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An Equiratio Mixture Model for Non-additive Components: A Case Study for Aspartame/ Acesulfame-K Mixtures

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Abstract

The Equiratio Mixture Model predicts the psychophysical function for an equiratio mixture type on the basis of the psychophysical functions for the unmixed components. The model reliably estimates the sweetness of mixtures of sugars and sugar-alchohols, but is unable to predict intensity for aspartame/sucrose mixtures. In this paper, the sweetness of aspartame/acesulfame-K mixtures in aqueous and acidic solutions is investigated. These two intensive sweeteners probably do not comply with the model's original assumption of sensory dependency among components. However, they reveal how the Equiratio Mixture Model could be modified to describe and predict mixture functions for non-additive substances.

To predict equiratio functions for all similar tasting substances, a new Equiratio Mixture Model should yield accurate predictions for components eliciting similar intensities at widely differing concentration levels, and for substances exhibiting hypo- or hyperadditivity. In addition, it should be able to correct violations of Stevens's power law. These three problems are resolved in a model that uses equi-intense units as the measure of physical concentration. An interaction index in the formula for the constant accounts for the degree of interaction between mixture components. Deviations from the power law are corrected by a nonlinear response output transformation, assuming a two-stage model of psychophysical judgment. **Chem. Senses 21: 1–11, 1996.**

Introduction

In 1983, Frijters and Oude Ophuis proposed a mixture model that predicts the psychophysical function for an equiratio mixture type on the basis of the psychophysical functions of the unmixed components. In an equiratio mixture series, the concentration ratio of the constituents is constant, whereas the total concentration level varies. For example, 0.125 M glucose mixed with 0.375 M fructose and 0.25 M glucose mixed with 0.75 M fructose are two mixtures from a glucose/fructose 0.25/0.75 series: the concentration ratios are equal, but the total concentration levels are different (0.5 and 1.0 M, respectively). The Equiratio Mixture Model (EMM) starts from power functions relating an unmixed tastant's concentration to the subject's response (Stevens, 1975):

$$R_{Ai} = k_A C_{A_i}^{n_A} \quad (1)$$

and

$$R_{Bj} = k_B C_{B_j}^{n_B} \quad (2)$$

The responses to concentration i of substance A (C_{Ai}) and to concentration j of substance B (C_{Bj}), both expressed in moles/l are denoted as R_{Ai} and R_{Bj}, respectively. For an equiratio mixture with concentration ratio $C_{Ai}/C_{Bj} = p/q$ ($p + q = 1$), the psychophysical mixture function is estimated on the basis of the psychophysical functions for the unmixed components:

$$R_{ABijpq} = k_{ABpq} C_{ABijpq}^{n_{ABpq}} = \frac{\frac{pk_A}{C_{Ast}} + \frac{qk_B}{C_{Bst}}}{\frac{p}{C_{Ast}} + \frac{q}{C_{Bst}}} \times C_{ABijpq}^{pn_A + qn_B} \quad (3)$$

where C_{Ast} and C_{Bst} are the concentrations of unmixed A and B giving rise to the same response as the standard stimulus in a magnitude estimation experiment.

According to Frijters and De Graaf (1987), the EMM describes the gustatory modality as an averaging system: the magnitude of the mixture response lies between the responses to the unmixed components at the same total concentration level. However, for substances equi-intense at widely different concentration levels ($k_A > k_B$), the model can predict a mixture intensity higher than any of the unmixed constituents (Berglund and Olsson, 1993; Schifferstein, 1995). Therefore, Baird (1991) suggested averaging the two constants geometrically:

$$k_{ABpq} = k_A^p \times k_B^q \quad (4)$$

Frijters and Oude Ophuis (1983) indicate that the EMM presupposes that the mixture components are mutually dependent: molecules of substance A should be as competitive as those of substance B in occupying taste receptor sites (p. 760). This statement probably implies that the two tastants should show complete or partial cross-adaptation (e.g. Meiselman, 1968; McBurney *et al.*, 1972). The EMM successfully predicts sweetness intensities for mixtures of 2, 4 and 8 sugars and sugar-alcohols (Frijters and Oude Ophuis, 1983; Frijters *et al.*, 1984; Frijters and De Graaf, 1987). The scarce reports on cross-adaptation, indeed, show that sugars and sugar-alcohols generally exhibit mutual cross-adaptation (McBurney *et al.*, 1972; Schiffman *et al.*, 1981).

Concentration levels

Nevertheless, the original EMM is unable to predict the intensity for mixtures of the cross adapting (see Lawless and Stevens, 1983) substances aspartame and sucrose (Schifferstein, 1995). The model's failure is probably caused by its inability to deal with substances equi-intense at substantially different concentration levels. The substance combinations for which it is successful, all produce equal intensities at roughly similar concentration levels. When $k_A > k_B$ (Equations 1 and 2), investigators tend to choose concentration ratios where $p < q$. In this case, the estimates of the mixture function parameters are dominated by the values of the constant and the exponent for the mixture component with the highest concentration level (Frank *et al.*, 1989). The model's predictions are incorrect: the original EMM over-estimates mixture intensities for aspartame/sucrose mixtures, whereas Baird's (1991) version under-estimates them (Schifferstein, 1995).

Following the idea that mixture phenomena can be evaluated most accurately by using equi-intense components (Yamaguchi *et al.*, 1970; Beidler, 1971; Bartoshuk and Cleveland, 1977; De Graaf and Frijters, 1986, 1988; Frank *et al.*, 1989), Schifferstein (1995) recently modified the EMM by substituting the number of equi-intense units for the concentration levels in the model equations. This modification enabled him to predict the sweetness intensity of aspartame/sucrose mixtures accurately.

