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# The equiratio taste mixture model successfully predicts the sensory response to the sweetness intensity of complex mixtures of sugars and sugar alcohols

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**Abstract.** The equiratio taste mixture model was originally developed for the prediction of psychophysical power functions of equiratio mixtures of substances that have a similar taste and that also exhibit mutual cross adaptation. Earlier studies have shown that the model is valid for mixtures of sugars and/or sugar alcohols. Two experiments are reported in which it is questioned whether the psychophysical functions of mixtures of higher physical complexity can be predicted by the model. In the first experiment the psychophysical power functions of binary and quaternary equiratio mixture types were determined experimentally and compared to those predicted by the generalized model. In the second, similar, experiment quaternary and eight-component mixture types were examined. The method of magnitude estimation, in combination with the sip and spit procedure, was used. The functions predicted by the model were almost identical to the functions established on the basis of the experimental data. These results reconfirm that the gustatory modality operates like an 'averaging' system when processing this kind of mixture. It is argued that for other kind of mixtures the model will predict incorrectly. The status of the equiratio mixture model is discussed.

## 1 Introduction

The equiratio taste mixture model (ETMM) is a psychophysical model developed for the prediction of the sensory response to the taste intensity of a binary mixture of sensory dependent substances that have similar taste qualities (Frijters and Oude Ophuis 1983). It has been previously tested in two experiments with mixtures of sweet-tasting substances (Frijters and Oude Ophuis 1983; Frijters et al 1984). In both experiments the model had good predictive validity. This motivated us to consider whether or not the ETMM can be generalized and used to predict the taste intensity response to mixtures composed of more than two components. In this paper we report two experiments in which mixtures of sweet-tasting substances were used. Binary and quaternary mixtures are investigated in the first experiment, and quaternary and eight-component mixtures are studied in the second experiment.

## 2 Theory

The object of the ETMM is estimation of the sensory response to the taste intensity of a mixture, on the basis of the predicted psychophysical equiratio mixture function. Two assumptions underly the model: (i) the compounds to be used for mixture composition have similar taste qualities, and (ii) these substances are not independently processed by the gustatory system. The latter is confirmed by the existence of mutual cross adaptation. According to Kroeze (1979), absence of cross adaptation is an adequate operational definition of peripheral independency, and this criterion has been adopted in a number of experiments (Meiselman 1968; McBurney 1969; McBurney and Barthoshuk 1973; Gent and McBurney, 1978).

Since a psychophysical equiratio mixture function can be established on the basis of experimentally obtained data, the predictive power of the model may be tested by

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comparing the psychophysical mixture function which is predicted by the model with the one which is directly obtained from a set of experimental data. In the present study a number of such comparisons are carried out. Before describing the generalized form of the ETMM for mixtures of more than two components, we shall briefly review the original model for binary mixtures.

Let the psychophysical power functions of the two substances, A and B, be given by:

$$R_{\mathrm{a}i} = k_{\mathrm{a}} C_{\mathrm{a}i}^{v}, \tag{1}$$

and

$$R_{\mathrm{b}j} = k_{\mathrm{b}} C_{\mathrm{b}j}^{w}, \tag{2}$$

respectively, where $R$ is the sensory response and $C$ is the molar concentration. The constants $k_{\mathrm{a}}$ and $k_{\mathrm{b}}$ and the exponents $v$ and $w$ are estimated when fitting the functions. The subscripts a and b refer to the two substances A and B, and $i$ and $j$ to their respective concentrations.

In addition to the general formula for a psychophysical power function of a single substance, a similar expression has also been derived for what has been termed an *equiratio mixture 'type'* (Frijters and Oude Ophuis 1983). This is a series of mixtures of two substances, A and B, where the ratio of the molar concentrations of the two substances is equal throughout the series, but where each member of the series has a different total concentration (total concentration is concentration of A plus concentration of B). The general formula of a psychophysical power function of a binary equiratio mixture type is given by:

$$R_{\mathrm{ab}\,ijpq} = k_{\mathrm{ab}\,pq} C_{\mathrm{ab}\,ijpq}^{z}, \tag{3}$$

where the sensory response to a mixture of concentration $i$ of substance A plus concentration $j$ of substance B is denoted by $R_{\mathrm{ab}\,ijpq}$. The subscripts $p$ and $q$ refer to the proportion of the concentrations of A and B, respectively ($p + q = 1$). These proportions are specific for each equiratio mixture type; changing their values creates another mixture type. The constant $k_{\mathrm{ab}}$ and the exponent $z$ in equation (3) have the same status as the comparable parameters in the power function of a single compound.

According to Frijters and Oude Ophuis (1983), the exponent $z$ can be estimated from the exponents of the functions of the single substances used for mixture composition. When these are denoted as $v$ and $w$, respectively, it follows that

$$z = pv + qw. \tag{4}$$

The constant $k_{\mathrm{ab}\,pq}$ can be obtained through:

$$k_{\mathrm{ab}pq} = \frac{(pk_{\mathrm{a}}/C_{\mathrm{a}'}) + (qk_{\mathrm{b}}/C_{\mathrm{b}'})}{(p/C_{\mathrm{a}'}) + (q/C_{\mathrm{b}'})}, \tag{5}$$

where $C_{\mathrm{a}'}$ and $C_{\mathrm{b}'}$ are the concentrations of A and B, respectively, that elicit a sensory response identical to the response to a specified 'standard' stimulus in a magnitude estimation experiment (cf Frijters and Oude Ophuis 1983).

These are the essentials of the ETMM for binary mixtures of sensory dependent substances with similar taste quality. Based on the same principles, this model can be generalized for the prediction of sensory responses to mixtures of higher physical complexity. As an example, we derive the ETMM for the general case of a quaternary equiratio mixture type.

