor intensity interactions in butanol/pyridine mixtures. Only mixtures that were frequently confused with the background stimulus exhibited compromise. For the majority of the mixtures he found partial addition: $R_A + R_B > R_{AB} > R_A > R_B$. Because he found $R_{AB} \approx (R_A + R_B)/\sqrt{2}$ for $R_A \approx R_B$, he concluded that mixture intensity could be predicted by a Euclidian Additivity (EA) model (Laffort and Dravnieks, 1982):

$$R_{AB} = (R_A^2 + R_B^2)^{1/2}. \quad (4)$$

The EA model shows hypo-additivity, symmetry, level independence and no compromise. Graphically, the perceived intensities of the unmixed components and the mixture are represented by the lengths of the sides of a triangle, in which a right angle is enclosed by the component intensities (Figure 3). The probabilities to identify a mixture as either unmixed component are represented by the areas formed when a perpendicular is drawn from the right angle to the opposite side. Only the relative proportions of cases in which the mixture is identified as one of its components are determined. *P(a)* is defined as $P(A)/[P(A) + P(B)]$ and

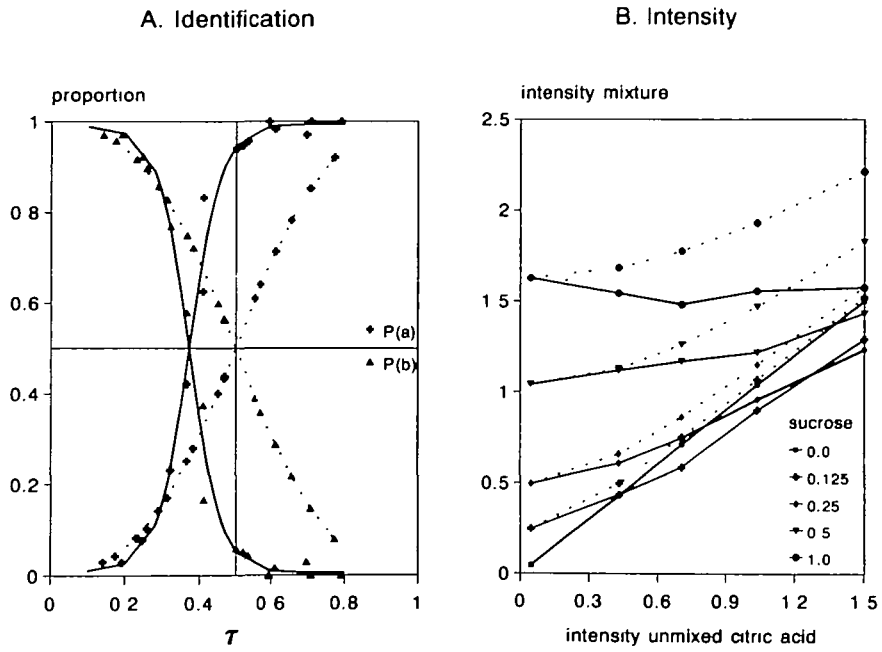

Figure 4 Evaluation of the predictive validity of Olsson's (1994) interaction model for sucrose/citric acid mixtures. Panel A shows predicted and observed values for the relative proportions of mixtures identified as unmixed sweetener [*P*(*a*)] or acid [*P*(*b*)] Panel B shows predicted and observed values for mixture intensity. Mixture intensity is plotted as a function of the intensity of unmixed citric acid, with separate curves drawn for each sucrose level Predicted values are connected with dotted curves, whereas the observed values are approximated by the drawn curves

$P(b) = P(\mathrm{B})/[P(\mathrm{A}) + P(\mathrm{B})]$. The model predicts these proportions by:

$$P(a) = R_A^2/(R_A^2 + R_B^2) \text{ and } P(b) = R_B^2/(R_A^2 + R_B^2). \quad (5)$$

The analyses of the current data have shown that the quality interaction between sucrose and citric acid is asymmetrical (Figure 1). The principles of level independence and hypo-additivity seem to hold for the intensity interaction. However, the intensity data also exhibit compromise and suggest deviations from symmetry (Figure 2). Consequently, it is not surprising that the model's estimates for the proportions of mixtures erroneously identified as unmixed sweetener [*P*(*a*)] or acid [*P*(*b*)] and for the perceived mixture intensity (R_{AB}) are not accurate. The predictions for the identification data in Figure 4A suffer from deviations from symmetry. The model predicts that $P(a) = P(b)$ for $\tau = 0.5$, whereas the experimental data show that $P(a) = P(b)$ when $\tau = 0.37$. Figure 4B shows that the model overestimates mixture intensity.