Sensory interactions

The upper part of Table 1 shows estimates of equi-intense mixture concentrations, for previously published studies on the EMM using concentration ratios 0.75/0.25, 0.50/0.50, 0.25/0.75, obtained from experimental regression equations and predicted model equations. Under the assumption that equi-intense solutions obtain the same magnitude estimates, a 'matching-by-scaling' procedure was employed: concentrations were calculated that correspond to the response equal to the modulus value (10). The equi-intense concentration levels predicted by the Beidler (1971) equation ($C_{Beidler}$) are obtained using the equation reported by De Graaf and Frijters (1986):

$$C_{Beidler} = \frac{C_A C_B}{pC_B + qC_A} \text{ with } C_A = \left[\frac{R}{k_A}\right]^{\frac{1}{n_A}}$$

$$\text{and } C_B = \left[\frac{R}{k_B}\right]^{\frac{1}{n_B}} \quad (5)$$

These values are similar to the predictions by the EMM

Table 1 Equi-intense concentrations according to Beidler's (1971) mixture equation, experimental regression equations, and two Equiratio Mixture Models (Frijters and Oude Ophuis, 1983, Baird, 1991) for three different ratios

Mixture type						0.75/0.25				0.50/0.50				0.25/0.75			
Components	Concentration range	k_A	n_A	k_B	n_B	Beidler	Experiment	Frijters & Oude Ophuis	Baird	Beidler	Experiment	Frijters & Oude Ophuis	Baird	Beidler	Experiment	Frijters & Oude Ophuis	Baird
Glucose/fructose	0.125–2.0 M	14.48	1.55	26.58	1.18	0.656	0.617	0.643	0 699	0.561	0.547	0 556	0 610	0 491	0 488	0.491	0.522
Sorbitol/sucrose	0.16–0.81 M	53.9	2.67	140.2	1.19	0.270	0.327	0.357	0 433	0.181	0.234	0 268	0 324	0 136	0.156	0 189	0 215
Fructose/sucrose	0.125–2.0 M	26.39	1.10	38.98	0 95					0.303	0.291	0.303	0 326				
Glucose/sorbitol	0.125–2.0 M	14.67	1.38	13.16	1.26					0.780	0.793	0 777	0.779				
Itaconic/ascorbic acid	3.125–50 mM	0.647	1.13	0.170	1.36	12.7	12.8	13.2	12.9	14.4	14.9	15 6	152	16.8	17.6	17.9	17.6
APM/AcK in water	0.256–10 mM	5.866	0.993	3.902	1.095	1 838	1.349	1.804	1 866	1.985	1.271	1 903	2 206	2.157	1.490	2.101	2.192
APM/AcK in acid	0.256–10 mM	6.481	0.810	4.008	0.640	2.004	1 440	1.872	2.057	2 424	1 251	2 144	2.533	3.067	1.311	2.675	3.198

Note: the subscripts in columns 3–6 refer to the substances that are mentioned first (A) or second (B) in column 1 The regression equations used for the calculations were reported by Frijters and Oude Ophuis (1983: glucose/fructose), Frijters *et al.* (1984: sorbitol/sucrose), Frijters and De Graaf (1987: fructose/sucrose and glucose/sorbitol), and Frijters and Stevens (1986: itaconic/ascorbic acid). The equations for aspartame/acesulfame-K mixtures were obtained in the present study.

modified by Schifferstein (1995)[1]. The predictions by the Frijters and Oude Ophuis (1983) EMM are given by:

$$C_{F\&O} = \left[R \times \frac{\frac{p}{C_{Ast}} + \frac{q}{C_{Bst}}}{\frac{pk_A}{C_{Ast}} + \frac{qk_B}{C_{Bst}}}\right]^{\frac{1}{pn_A + qn_B}} \quad (6)$$

where C_{Ast} and C_{Bst} are concentration levels with responses equal to the standard solution in a magnitude estimation experiment. The predictions of Baird's (1991) modified version are calculated from:

$$C_{Baird} = \left[\frac{R}{k_A^p k_B^q}\right]^{\frac{1}{pn_A + qn_B}} \quad (7)$$

If the equi-intense concentration in Table 1 is lower than the concentration predicted by the Beidler equation, a mixture type exhibits hyperadditivity. These concentrations are underlined in Table 1. In accordance with previous reports, hyperadditivity is found for glucose/fructose (De Graaf & Frijters, 1986) and fructose/sucrose (De Graaf & Frijters, 1988). Frijters and Oude Ophuis's (1983) EMM predicts both hypo- and hyperadditivity, whereas Baird's (1991) version predicts primarily hypoadditivity. Schifferstein's (1995) version of the EMM predicts additivity[1]. The EMM's underestimation of observed mixture intensity has probably not been a serious problem in previous studies because the substance combinations used elicit a small degree of hyperadditivity, at most. Equiratio mixtures of sugars and sugar-alcohols typically elicit sweetness intensities intermediate between the intensities of their unmixed components (De Graaf and Frijters, 1987).

In summary, the EMM fails to predict mixture intensity for substances equi-intense in different concentration ranges (aspartame/sucrose). The substance combinations for which the EMM has been successful produce similar intensities at similar concentration levels, show cross-adaptation and exhibit only small deviations from sensory additivity. However, these substance combinations are not representative for all mixtures of similar tasting substances. Therefore, the present study investigates whether the EMM can be expanded to describe and predict mixture intensity for other substances eliciting similar tastes, irrespective of their degree of sensory dependence.