Let the psychophysical functions of the substances A, B, C, and D be given by, respectively

$$R_{\mathrm{a}i} = k_{\mathrm{a}} C_{\mathrm{a}i}^{v}, \qquad R_{\mathrm{b}j} = k_{\mathrm{b}} C_{\mathrm{b}j}^{w}, \qquad R_{\mathrm{c}k} = k_{\mathrm{c}} C_{\mathrm{c}k}^{x}, \qquad R_{\mathrm{d}l} = k_{\mathrm{d}} C_{\mathrm{d}l}^{y}.$$

If the various parameters of these functions are used to extend equations (3)–(5), one obtains equations (6)–(8). The general formula for a quaternary equiratio mixture type is given by:

$$R_{\mathrm{abcd}\,ijklpqrs} = k_{\mathrm{abcd}\,pqrs} C^{z}_{\mathrm{abcd}\,ijklpqrs} \,, \tag{6}$$

where $R_{\mathrm{abcd}\,ijklpqrs}$ represents the sensory response to a mixture of concentration $i$ of A plus $j$ of B plus $k$ of C and $l$ of D. The total concentration is expressed as $C_{\mathrm{abcd}\,ijklpqrs}$. The subscripts $p$, $q$, $r$, and $s$ refer to the proportions of the concentrations of the individual compounds (ie, $p + q + r + s = 1$).

According to the generalized ETMM, the exponent $z$ in equation (6) can be estimated by:

$$\hat{z} = pv + qw + rx + sy \,, \tag{7}$$

and the constant $k_{\mathrm{abcd}\,pqrs}$ by:

$$\hat{k}_{\mathrm{abcd}\,pqrs} = \frac{(pk_{\mathrm{a}}/C_{\mathrm{a}'}) + (qk_{\mathrm{b}}/C_{\mathrm{b}'}) + (rk_{\mathrm{c}}/C_{\mathrm{c}'}) + (sk_{\mathrm{d}}/C_{\mathrm{d}'})}{(p/C_{\mathrm{a}'}) + (q/C_{\mathrm{b}'}) + (r/C_{\mathrm{c}'}) + (s/C_{\mathrm{d}'})} \,. \tag{8}$$

If the psychophysical functions of the substances A, B, C, and D have been established on the basis of the experimental data, then the response to any particular mixture of these substances can be predicted by the following power function:

$$\hat{R}_{\mathrm{abcd}\,ijklpqrs} = \left[\frac{(pk_{\mathrm{a}}/C_{\mathrm{a}'}) + (qk_{\mathrm{b}}/C_{\mathrm{b}'}) + (rk_{\mathrm{c}}/C_{\mathrm{c}'}) + (sk_{\mathrm{d}}/C_{\mathrm{d}'})}{(p/C_{\mathrm{a}'}) + (q/C_{\mathrm{b}'}) + (r/C_{\mathrm{c}'}) + (s/C_{\mathrm{d}'})}\right] C^{pv+qw+rx+sy}_{\mathrm{abcd}\,ijklpqrs} \,. \tag{9}$$

Based on the same principles, the original equations (3)–(5) for the binary case can be extended to any order of complexity.

## 3 Experiment 1

This experiment was designed to investigate the generalizability of the ETMM in predicting the responses to quaternary equiratio mixtures. Three equiratio mixture types were prepared; two binary and one quaternary. The substances used were fructose, sucrose, sorbitol, and glucose. The binary equiratio mixture types were fructose–sucrose (0.50/0.50) and sorbitol–glucose (0.50/0.50). (The notation 0.50/0.50 means that each mixture in the series contains an equal molarity of both substances.) The quaternary equiratio mixture type comprised fructose–sucrose–sorbitol–glucose in the ratios of 0.25/0.25/0.25/0.25 (ie, the concentration of each of the four substances was equal to one quarter of the total concentration of each mixture in the series). For each of the seven series of solutions (ie, four single substances, two binary mixture types, and one quaternary mixture type) a psychophysical power function was determined experimentally. The functions of the binary mixture types and the quaternary mixture type were compared to the corresponding functions predicted by the generalized ETMM.

### 3.1 *Methods*

3.1.1 *Subjects.* The twenty subjects (fourteen females and six males) were paid volunteers and ranged in age from 19 to 24 years. All were undergraduates of the Agricultural University and had no prior experience of psychophysical experiments.

3.1.2 *Stimuli.* Solutions of fructose (F) (Merck 5321), sucrose (S) (Merck 7653), sorbitol (B) (BDH Chemicals 30242), and glucose (G) (Merck 15639) were prepared in demineralized water. Mixtures of fructose–sucrose (0.50/0.50), sorbitol–glucose (0.50/0.50), and fructose–sucrose–sorbitol–glucose (0.25/0.25/0.25/0.25) were prepared in a similar manner. Each of the seven series of stimuli comprised five solutions of concentration 0.125, 0.250, 0.500, 1.000, and 2.000 M. All solutions were prepared at least 24 h before presentation to the subjects and were stored at 4 °C for no longer than 3 days before use. A stimulus consisted of 10 - 15 ml of solution, presented in a hard plastic medicine cup at room temperature (22 °C).

3.1.3 *Procedure.* A random series of all thirty-five stimuli was presented to each of the twenty subjects in each of two sessions held on consecutive days. The method of magnitude estimation (Stevens 1956) was used, with a fixed standard stimulus and a fixed modulus: the 0.500 M solution of the quaternary mixture was used as the standard stimulus, with a value of 10 assigned by the experimenter. Before a series was presented the subjects were asked to rinse their mouths with demineralized water and to taste the standard stimulus. They were requested to taste the standard stimulus again after every five stimuli. The interval between two consecutive stimuli was exactly 1 min. All subjects rinsed their mouths with demineralized water between stimuli. In the instructions it was explicitly stated that the subject should estimate the taste intensity as a ratio of the intensity of the standard stimulus, and should ignore the hedonic value. The subjects were not aware of the purpose of the experiment and were not given any information about the sweeteners or concentrations used.