Validity of the model for taste interactions

The calculations presented above have shown that the Olsson model cannot describe the intensity and quality interactions in sucrose/citric acid mixtures accurately. Does this imply that the model cannot be used to describe any taste interactions in mixtures of dissimilar tasting substances?

As regards the principle of symmetry, it should be noted that asymmetry is common for quality interactions in taste mixtures. An impression of the degree of asymmetry can be derived from studies assessing the intensities of the component sensations within the mixture. Olsson (1993) gives a formula to calculate the component quality proportion (τ') which gives the relative contribution of each component to the intensity of the mixture percept:

$$\tau' = R_A'/(R_A' + R_B'). \quad (6)$$

In this equation, R_A' and R_B' are the responses to the specific intensities of the components in the mixture.

Figure 5 shows τ' values for sucrose/citric acid (Schifferstein and Frijters, 1990), sucrose/NaCl (De Graaf and Frijters, 1989), quinine/NaCl (Schifferstein and Frijters, 1992, Experiment 2) and quinine/sucrose (Lawless, 1979) mixtures as a function of τ. The former three studies assessed the specific intensities and the total intensities of the mixed and unmixed components in separate sessions using a difference estimation procedure. In the latter study, the two specific intensities of each stimulus (bitterness and

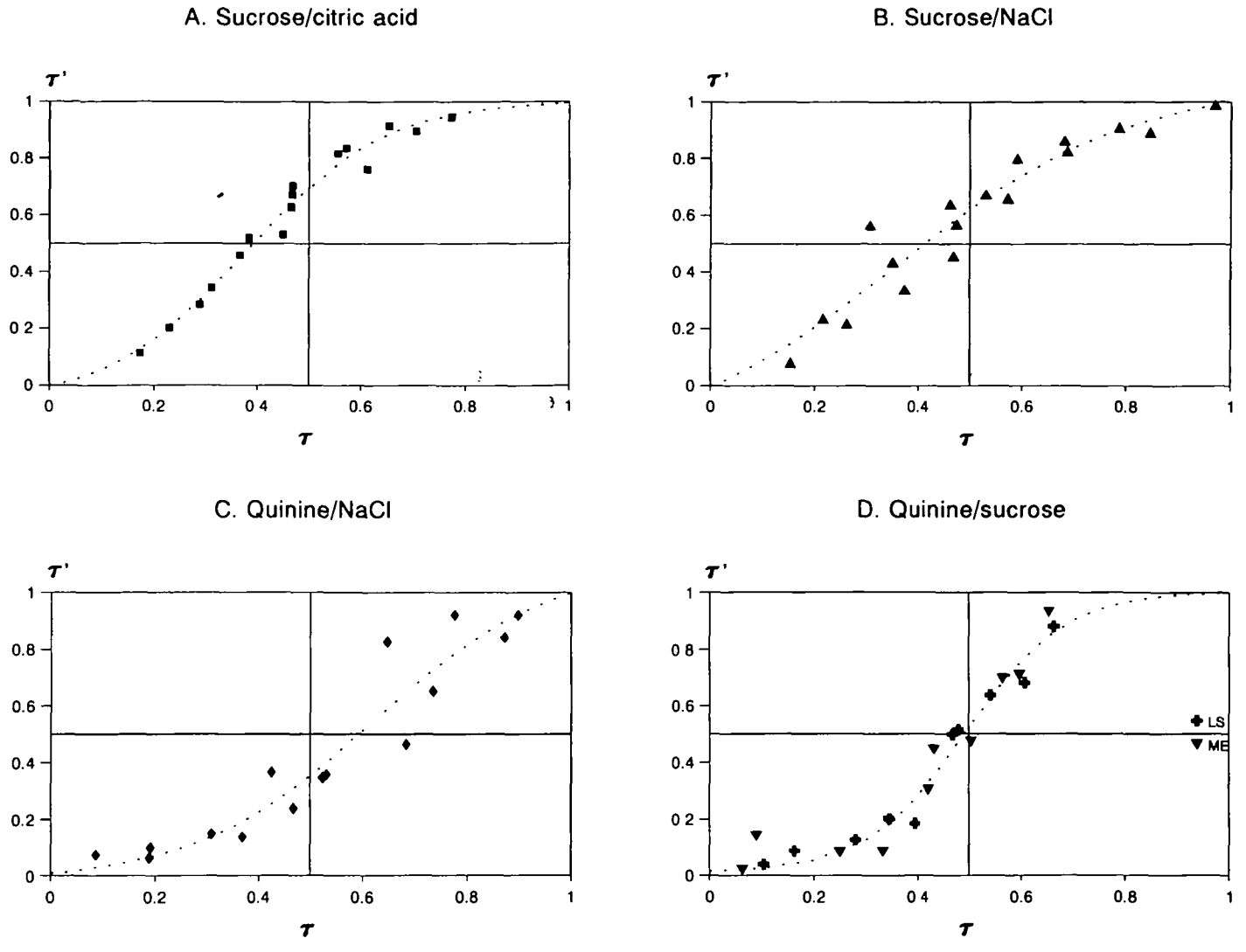

Figure 5 The component quality proportion in the mixture ($\tau' = R'_A/R'_A + R'_B$) as a function of the relative intensity of the unmixed components ($\tau = R_A/R_A + R_B$) for sucrose/citric acid (Schifferstein and Frijters, 1990), sucrose/NaCl (De Graaf and Frijters, 1989), quinine HCl/NaCl (Schifferstein and Frijters, 1992, Experiment 2) and quinine sulphate/sucrose (Lawless, 1979) mixtures. Substance A corresponds to the substance mentioned first in the panel heading. In Panel D, separate symbols are used for values based on line scale judgements (LS) and magnitude estimates (ME).

sweetness) were expressed simultaneously in magnitude estimates or in line scale judgements.

Comparing the τ' curve for sucrose/citric acid mixtures to the $P(a)$ curve in Figure 4 shows that $P(a) = 0.5$ at approximately the same τ-value as where $\tau' = 0.5$: $P(a) = 0.5$ for $\tau = 0.37$ and $\tau' = 0.5$ for $\tau = 0.39$. This implies that the probabilities of identifying a mixture as either component are equal for the two components, when the specific sensations in the mixture are equi-intense. When $\tau' = 0.5$, τ equals 0.41 for sucrose/NaCl, 0.59 for quinine/NaCl and 0.49 for quinine/sucrose. When $\tau = 0.5$, the estimated values for τ' are 0.70, 0.62, 0.35 and 0.52 in Figure 5A–D, respectively. Apparently, asymmetry is evident in three of the four mixture types evaluated. These findings indicate that asymmetrical mixture suppression is quite a common finding for mixtures of dissimilar tasting substances, which is not in accordance with the Olsson (1994) model.