The present study investigates the sweetness perception of equiratio mixtures of aspartame and acesulfame-K. These sweeteners were chosen because they exhibit considerable hyperadditvity (Frank *et al.*, 1989; Matysiak and Noble, 1991; von Rymon Lipinski, 1991; Ayya and Lawless, 1992) and they exhibit a small degree of cross adaptation, at most (Schiffman *et al.*, 1981). The first experiment assessed sweetness intensities in aqueous solutions. To mimic aspartame/acesulfame-K interactions in soft drinks, a second experiment was performed for sweetener mixtures in acidic solution.

[1]The predictions of the EMM modified by Schifferstein (1995) are equal to those by the Beidler (1971) equation for the response level at which the equi-intense concentration units are defined.

Materials and methods

Subjects

Twenty-four unpaid volunteers, 11 men and 13 women, ranging in age from 19 to 29 years, participated in the first experiment. In the second experiment, 24 paid volunteers, 11 men and 13 women, aged 18–29 years, participated. Most subjects were students of the Agricultural University. They were naive with respect to the substances used and the purpose of the study.

Stimuli

The stimuli were solutions of aspartame, APM (Sanecta®, Holland Sweetener Company) and acesulfame-K, AcK (Sunett®, Hoechst), and mixtures of these two substances in demineralized water (Experiment 1) or in 0.75 g/l citric acid (monohydrate, Merck 244; Experiment 2). According to Bonnans and Noble (1993), 0.75 g/l citric acid corresponds to a concentration level typically used in beverages. The five concentration ratios were APM/AcK 1.0/0.0, 0.75/0.25, 0.50/0.50, 0.25/0.75 and 0.0/1.0. The total concentrations in each of the series were 0.256, 0.64, 1.6, 4.0 and 10.0 mM. The solution containing 1.6 mM APM was used as the standard stimulus. For each experiment, 25 solutions were prepared at least 24 h prior to tasting. Solutions were stored in a dark, refrigerated room at 4°C for no longer than 4 days.

Procedure

The subjects were instructed to judge the sweetness intensity of each stimulus in proportion to the intenstiy of the standard stimulus (1.6 mM APM) which had an assigned value of 10. If no sweet taste was perceived, the subjects were instructed to give a zero response. A standard stimulus was presented at the beginning of the session, after the 12th, 25th and 37th stimulus. The instructions emphasized that only the sweetness intensity was to be judged. The hedonic value and side tastes of the stimuli were to be disregarded.

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 60 s. The subjects were requested to rinse their mouths thoroughly with demineralized water after each stimulus. During the experimental session, all 25 mixtures were evaluated twice. The stimuli were presented in a different random order to each subject.

Data analysis

The arithmetic mean of the log-transformed non-zero responses (μ) was corrected for the proportion of zero responses (δ) by the formula (Owen and DeRouen, 1980):

$$R = (1 - \delta)e^{\mu} \tag{8}$$

A 95% confidence interval for the geometric mean of the responses was approximated by calculating

$$e^{\ln(R) \pm 2\sigma} \tag{9}$$

(Alf and Grossberg, 1979), where σ denotes the standard error of μ. The log-transformed geometric means were used in linear regression equations estimating the constant k and the exponent n of the power functions for aspartame, acesulfame-K, and the three equiratio mixture series:

$$\ln(R) = \ln(k) + n\ln(C) \tag{10}$$

From these regression equations, the predicted mean responses $\hat{R}_{exp}$ were obtained.

The estimated values of constants and exponents of the psychophysical functions of unmixed aspartame and acesulfame-K were used to calculate the functions predicted by the Frijters and Oude Ophuis EMM (Equation 3). The response to the standard stimulus C_{Aspst}, predicted by the psychophysical regression equation (9.35 in Experiment 1 and 9.48 in Experiment 2), was inserted in the regression equation for acesulfame-K to obtain C_{AcKst}. Also, the modified values for k_{ABpq} as used by Baird (1991) were calculated (Equation 4). The regression equations and the model equations were used to estimate equi-intense concentration levels for the response level $R = 10$ (Equations 5–7).

The log-transformed responses were subjected to repeated measures analysis of variance (ANOVA). Responses equal