### 3.2 *Results*

A total of forty responses (twenty subjects × two sessions) was obtained for each of the thirty-five stimuli. For each of these distributions the arithmetic mean of the natural logarithm was calculated. The geometric mean ($R$) of the distribution was obtained by taking the antilog of the corresponding mean of the distribution of log-transformed values. In those cases where a distribution contained one or more 'zero' responses the geometric mean was calculated by the formula (cf Frijters and Oude Ophuis 1983)

$$R = (1 - \sigma)\exp\mu, \tag{10}$$

where $\sigma$ denotes the proportion of zero responses and $\mu$ is the mean of the (left-censored) distribution of log-transformed (nonzero) responses. The 95% intervals for each value of $R$ were determined according to Alf and Grossberg (1979). The values of $R$ are shown in figure 1. For the three mixture types these values, plus their confidence intervals, are also given in table 1 (columns 3 and 4, respectively).

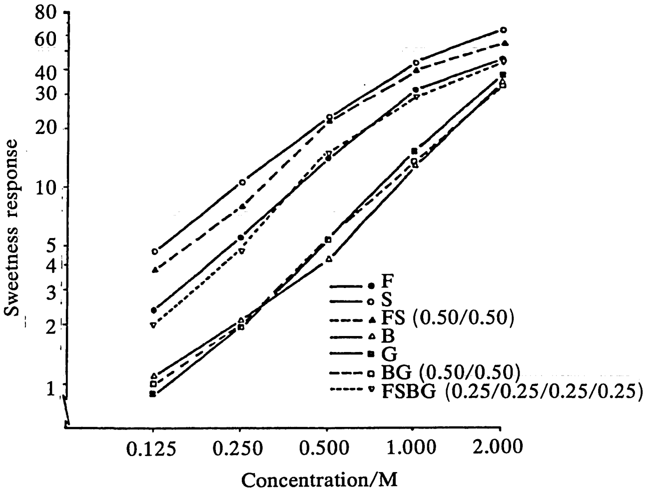

**Figure 1.** Experimentally obtained sweetness responses to solutions of four single substances (fructose, F; sucrose S; sorbitol B; glucose G) and mixtures of two binary equiratio mixture types and one quaternary equiratio mixture type.

These values were subsequently used for the determination of seven psychophysical power functions using linear regression on the log-transformed variables, where $\ln C$ and $\ln R$ were the independent and dependent variables, respectively. The functions thus obtained are given in table 2, together with the coefficients of determination ($r^2$) based on the log-log regression. By substitution of the concentrations into these

**Table 1.** Experimentally obtained and predicted sensory response values for the five mixtures of each of the two binary equiratio mixture types and the quaternary equiratio mixture type.

| Mixture | Concentration/M | $R$ | Confidence interval (95%) | $R$ predicted by | | |
|---|---|---|---|---|---|---|
| | | | | experiment[a] | model (1)[b] | model (2)[c] |
| FS (0.50/0.50) | 0.125 | 3.8 | 3.0-5.0 | 4.3 | 4.0 | |
| | 0.250 | 8.0 | 6.4-10.0 | 8.6 | 8.2 | |
| | 0.500 | 22.0 | 18.5-26.1 | 17.3 | 16.8 | |
| | 1.000 | 40.3 | 33.4-48.4 | 34.8 | 34.2 | |
| | 2.000 | 56.5 | 44.0-72.6 | 70.1 | 69.3 | |
| BG (0.50/0.50) | 0.125 | 1.0 | 0.7-1.5 | 0.9 | 0.9 | |
| | 0.250 | 2.0 | 1.6-2.6 | 2.2 | 2.2 | |
| | 0.500 | 5.4 | 4.4-6.6 | 5.5 | 5.6 | |
| | 1.000 | 13.7 | 11.1-16.8 | 13.6 | 14.0 | |
| | 2.000 | 34.7 | 29.2-41.2 | 33.8 | 34.8 | |
| FSBG (0.25/0.25/0.25/0.25) | 0.125 | 2.0 | 1.5-2.6 | 2.2 | 2.5 | 2.6 |
| | 0.250 | 4.8 | 4.0-6.0 | 5.0 | 5.5 | 5.7 |
| | 0.500 | 15.1 | 12.7-17.9 | 11.4 | 12.5 | 12.8 |
| | 1.000 | 29.6 | 23.7-37.0 | 25.7 | 28.1 | 28.7 |
| | 2.000 | 46.0 | 35.3-60.5 | 58.2 | 63.4 | 64.2 |

F, fructose; S, sucrose; B, sorbitol; G, glucose.

[a] These values were obtained from the psychophysical functions derived from the experimental data.

[b] These values were obtained from the psychophysical functions predicted on the basis of the experimentally determined functions for the single compounds.

[c] These values were obtained from the quaternary function predicted on the basis of the two experimentally determined binary functions.

**Table 2.** Experimentally determined and predicted psychophysical functions for four single substances and mixtures of two binary equiratio mixture types and one quaternary equiratio mixture type. $r^2$ is the coefficient of determination.

| Substance | $R$ experimentally determined[a] | $r^2$ | $R$ predicted |
|---|---|---|---|
| Fructose (F) | $26.39\ C^{1.10}$ | 0.982 | |
| Sucrose (S) | $38.98\ C^{0.95}$ | 0.980 | |
| Sorbitol (B) | $13.16\ C^{1.26}$ | 0.997 | |
| Glucose (G) | $14.67\ C^{1.38}$ | 0.988 | |
| FS (0.50/0.50) | $34.78\ C^{1.01}$ | 0.971 | $34.18\ C^{1.03}$ |
| BG (0.50/0.50) | $13.59\ C^{1.32}$ | 0.998 | $13.95\ C^{1.32}$ |
| FSBG (0.25/0.25/0.25/0.25) | $25.74\ C^{1.17}$ | 0.974 | $28.10\ C^{1.17}$ (1)[b]<br>$28.68\ C^{1.16}$ (2)[c] |

[a] The mean of the 95% confidence intervals for the seven exponents is ±0.22.

[b] Obtained from the psychophysical functions predicted on the basis of the experimentally determined functions for the single compounds.

[c] Obtained from the quaternary function predicted on the basis of the two experimentally determined binary functions.

functions, the sweetness responses to the mixtures, as estimated from these experimentally determined functions, were obtained. These are given in column 5 of table 1.