The principle of partially additive components underlying the mixture intensity estimates was violated by the sucrose/citric acid mixtures. The EA model reflects a special case of the Vector Summation model (Equation 1), in which the two component vectors are orthogonal ($\alpha = 90°$). Schifferstein and Frijters (1993) obtained an optimal fit for the Vector Summation model when α was 110° for sucrose/citric acid, 88° for sucrose/NaCl and 108° for quinine HCl/NaCl. The proportions of explained variance (U) for the four

mixture types equalled 0.976, 0.968 and 0.909, respectively. Since these α-values deviate from 90°, the proportions of explained variance are expected to decrease when the EA model is used. Indeed, the proportions of explained variance are 0.606, 0.963 and 0.800, respectively. Thus, the model performed worst for citric acid/sucrose, but it was also far from perfect for other mixture types.

The two model assumptions that were not violated, could be general principles underlying taste interactions. Hypo-additivity and mixture suppression are common findings for combinations of dissimilar tasting substances (e.g. Pangborn, 1960; Pfaffmann *et al.*, 1971; Lawless, 1986). The occurrence of level independence has not yet been investigated extensively for taste mixtures. When the relationship between the sum of intensities for the unmixed components and the intensity of the mixture was estimated for the data in Figure 5 (panels A–C) for approximately equi-intense components ($0.40 < \tau < 0.60$), none of the three intercepts was significantly different from zero (two-tailed *t*-test, $P > 0.05$) and regression through the origin provided good degrees of fit ($R^2 \geq 0.999$). In addition, the fact that no systematic deviations occur from the sigmoidal curves in Figures 1 and 5 suggests that level independence holds for qualitative interactions, too.

Conclusion

Two principles underlying Olsson's (1994) interaction model are not valid for taste mixtures and, consequently, the model cannot be used to predict intensity and quality for mixtures of dissimilar tasting substances. If the principle of level dependency holds for interactions among dissimilar tasting substances, $P(a)$, τ, τ' and σ may be useful diagnostic tools in future taste interaction research. Figure 5 suggests that the τ'-value at which τ equals 0.5 provides a useful index for the degree of asymmetry of the suppression between two components. Analogously, the τ-value at which τ' and $P(a)$ equal 0.5 provides an index for the degree of asymmetry.

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