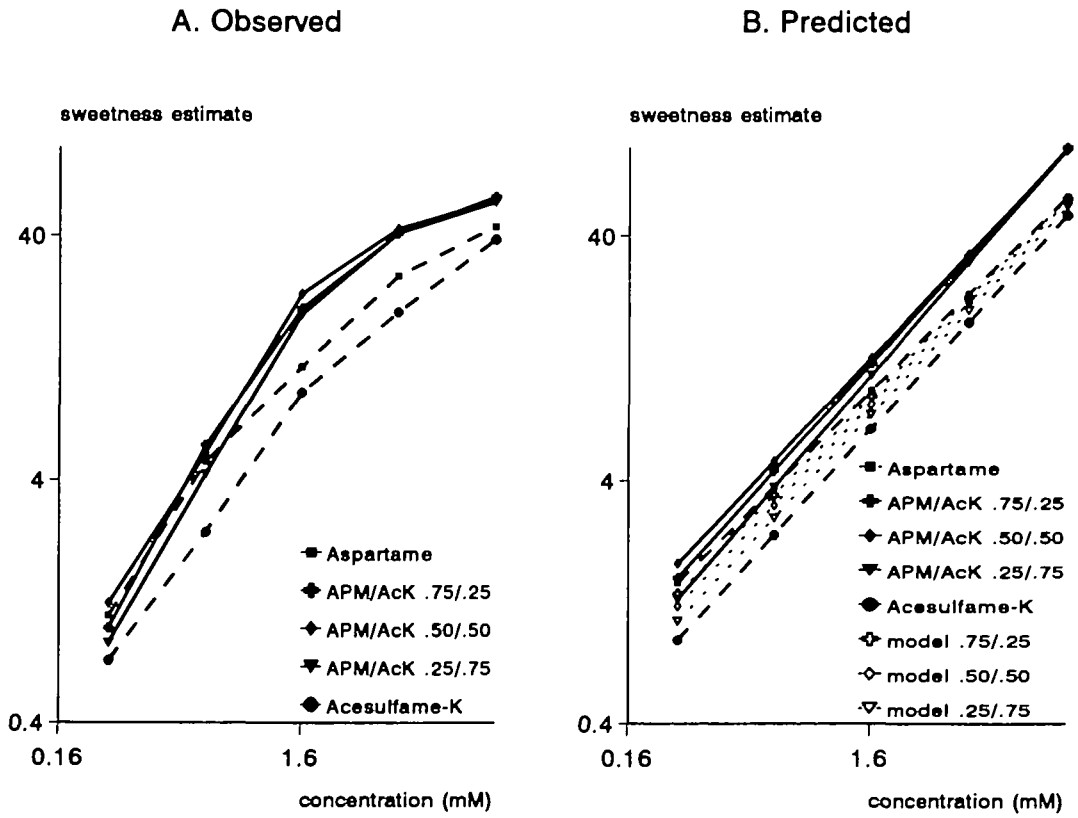

Figure 1 The sweetness of aspartame, acesulfame-K and aspartame/acesulfame-K equiratio mixtures in aqueous solution. Panel A shows the geometric mean sweetness estimates as a function of the total concentration of the stimulus. Panel B shows the regression lines calculated for these curves, and the lines predicted on the basis of the Frijters & Oude Ophuis (1983) Equiratio Mixture Model.

to 0 were replaced by a response R_0, so that the geometric mean for each stimulus equalled R. R_0 varied from 0.33 to 14.35 in Experiment 1, and from 0.79 to 4.15 in Experiment 2. It was calculated by the formula:

$$R_0 = e^{\frac{\ln R - (1-\delta)\mu}{\delta}} \quad (11)$$

Results

The sweetness responses given to aspartame/acesulfame-K mixtures in aqueous solutions (Experiment 1) and acidic solutions (Experiment 2) are presented in Figures 1 and 2. ANOVA showed significant effects of stimulus type, concentration level and stimulus type × concentration interaction in both conditions ($P < 0.001$). In Figures 1A and 2A, the aspartame curves fall above the acesulfame-K curves. Apparently, aspartame tastes sweeter than acesulfame at the same concentration level. The experimental mixture curves mostly lie above the curves for both unmixed substances, indicating hyperadditivity among the two substances. Paired comparison of the aspartame curve with any other curve yielded a significant stimulus type main effect for all comparisons ($P < 0.001$).

An overall ANOVA testing for differences between aqueous and acidic solutions reveals significant condition × concentration [$F(4,184) = 16.0$, $P < 0.001$] and condition × stimulus type × concentration [$F(16,736) = 2.01$, $P = 0.01$] interactions. The first interaction shows that the psychophysical functions in water are significantly steeper than those in acid. The five estimated power law exponents are all higher in water than in acid (Tables 1 and 2). The second statistical interaction points out that the sensory interaction pattern in water is not identical to that in acid.

Nine out of 10 estimated power functions are inadequate to describe the data. For every regression function except unmixed acesulfame-K in acidic solution, one or more predicted intensities ($\hat{R}_{exp}$) fall outside the 95% confidence interval for R. The degree of explained variance increases significantly when a quadratic term is inserted in the regression equations for these nine stimulus types (Table 3).

The original EMM predicts curves that fall approximately between the curves for unmixed aspartame and unmixed acesulfame-K. All these predictions underestimate the sweet-