To be able to apply the ETMM for the prediction of the psychophysical functions of the equiratio mixture types, the concentration of each substance that could have been expected to give rise to a response of the same magnitude as the response to the standard stimulus must be known. In this experiment, the 0.500 M solution of the FSBG (0.25/0.25/0.25/0.25) mixture type was used as the standard stimulus. In the instructions it had an assigned value of 10. However, unknown to the subjects, the same solution was also included in the series of stimuli. The concentrations of the various mixture types c.q. single substances hypothetically eliciting the same response value (15.07) were obtained by setting each of the six experimentally determined psychophysical functions equal to this value of 15.07. The concentrations thus obtained are: fructose, 0.6005 M; sucrose 0.3698 M; sorbitol 1.1139 M; glucose 1.0198 M; fructose-sucrose (0.50/0.50), 0.4374 M; sorbitol-glucose (0.50/0.50), 1.0823 M.

From these values, plus the psychophysical functions for the single substances calculated on the basis of the experimental data (table 2), three psychophysical mixture functions were predicted (table 2). The first two are the functions of the binary equiratio mixture types. These were obtained using equations (4) and (5). Table 1, column 6 contains the estimated sensory sweetness responses to the individual mixtures, as calculated from the predicted mixture functions (table 2). The psychophysical function for the quaternary equiratio mixture type was predicted in two different ways, denoted as model (1) and model (2). In model (1) the function was obtained by taking the four psychophysical functions of the individual compounds which constitute the mixture type, and using equations (7) and (8). This means that the generalized form of the ETMM was applied. Table 1, column 6 contains the estimated sensory sweetness responses to the individual mixtures of this type. These values were calculated by substituting the concentrations into the predicted mixture function (table 2). In model (2) the function was obtained by taking the pair of experimentally determined psychophysical functions for the two binary mixture types (as if these were single substances instead of mixtures) and then using equations (4) and (5). Table 1, column 7 contains the estimated sweetness responses to the individual mixtures as calculated from these predicted functions.

It can be seen that the sensory taste intensity responses estimated from the predicted functions (table 1) are similar in magnitude to those estimated from the psychophysical functions determined on the basis of the experimental data (compare columns 6 and 7 to column 5). It can also be seen in the same table that at the concentration of 2.000 M there are differences between the values actually obtained in the experiment and those calculated from the psychophysical functions established on the basis of these experimental values (compare columns 3 and 5). The experimental values are lower than the predicted values. This suggests that the power functions do not perfectly describe the psychophysical relationship between concentration and response at high sweetener concentration levels, despite the high goodness of fit that can be inferred from the magnitudes of the coefficients of determination (table 2, column 3).

### 3.3 *Conclusions*

The results of this experiment reconfirm the validity of the equiratio taste mixture model for the prediction of psychophysical equiratio mixture functions for binary mixture types. In previous studies good predictions were observed for glucose-fructose (Frijters and Oude Ophuis 1983) and sorbitol-sucrose (Frijters et al 1984) mixture types. The psychophysical functions we have obtained here of the binary mixture types of fructose-sucrose and of sorbitol-glucose are virtually identical to those predicted by the model: the exponents are, respectively, 1% and 0% different from the predicted values, and the constants are 1.7% and 2.6% different, respectively.

The results also show that the model can be generalized to predict the psychophysical function (and therefore also the sensory taste responses) of the quaternary equiratio mixture type. The predicted functions in table 2 are almost identical to the function determined experimentally, and only the constants, which are predicted as 28.10 and 28.68, are slightly higher than the expected value of 25.74 (9.2% and 11.4% different, respectively). A comparison of the two predicted psychophysical functions for the quaternary mixture type (table 2) shows that both procedures result in virtually the same prediction.

The main conclusion to be drawn from this experiment is that the ETMM can be generalized from the level of binary to quaternary equiratio mixtures.

## 4 Experiment 2

This experiment was designed to investigate whether or not the ETMM can be applied to predict the sensory taste intensity response to mixtures of a higher than quaternary order of physical complexity. It was almost arbitrarily decided to study an eight-component mixture type and the substances used to prepare the eight-component mixture type were chosen more or less at random.

Two quaternary equiratio mixture types and one eight-component equiratio mixture type were constructed using fructose, sucrose, xylitol, maltose, sorbitol, glucose, xylose, and galactose. The quaternary mixture types were fructose - sucrose - xylitol - maltose (0.25/0.25/0.25/0.25) and sorbitol - glucose - xylose - galactose (0.25/0.25/0.25/0.25). The eight-component mixture type consisted of a series of equiratio mixtures of all eight compounds. The psychophysical functions for each of the eight single substances and the equiratio mixture types were determined experimentally.

### 4.1 *Method*

4.1.1 *Subjects.* The twenty subjects (seventeen females and three males) were paid volunteers and ranged in age from 18 to 26 years. All were undergraduates of the Agricultural University and had no prior experience of psychophysical experiments.

4.1.2 *Stimuli.* Solutions of fructose (F) (Merck 5321), sucrose (S) (Merck 7653), xylitol (X) (BDH Chemicals 38101), maltose (M) (Sigma M 5885), sorbitol (B) (BDH Chemicals 30242), glucose (G) (Merck 15639), xylose (Y) (Sigma X 1500), and galactose (L) (Sigma G 0625) were prepared in demineralized water. Mixtures of fructose - sucrose - xylitol - maltose (0.25/0.25/0.25/0.25), sorbitol - glucose - xylose - galactose (0.25/0.25/0.25/0.25), and fructose - sucrose - xylitol - maltose - sorbitol - glucose - xylose - galactose (0.125/0.125/0.125/0.125/0.125/0.125/0.125/0.125) were prepared in a similar manner. Each of the eleven series of mixtures consisted of five solutions of 0.125, 0.250, 0.500, 1.000, and 2.000 M. Preparation, storage, and presentation of the solutions were the same as in the first experiment.

4.1.3 *Procedure.* The experimental procedure was identical to that in the first experiment, except for the following details. Each subject participated in two sessions within a period of a week. In each session a random series of fifty-five stimuli was presented to each of the subjects. The 0.500 M solution of the eight-component mixture was used as the standard stimulus, with an assigned value of 10.

### 4.2 *Results*

The analysis of the raw data and the calculation of the psychophysical functions of the single substances, the quaternary mixtures, and the eight-component mixture were as in the previous experiment. Figures 2a, 2b, and 3 show the experimentally obtained responses. For the mixtures, the numerical values of $R$ are also given in column 3 of table 3, together with their 95% confidence intervals (column 4).

From the values given in the figures 2 and 3, eleven psychophysical power functions were calculated. These functions plus the corresponding coefficients of determination are given in table 4. By substitution of the concentrations into these functions, the sweetness responses to the mixtures were estimated. These values are given in column 5 of table 3.

As in the first experiment, the concentration of each substance c.q. mixture type that could have been expected to give rise to a response of the same magnitude as the response to the standard stimulus must be known in order to be able to use the model. The standard used in this experiment was identical to the 0.500 M solution of the eight-component mixture type. The same stimulus included in the experiment had an

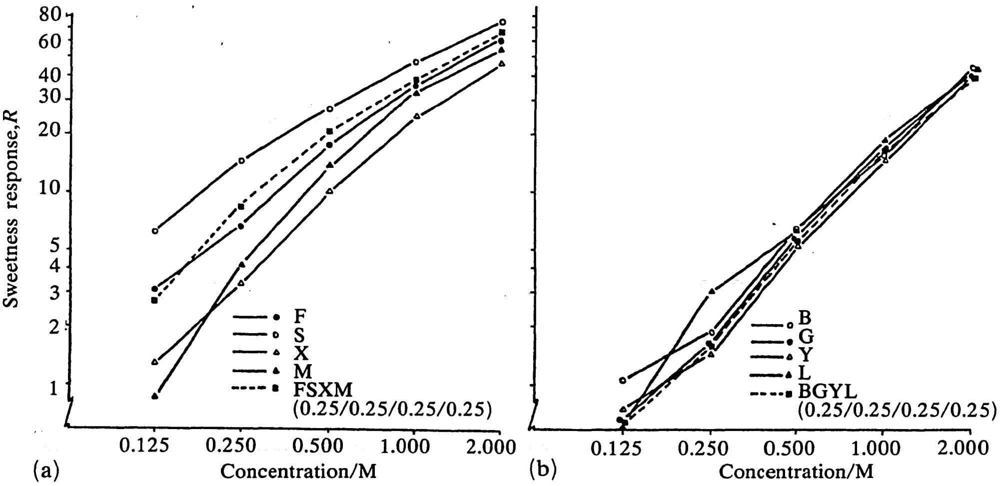

**Figure 2.** Experimentally obtained sweetness responses to solutions of eight single substances [fructose, F; sucrose, S; xylitol, X; maltose, M in (a); sorbitol, B; glucose, G; xylose, Y; galactose, L in (b)] and the two corresponding quaternary equiratio mixture types.

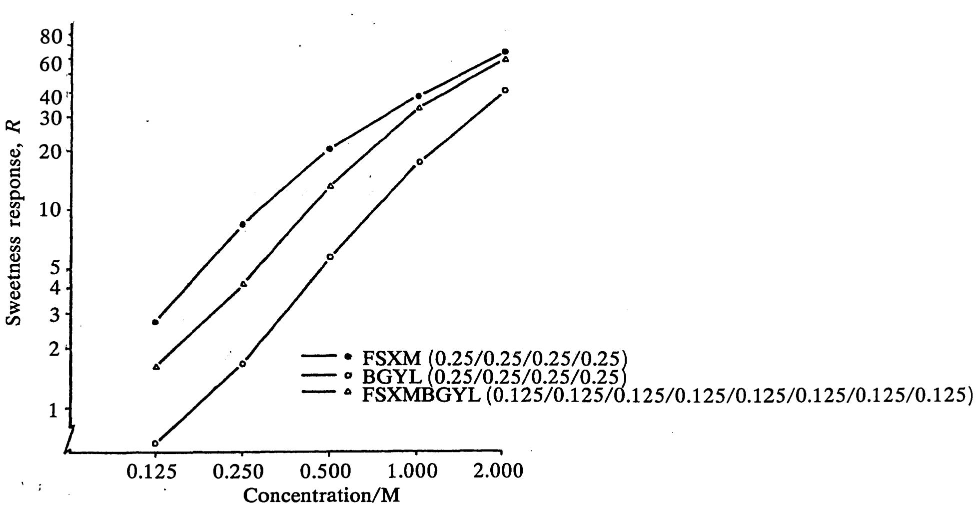

**Figure 3.** Experimentally obtained sweetness responses to mixtures of two quaternary equiratio mixture types (fructose-sucrose-xylitol-maltose, FSXM, and sorbitol-glucose-xylose-galactose, BGYL), and the corresponding eight-component equiratio mixture type.

**Table 3.** Experimentally obtained and predicted sensory response values for the five mixtures of each of the two quaternary equiratio mixture types and the eight-component equiratio mixture type.