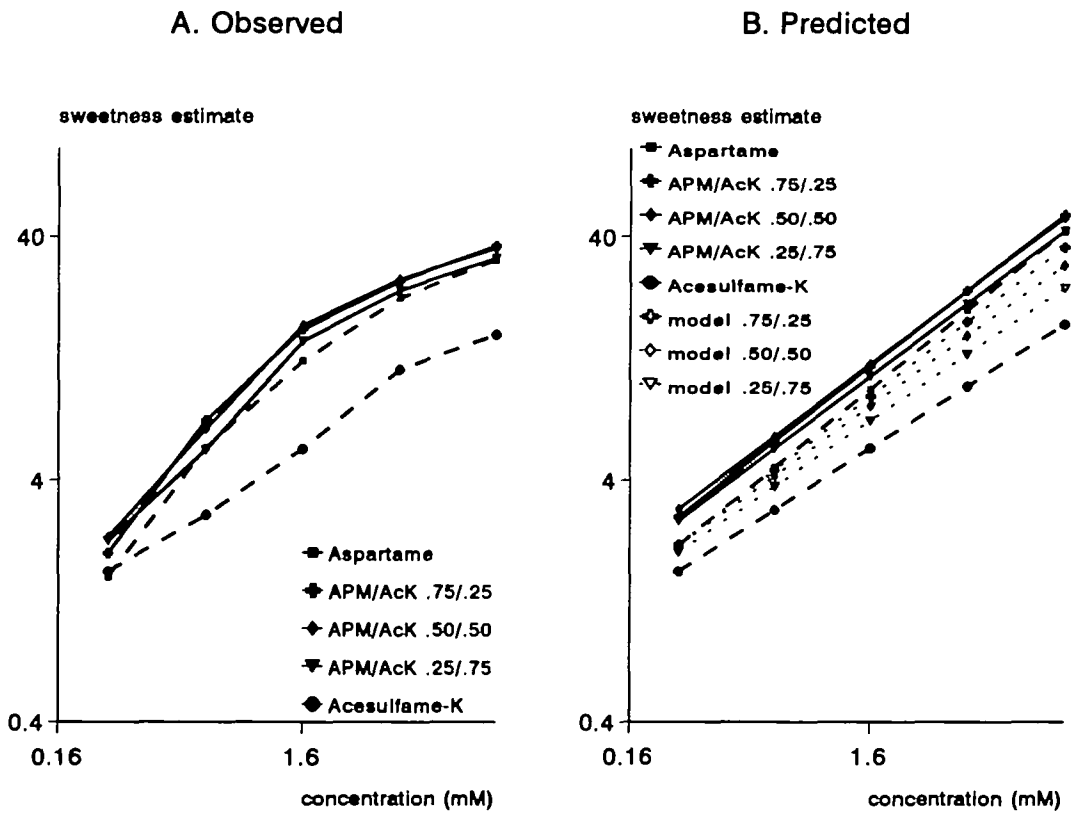

Figure 2 The sweetness of aspartame, acesulfame-K and aspartame/acesulfame-K equiratio mixtures in 0 75 g/l citric acid. Panel A shows the geometric mean sweetness estimates as a function of the total concentration of the stimulus. Panel B shows the regression lines calculated for these curves, and the lines predicted on the basis of the Frijters & Oude Ophuis (1983) Equiratio Mixture Model.

ness intensity of the mixtures. For 63% of the mixtures, the predicted responses fall outside the 95% confidence interval for R. The predictions made by the model as modified by Baird (1991) are even worse: the predicted k-values for the mixtures are lower (Table 2) and, consequently, the degree of underestimation is larger.

An inspection of the estimated equi-intense concentration levels (Table 1) yields a similar result: The experimental data and the Frijters and Oude Ophuis model indicate hyperadditivity, but the degree of hyperadditivity is larger for the experimental data. The Baird model predicts hypo-additivity.

Table 2 Parameters for empirical and calculated psychophysical functions for aspartame, acesulfame-K and equiratio aspartame/acesulfame-K mixtures

Stimulus	Experiment		Equiratio model		
	k	n	$k_{F\&O}$	k_B	n
In water					
APM/AcK 0.75/0.25	7.183	1.106	5.486	5.298	1 018
APM/AcK 0.50/0.50	7.747	1.064	5.044	4.784	1.044
APM/AcK 0.25/0.75	6.302	1.157	4.523	4.321	1.069
In acid					
APM/AcK 0.75/0.25	7.526	0.779	6.179	5.747	0.768
APM/AcK 0.50/0.50	8.453	0 751	5.753	5.097	0.725
APM/AcK 0.25/0.75	8 165	0.749	5.107	4.520	0.683

Note k in the Equiratio model was estimated using Equation 3 ($k_{F\&O}$) or Equation 4 (k_B).

Table 3 Proportion of variance accounted for by regression equations of the form $\ln(R) = a + b\,(\ln C) + c\,(\ln C)^2$

Stimulus type	Increase in R^2	
	Linear term	Quadratic term
In water		
Aspartame	0.714	0.025*
APM/AcK 0.75/0.25	0.736	0.026*
APM/AcK 0.50/0.50	0.744	0.056*
APM/AcK 0.25/0.75	0.758	0.060*
Acesulfame-K	0.688	0.013*
In acid		
Aspartame	0.665	0.033*
APM/AcK 0.75/0.25	0.589	0.025*
APM/AcK 0.50/0.50	0.568	0.035*
APM/AcK 0.25/0.75	0.594	0.043*
Acesulfame-K	0.433	0.001

Note: The regression analyses were performed on the individual responses used for the ANOVAs (see text). *Indicates a significant increase in R^2 for $P < 0.01$ (Williams, 1986).

Discussion

To estimate intensity accurately for all mixtures of similar tasting substances, three aspects of the EMM should be improved. It should be able to deal with substances that elicit similar intensities at different concentration levels, it should incorporate sensory interactions, and it should correct deviations from Stevens's power law. In the following, these three points are discussed and modifications of the EMM are put forward.

The measure of physical concentration

To predict mixture intensity for substances that are equi-intense at highly distinctive concentration levels, Schifferstein (1995) replaced concentrations (in molarity) in the EMM by units that evoke approximately equal intensities: intensity units (IUs). First, concentration levels are determined at which the unmixed substances A and B are equi-intense. This level of A and this level of B are arbitrarily defined to equal one IU. Subsequently, all other concentration levels in molarity are transformed into the equivalent numbers of IUs. The p'/q' ratio used in calculations for the EMM is based on the ratio of IUs, and can be close to 1 even though the concentration ratio in molarity (p/q) may approach infinity or zero. For the response level at which the equi-intense units are defined, the predictions of the model equal those made by the Beidler equation (Schifferstein, 1995). Since Schifferstein's (1995) modified EMM provides accurate predictions for mixture types the original model cannot account for, it is used below as the basis for a new Equiratio Mixture Model.