| Mixture | Concentration/M | $R$ | Confidence interval (95%) | $R$ predicted by | | |
|---|---|---|---|---|---|---|
| | | | | experiment[a] | model (1)[b] | model (2)[c] |
| FSXM (0.25/0.25/0.25/0.25) | 0.125 | 2.7 | 2.1 - 3.6 | 3.4 | 2.9 | |
| | 0.250 | 8.5 | 7.1 - 10.2 | 7.5 | 6.7 | |
| | 0.500 | 20.6 | 17.0 - 25.0 | 16.4 | 15.5 | |
| | 1.000 | 37.9 | 30.5 - 47.2 | 36.2 | 35.7 | |
| | 2.000 | 66.6 | 54.9 - 80.9 | 79.6 | 82.5 | |
| BGYL (0.25/0.25/0.25/0.25) | 0.125 | 0.7 | 0.4 - 1.1 | 0.7 | 0.7 | |
| | 0.250 | 1.7 | 1.2 - 2.4 | 1.9 | 2.1 | |
| | 0.500 | 5.9 | 4.7 - 7.3 | 5.5 | 5.9 | |
| | 1.000 | 17.8 | 14.7 - 21.5 | 15.8 | 16.5 | |
| | 2.000 | 41.6 | 33.8 - 51.2 | 45.7 | 46.6 | |
| FSXMBGYL (0.125/0.125/0.125/0.125/0.125/0.125/0.125/0.125) | 0.125 | 1.6 | 1.3 - 2.2 | 1.8 | 1.8 | 1.8 |
| | 0.250 | 4.3 | 3.5 - 5.2 | 4.5 | 4.5 | 4.6 |
| | 0.500 | 13.4 | 11.2 - 16.0 | 11.5 | 11.4 | 11.7 |
| | 1.000 | 34.7 | 28.8 - 41.9 | 29.2 | 29.2 | 29.5 |
| | 2.000 | 61.0 | 52.2 - 72.6 | 74.1 | 74.6 | 73.6 |

F, fructose; S, sucrose; X, xylitol: M, maltose; B, sorbitol; G, glucose; Y, xylose; L, galactose.

[a] These values were obtained from the psychophysical functions established on the basis of the experimental data.

[b] These values were obtained from the eight-component mixture function predicted on the basis of the experimentally determined functions of the single compounds.

[c] These values were obtained from the eight-component mixture function predicted on the basis of the two experimentally determined quaternary functions.

**Table 4.** Experimentally determined and predicted psychophysical functions for eight single substances and mixtures of two quaternary equiratio mixture types and one eight-component equiratio mixture type. $r^2$ is the coefficient of determination.

| Substance | $R$ experimentally determined[a] | $r^2$ | $R$ predicted |
|---|---|---|---|
| Fructose (F) | $32.70\ C^{1.10}$ | 0.990 | |
| Sucrose (S) | $46.15\ C^{0.90}$ | 0.985 | |
| Xylitol (X) | $22.03\ C^{1.32}$ | 0.992 | |
| Maltose (M) | $28.55\ C^{1.51}$ | 0.962 | |
| Sorbitol (B) | $16.60\ C^{1.39}$ | 0.991 | |
| Glucose (G) | $16.28\ C^{1.54}$ | 0.996 | |
| Xylose (Y) | $15.39\ C^{1.53}$ | 0.993 | |
| Galactose (L) | $17.77\ C^{1.51}$ | 0.981 | |
| FSXM (0.25/0.25/0.25/0.25) | $36.22\ C^{1.14}$ | 0.976 | $35.70\ C^{1.21}$ |
| BGYL (0.25/0.25/0.25/0.25) | $15.80\ C^{1.53}$ | 0.996 | $16.54\ C^{1.49}$ |
| FSXMBGYL (0.125/0.125/0.125/0.125/0.125/0.125/0.125/0.125) | $29.16\ C^{1.35}$ | 0.988 | $29.23\ C^{1.35}$ (1)[b]<br>$29.48\ C^{1.35}$ (2)[c] |

[a] The mean of the 95% confidence intervals for the eleven exponents is ±0.24.

[b] Obtained from the eight-component mixture function predicted on the basis of the experimentally determined functions of the single compounds.

[c] Obtained from the eight-component mixture function predicted on the basis of the two experimentally determined quaternary functions.

associated response value of 13.40. The concentrations of the substances and equiratio mixture types with an estimated response of 13.40 (obtained by setting the experimentally determined functions equal to 13.40) are: fructose, 0.4451 M; sucrose, 0.2720 M; xylitol, 0.6868 M; maltose, 0.6054 M; sorbitol, 0.8572 M; glucose, 0.8813 M; xylose, 0.9134 M; galactose, 0.8298 M; fructose - sucrose - xylitol - maltose (0.25/0.25/0.25/0.25), 0.4422 M; sorbitol - glucose - xylose - galactose (0.25/0.25/0.25/0.25), 0.8980 M.

On the basis of these values, plus the experimentally determined psychophysical functions (table 4), three psychophysical functions were predicted (table 4). The first two are the functions of the quaternary mixture types. These were obtained using equations (7) and (8). Table 3, column 6 contains the estimated sensory sweetness responses to the individual mixtures, as calculated from the predicted quaternary mixture functions (table 4). The eight-component equiratio mixture function was predicted in two different ways. First [model (1)], on the basis of the eight psychophysical functions of the single substances, using extended versions of equations (7) and (8), and second [model (2)], on the basis of the two experimentally determined functions of the quaternary mixture types, using equations (4) and (5). In the latter case the normal ETMM is applied and each of the quaternary mixture types is created as if it was a single substance. Columns 6 and 7 in table 3 contain the values of the sensory responses to the individual mixtures, as calculated from the predicted eight-component mixture functions. These are very similar to the values estimated on the basis of the experimentally determined psychophysical functions. As in the first experiment, the values of the responses to the 2.000 M solutions estimated from the experimentally obtained mixture functions are higher than the values actually obtained in the experiment (compare column 5 to column 3 in table 3).

### 4.3 *Conclusions*

Table 4 shows that the quaternary mixture functions predicted by the equiratio taste mixture model are almost identical to those established on the basis of the experimental data. The predicted exponent of the fructose - sucrose - xylitol - maltose (0.25/0.25/0.25/0.25) mixture type is 6% higher than the predicted value, but does not differ statistically ($t_4 = 0.67$). The constant of the predicted function is about 1% less than the experimentally obtained value. For the other quaternary mixture type, sorbitol - glucose - xylose - galactose (0.25/0.25/0.25/0.25), the predicted and estimated exponents and constants are 3% lower and 5% higher, respectively. In line with the findings of the first experiment, it can be concluded that the generalized ETMM can be used to predict precisely responses to quaternary mixtures.

The results in table 4 also show that the psychophysical function of the eight-component mixture type is predicted with great precision. Apparently, it makes no difference whether this function is predicted on the basis of the eight psychophysical functions of the single substances (generalized ETMM), or whether this is done on the basis of the two experimentally determined functions of the quaternary mixture types. In both cases the predicted exponent is identical to that of the experimentally determined function. The predicted constants are 0.2% and 1% higher, respectively, than the experimentally obtained constants. This result shows clearly that the model can safely be generalized to mixtures of high complexity.

## 5 General discussion

Our results show that the equiratio taste mixture model is valid not only for binary mixtures, but also for higher-order mixtures of sugars and/or sugar alcohols. The applicability of the model to combinations of other sensory dependent substances with a similar taste has yet to be investigated, although preliminary research (Frijters and

Stevens 1986, unpublished report) suggests that the sourness intensity response to mixtures of weak organic acids can be successfully predicted by the model.

The model seems to be an adequate representation of the operation of the gustatory system when processing mixtures of dependent substances which have similar tastes. From the viewpoint of the content of the model, it can be concluded that it describes the gustatory modality as an 'averaging' system. In the case of a binary mixture, the magnitude of the response is intermediate between the magnitudes of the responses to the unmixed compounds of equal molarity. This phenomenon was also observed in previous studies of equiratio sweetener mixtures (Frijters and Oude Ophuis 1983; Frijters et al 1984). In addition to the evidence from these studies, de Graaf and Frijters (1987) have also shown, by analyzing the data from a number of other mixture studies (Cameron 1947; Stone and Oliver 1969; Stone et al 1969; Yamaguchi et al 1970; Curtis et al 1984; Munton and Birch 1985; McBride 1982, 1983b, 1986), that 'averaging' is the rule in binary mixtures. The present experiments have shown that in cases of mixtures of more than two components, the response to the mixture is some kind of average of the values of the responses to the unmixed compounds of a molar concentration equal to that of the mixture.

Because the substances used for mixture composition are sensory dependent substances of similar taste, competition for adsorption at the same receptor sites seems to be adequate to explain the averaging principle. However, our results do not necessarily preclude the possibility of averaging at a neural or central level. If, however, averaging is the result of peripheral competition between the molecules of the different substances in the mixture, then it can be hypothesized that the ETMM will not correctly predict the sensory response to all possible mixtures. For example, mixtures of substances which operate independently at the periphery (ie, they do not show cross adaptation), might not be expected to follow the averaging rule. Also, mixtures of substances of different taste qualities may be expected to elicit a sensory response to the total intensity of that mixture which is lower than would be predicted by the ETMM. The predicted depression of the mixture intensity response would probably be due to the phenomenon of central mixture suppression which has been shown to occur in these types of mixture (Kroeze 1978, 1979; Kroeze and Bartoshuk 1985).

McBride (1986) has noted that the ETMM rests upon the substitutability assumption. According to McBride, if the molecules of the substances in the mixture compete for the same receptor sites, they can be considered as substitutes for each other. He further notes (page 590) that: "*For substitutability to hold, the sweetness of a* [*binary*] *mixture would always have to lie between the intensities of equivalent concentrations of its components*". McBride reports some data on binary mixtures of sucrose and fructose which he considers to be contradictory to this rule (his figure 7). De Graaf and Frijters (1987) have argued that this apparent inconsistency may arise for two reasons. The first is that McBride used percentage weight per volume (% w/v) as a unit of concentration, and not molarity. It is obvious that solutions of two compounds with a different molecular weight which are equally concentrated on the basis of % w/v are not equally concentrated on the basis of molarity. As a consequence, McBride compared the sweetness of solutions of sucrose, fructose, and sucrose-fructose of unequal molarity. A second factor which may explain the discrepancy between our findings and McBride's is that in his study the sweetness values for the mixtures and single compounds were obtained in different experiments, carried out with different subjects. These experimental factors may have contributed to errors in the estimated values. De Graaf and Frijters (1987) replotted McBride's sucrose-fructose data (see their figure 9, panel C) and found most of the perceived sweetness intensities of the equiratio mixtures to be intermediate between the intensities of the concentrations of the unmixed compounds. In view of the evidence discussed, we maintain that the value of the sweetness response to a mixture is intermediate between the responses to equimolar concentrations of the unmixed substances. This was also confirmed again by de Graaf et al (1987) in an extensive study in which sucrose–fructose mixtures were investigated at five different levels, ranging from 0.125 M to 2.000 M.

Interpretation of the ETMM will depend to some extent on the meaning that is attached to magnitude estimation as a scaling procedure, since the model incorporates psychophysical power functions obtained with this technique (cf Frijters and Oude Ophuis 1983). According to Stevens (eg, 1975), the numerical response obtained using magnitude estimation instructions is a direct and unbiased estimate of the perceived intensity of the stimulus. This view represents a behaviouristic stimulus-response (S-R) conception of psychophysics (Shepard 1981; McKenna 1985). In contrast, in the stimulus-output-response (S-O-R) paradigm of psychophysical judgement a psychophysical stage relating stimulus to sensation (psychophysical input function), and a judgemental stage relating sensation to overt response (judgemental output function) are distinguished (Torgerson 1961; Attneave 1962; Treisman 1964). Investigators who have adopted the S-O-R view have shown that the judgement function generated with magnitude estimation is a nonlinear and positively accelerating function of the internal sensation (eg, Curtis et al 1968; Rule et al 1970; Weiss 1972; Rule and Curtis 1977; Veit 1978). In other words: the sweetness response to a particular sugar-containing stimulus is not identical to, or a linear representation of, the perceived sweetness of that stimulus.

The existence of a nonlinear response output function, in addition to a psychophysical input function, is of no consequence to the ETMM, because it is an S-R model which predicts the sensory response to a mixture on the basis of sensory responses to stimulus compounds. It does not predict perceived sweetness intensities on the basis of other perceived sweetness intensities. If an equiratio mixture function is predicted on the basis of psychophysical power functions (here meaning S-R functions) of single substances *determined in the same experiment under identical conditions*, then the predicted power function is 'biased' to the same degree as the power function of the single compounds. This follows from the fact that the perceived sweetness intensities of the solutions of both substances and the mixtures are 'biased' to the same degree by the same response output function. Although the psychophysical input function is substance and mixture-type specific, the response output function is not.