A measure for the degree of interaction

Possibly, as a consequence of the assumption of sensory dependent components, empirical tests of the EMM have been confined to substance combinations that behave approximately additively. Nevertheless, Frijters and Oude Ophuis's (1983) model predicts deviations from additivity (Table 1). It seems sensible to provide a formal basis for these interactions in the model. As a consequence, the model will be able to handle interacting components for which such a modification is necessary (e.g. aspartame/acesulfame-K mixtures).

Table 1 shows that two substances show either hyper- or hypoadditivity at all three concentration ratios. Consequently, it should be possible to derive an interaction index I for any pair of substances, which can be used to correct the EMM for any hyper- or hypoadditivity. In Schifferstein's (1995) model, the power law is essentially reduced to a one-parameter model: the predicted value of the constant k' equals some arbitrary, predetermined value, usually fixed at the value 10. The only parameter that is estimated is the value for the exponent of the mixture function. The interaction among tastants can be incorporated in the model by increasing (hyperadditivity) or decreasing (hypoadditivity) the value of k'. Figure 3 shows the relationship between the value for k' estimated for empirical mixture equations as a function of the concentration ratio defined in IUs (p'/q') for several substance combinations. The curves tend to show a minimum or maximum near $p' = 0.5$. Therefore, I suggest estimating the interaction index I for a curve symmetrical around $p' = 0.5$ by the formula:

$$k' = 10 + I\sqrt{p'q'} \qquad (12)$$

The value of I can be obtained by regression through the origin. The values thus estimated are 1.06 (glucose/fructose), 0.33 (APM/sucrose), –0.86 (itaconic/ascorbic acid), –8.04 (sorbitol/sucrose), 8.12 (APM/AcK in water) and 14.85 (APM/AcK in acid). The corresponding curves are drawn in Figure 3.

The form of the psychophysical functions

The Equiratio Model starts from the assumption that Stevens's power law gives a good description of the psychophysical relationship among the physical concentration of a substance and the response. As in previous experiments (Frijters and Oude Ophuis, 1983; Frijters *et al.*, 1984; Frijters and De Graaf, 1987; Schifferstein, 1995), however, several values of $\hat{R}_{exp}$ lie outside the confidence interval for R. Several psychophysical relationships appear to deviate from linearity in a log-log plot. Stevens's power law is unable to describe the psychophysical functions for

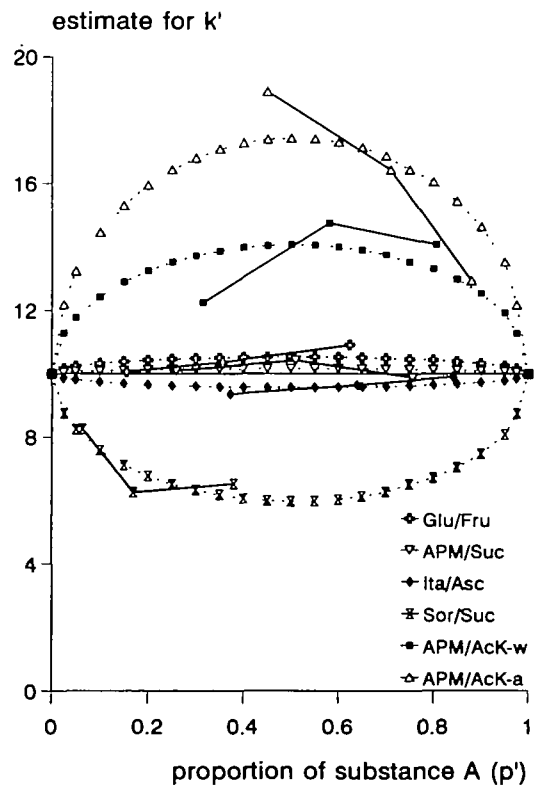

Figure 3 Values for k' estimated for empirical mixture equations and approximated by Equation 12, plotted as a function of the proportion of one mixture component (p') defined in IUs. The data are from Frijters and Oude Ophuis (1983: glucose/fructose), Schifferstein (1995: aspartame/sucrose), Frijters and Stevens (1986: itaconic/ascorbic acid), Frijters *et al.* (1984: sorbitol/sucrose) and the present study (aspartame/acesulfame-K in water or acid).

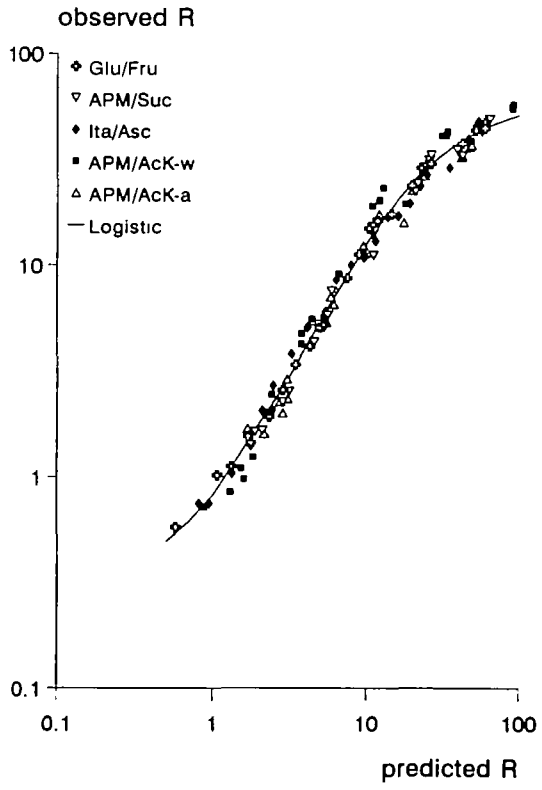

Figure 4 Relationship among observed responses and those predicted by regression equations for five mixture types. The curve indicates the logistic function estimated to describe this relationship (Equation 13). The data are from Frijters and Oude Ophuis (1983: glucose/fructose), Schifferstein (1995: aspartame/sucrose), Frijters and Stevens (1986: itaconic/ascorbic acid), and the present study (aspartame/acesulfame-K in water or acid).

the intensive sweeteners and its mixtures. This non-linearity is probably not due to the occurrence of non-sweet side tastes at high concentration levels. According to Ayya and Lawless (1992), bitterness ratings for aspartame/acesulfame-K mixtures are equal to or lower than those for the unmixed sweeteners, whereas the curvature in their functions seems larger (Figures 1–2).

Failures in Stevens's law are not an intrinsic feature of the EMM, but of the power law. The power function may be considered a first order approximation to the form of a psychophysical function, thereby neglecting all the deviations. However, the predictive validity of the EMM may be increased when a two-stage model of psychophysical judgment is assumed. In the first stage, perceived sweetness intensity is related to concentration by a power function. In the second stage, the response is a nonlinear function of perceived intensity. In the two-stage model, the EMM should predict the empirical mixture regression functions. The empirical and the estimated mixture functions are subsequently transformed by a non-linear response output function in order to predict the responses.

Figure 4 plots observed responses (R) as a function of the intensities predicted by the regression equations ($\hat{R}_{exp}$) for several mixture types. This plot shows that the relationship among predicted and observed responses is similar for these experiments, and approximates a slightly sigmoidal shape. This function was approximated by a logistic curve, which yielded the estimated equation:

$$\ln(R) = \frac{5.57}{1 + 3.70e^{-0.95\ln(\hat{R}_{exp})}} - 1.395 \qquad (13)$$

Predictions

The quality of the predictions of the original EMM can be compared to those of the improved model in which equi-intense units are used (Schifferstein, 1995), k' is corrected for mixture interactions (Equation 12), and the non-linear response output transformation is applied to the calculated predictions (Equation 13). The degree to which the empirical data (R) are predicted by the model ($\hat{R}$) was evaluated using the proportion of explained variance U (Eisler and Roskam, 1977) for the log-transformed responses. U is then given by the formula:

$$U = 1 - \frac{\Sigma[\ln(R) - \ln(\hat{R})]^2}{\Sigma[\ln(R) - \overline{\ln(R)}]^2} \qquad (14)$$

where $\overline{\ln(R)}$ indicates the mean value of $\ln(R)$. U ranges from 1 for an optimal fit to minus infinity.

Table 4 shows that the quality of the predictions of an Equiratio Mixture Model based on equi-intense units in which an interaction term is incorporated are as good as the predictions of the empirical regression equations. Correcting these linear equations for a nonlinear response output function yields U-values near to 1. Consequently, the new Equiratio Mixture Model gives nearly perfect predictions of the mean magnitude estimation responses to mixtures of similar tasting substances whose interaction index I is known.

When using the new EMM, the following remarks apply. First of all, the use of IUs instead of molarity seems primarily advantageous for substances eliciting equi-intense sensations

Table 4 The quality of predictions (U-values) for Equiratio models and experimental regression equations

Mixture type components	Model predictions				Experimental data	
	Frijters & Oude Ophuis	IU	IU + I	IU + I + ROF	Regression equations	Regression + ROF
Glucose/fructose	0.975	0.974	0.975	0.996	0.977	0.998
APM/sucrose	–2.872	0.958	0.958	0.992	0.960	0.995
Itaconic/ascorbic acid	0.978	0.974	0.976	0.991	0.979	0.989
APM/AcK in water	0.860	0.850	0.919	0.966	0.919	0.965
APM/AcK in acid	0.805	0.730	0.940	0.982	0.937	0.981

Note: U-values are given for the original Equiratio Mixture Model (Frijters and Oude Ophuis, 1983), the model in which intensity units are used (IU: Schifferstein, 1995), the IU-model including an interaction term (IU + I), and the model with an additional correction for the nonlinear response output function (IU + I + ROF). The U-values are also given for the empirical regressions equations and these equations corrected for the non-linear response output function.

The data are from Frijters and Oude Ophuis (1983: glucose/fructose), Schifferstein (1995. aspartame/sucrose), Frijters and Stevens (1986: itaconic/ascorbic acid) and the present study (aspartame/acesulfame-K).

at entirely different physical concentrations. Secondly, the new EMM is less parsimonious than the original version, since it involves the estimation of an additional parameter, *I*. This parameter improves predictions only when the substances exhibit a substantial degree of interaction. Possibly, *I* needs to be estimated only for substances that do not obey the EMM's original assumption of mutual sensory dependency. The addition of a response output function not necessarily increases the number of parameters to be estimated. The exact form of this function probably depends on task instructions and experimental stimulus context (e.g. Parducci, 1974; Poulton, 1979). However, when stimulus sets (spacing, frequency, range), standard solutions, modulus values and scaling methods are comparable to those used in Figure 4, Equation 13 can probably be used for the transformation of any set of predictions. By using different response output functions for different scaling methods, the application of the EMM is no longer confined to experiments using magnitude estimation, but can also be used for experiments employing category rating scales or line scales.

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REFERENCES

Alf, E.F. and Grossberg, J.M. (1979) The geometric mean: confidence limits and significance tests. *Percept. Psychophys.*, **26,** 419–421.

Ayya, N. and Lawless, H.T. (1992) Quantitative and qualitative evaluation of high-intensity sweeteners and sweetener mixtures. *Chem. Senses*, **17,** 245–259.

Baird, J.C. (1991) Personal communication. Department of Psychology, Dartmouth College, Hanover NH. Reported by Berglund and Olsson (1993).

Bartoshuk, L.M and Cleveland, C.T. (1977) Mixtures of substances with similar tastes: a test of a psychophysical model of taste mixture interactions. *Sens. Processes.*, **1,** 177–186.

Beidler, L.M. (1971) Taste receptor stimulation with salts and acids. In Beidler, L.M. (ed.) *Handbook of Sensory Physiology, Vol. IV. Chemical Senses, Part 2, Taste.* Springer Verlag, New York, pp. 200–220.

Berglund, B. and Olsson, M.J. (1993) A theoretical and empirical evaluation of perceptual and psychophysical models for odor-intensity interaction. *Reports from the Department of Psychology, Stockholm University, no. 764.*

Bonnans, S. and Noble, A.C. (1993) Effect of sweetener type and of sweetener and acid level on temporal perception of sweetness, sourness, and fruitiness. *Chem. Senses*, **18,** 273–283.

De Graaf, C. and Frijters, J.E.R. (1986) A psychophysical investigation of Beidler's mixture equation. *Chem. Senses*, **11,** 295–314.

De Graaf, C. and Frijters, J.E.R. (1987) Sweetness intensity of a binary sugar mixture lies between intensities of its components, when each is tasted alone and at the same total molarity as the mixture. *Chem. Senses.*, **12,** 113–129.

De Graaf, C. and Frijters, J.E.R. (1988) Assessment of the taste interaction between two qualitatively similar-tasting substances a comparison between comparison rules. *J. Exp. Psychol.: Hum. Percept. Perform.*, **14,** 526–538.

Eisler,H. and Roskam, E.E. (1977) Multidimensional similarity. an experimental and theoretical comparison of vector, distance, and set theoretical models. I. Models and internal consistency of data. *Acta Psychol.*, **41,** 1–46.

Frank, R.A., Mize, S.J S and Carter, R. (1989) An assessment of binary mixture interactions for nine sweeteners. *Chem. Senses*, **14,** 621–632.

Frijters, J.E.R. and De Graaf, C. (1987) The equiratio taste mixture model successfully predicts the sensory response to the sweetness intensity of complex mixtures of sugars and sugar alcohols. *Perception*, **16,** 615–628.

Frijters, J.E.R., De Graaf, C. and Koolen, H.C.M. (1984) The validity of the equiratio taste mixture model investigated with sorbitol-sucrose mixtures. *Chem. Senses*, **9,** 241–248.

Frijters, J.E.R. and Oude Ophuis, P.A.M. (1983) The construction and prediction of psychophysical power functions for the sweetness of equiratio sugar mixtures. *Perception*, **12,** 753–767.

Frijters, J.E.R. and Stevens, D.A. (1986) *Psychophysical taste functions of equiratio acid mixtures.* Internal report Clark University, Worcester, MA.

Lawless, H.T. and Stevens, D.A. (1983) Cross adaptation of sucrose and intensive sweeteners, *Chem. Senses*, **7,** 309–315.

Matysiak, N.L. and Noble, A.C. (1991) Comparison of temporal perception of fruitiness in model systems sweetened with aspartame, an aspartame + acesulfame K blend, or sucrose. *J. Fd Sci.*, **56,** 823–826.

McBurney, D.H., Smith, D.V., and Shick, T.R. (1972) Gustatory cross adaptation: sourness and bitterness. *Percept. Psychophys.*, **10,** 228–232.

Meiselman, H.L. (1968) Adaptation and cross-adaptation of the four gustatory qualities. *Percept. Psychophys.*, **4,** 368–372.

Owen, W.J. and DeRouen, T.A. (1980) Estimation of the mean for lognormal data containing zeroes and left-censored values with applications to the measurement of worker exposure to air and contaminants *Biometrics*, **36,** 707–719.

Parducci, A. (1974) Contextual effects: A range-frequency analysis. In Carterette, E.C. and Friedman, M.P. (eds) *Handbook of Perception. Vol. II. Psychophysical Judgment and Measurement*. Academic Press, New York, pp. 127–141.

Poulton, E.C. (1979) Models for biases in judging sensory magnitude. *Psychol. Bull.*, **86,** 777–803.

Schifferstein, H N.J. (1995) Prediction of sweetness intensity for equiratio aspartame/sucrose mixtures. *Chem. Senses*, **20,** 211–219.

Schiffman, S.S., Cain, H. and Lindley, M.G. (1981) Multiple receptor sites mediate sweetness: Evidence from cross adaptation. *Pharmacol. Biochem. & Behav.*, **15,** 377–388.

Stevens, S.S. (1975) *Psychophysics*. Wiley, New York.

von Rymon Lipinski, G.W. (1991) Sensory properties of acesulfame-K. In: Mayer, D.G. and Kemper, F.H. (eds) *Acesulfame-K*. Marcel Dekker, New York, pp. 197–207.

Williams, R.B.G. (1986) *Intermediate Statistics for Geographers and Earth Scientists*. Macmillan, Hampshire, UK.

Yamaguchi, S., Yoshikawa, T., Ikeda, S. and Ninomiya, T. (1970) Studies on the taste of some sweet substances. Part II. Interrelationships among them. *Agricult. Biol. Chem.*, **34,** 187–197.

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