The shape of the psychophysical power function derived for a particular compound varies from experiment to experiment. For example, the function for glucose was $R = 14.67\,C^{1.38}$ in the first experiment, and $R = 16.28\,C^{1.54}$ in the second. The difference between the constants can be explained because of the use of a different standard stimulus in the two experiments, but the difference between the exponents cannot be attributed to this experimental difference. Based on a review of published studies, Meiselman (1972) reported that the exponents of the power functions of sucrose obtained in ratio scaling experiments varied between 0.46 and 2.93. Even within experiments where the sip and spit procedure was used in combination with magnitude estimation, the variability was substantial. Meiselman (1980) noted that the exponent varied from 0.69 to 1.67 over these experiments. Baird and Noma (1978) described how all kinds of experimental factors may affect the shape of the psychophysical power function; for example, stimulus range, stimulus distribution, position of the standard stimulus, type of instructions given, and numerical value assigned to a fixed standard. These authors therefore concluded (page 105) that: "*The compelling evidence is that response scales depend on the context in which they are obtained*". Since this holds for the psychophysical power functions of single substances, it is obvious that the same applies to the power function for any equiratio mixture type that is predicted by the ETMM. It can thus be concluded that predicted power functions are not context independent, despite the high validity of the model showing that the *relationship* between psychological functions of individual compounds and those in their equiratio mixture types is invariant in different experimental contexts.

## References

AlF E F, Grossberg J M, 1979 "The geometric mean: confidence limits and significance tests" *Perception & Psychophysics* **26** 419 - 421

Attneave G, 1962 "Perception and related areas" in *Psychology: A Study of Science* study II, volume IV, ed S Koch (New York: McGraw-Hill) pp 619 - 659

Baird J C, Noma E, 1978 *Fundamentals of Scaling and Psychophysics* (New York: John Wiley) pp 1 - 287

Cameron A T, 1947 "The taste sense and the relative sweetness of sugars and other sweet substances" Science Report Series No 9, Sugar Research Foundation, New York, USA

Curtis D W, Attneave F, Harrington T L, 1968 "A test of a two-stage model of magnitude estimation" *Perception & Psychophysics* **3** 25 - 31

Curtis D W, Stevens D A, Lawless H T, 1984 "Perceived intensity of the taste of sugar mixtures and acid mixtures" *Chemical Senses* **9** 107 - 120

Frijters J E R, Graaf C de, Koolen H C M, 1984 "The validity of the equiratio taste mixture model investigated with sorbitol - sucrose mixtures" *Chemical Senses* **9** 241 - 248

Frijters J E R, 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

Gent J, McBurney D H, 1978 "Time course of gustatory adaptation" *Perception & Psychophysics* **23** 171 - 175

Graaf C de, Frijters J E R, 1987 "Sweetness intensity of binary sugar mixtures lies in between sweetness intensities of equimolar concentrations of the mixture's constituents" *Chemical Senses* **12** 113 - 129

Graaf C de, Frijters J E R, Trijp H C M van, 1987 "Taste interaction between glucose and fructose assessed by functional measurement" *Perception & Psychophysics* **41** 383 - 392

Kroeze J H A, 1978 "The taste of sodium chloride: masking and adaptation" *Chemical Senses and Flavour* **3** 443 - 449

Kroeze J H A, 1979 "Masking and adaptation of sugar sweetness intensity" *Physiology and Behavior* **22** 347 - 351

Kroeze J H A, Bartoshuk L M, 1985 "Bitterness suppression as revealed by split-tongue taste stimulation in humans" *Physiology and Behavior* **35** 779 - 783

McBride R L, 1982 *Towards a Unified Theory of Psychophysics* Doctoral Dissertation, Macquarie University, Sydney, New South Wales, Australia

McBride R L, 1983a "A JND category-scale convergence in taste" *Perception & Psychophysics* **34** 77 - 83

McBride R L, 1983b "Category scales of sweetness are consistent with sweetness matching data" *Perception & Psychophysics* **34** 175 - 179

McBride R L, 1986 "The sweetness of binary mixtures of sucrose, fructose, and glucose" *Journal of Experimental Psychology: Human Perception and Performance* **12** 584 - 591

McBurney D H, 1969 "Effects of adaptation on human taste function" in *Olfaction and Taste* volume III, ed C Pfaffmann (New York: Rockefeller University Press) pp 407 - 419

McBurney D H, Bartoshuk L M, 1973 "Interactions between stimuli with different taste qualities" *Physiology and Behavior* **10** 1101 - 1106

McKenna F P, 1985 "Another look at the 'new psychophysics'" *British Journal of Psychology* **76** 97 - 109

Meiselman H L, 1968 "Adaptation and cross-adaptation of the four gustatory qualities" *Perception & Psychophysics* **4** 368 - 372

Meiselman H L, 1972 "Human taste perception" *CRC Critical Reviews in Food Technology* **3** 89 - 119

Meiselman H L, 1981 "Variables affecting the psychophysical function for taste" in *Olfaction and Taste* volume VII, ed H van der Starre (London: IRL Press) pp 359 - 362

Munton S L, Birch G G, 1985 "Accession of sweet stimuli to receptor sites: 1., Absolute dominance of 1 molecular species in binary mixtures" *Journal of Theoretical Biology* **112** 539 - 552

Rule S J, Curtis D W, 1977 "Subject differences in input and output transformations from magnitude estimations of differences" *Acta Psychologica* **41** 61 - 65

Rule S J, Curtis D W, Markley R P, 1970 "Input and output transformations from magnitude estimation" *Journal of Experimental Psychology* **86** 343 - 349

Shepard R N, 1981 "Psychological relations and psychophysical scales: On the status of direct psychophysical measurement" *Journal of Mathematical Psychology* **24** 21 - 57

Stevens S S, 1956 "The direct estimation of sensory magnitude - loudness" *American Journal of Psychology* **69** 1 - 25

Stevens S S, 1975 *Psychophysics* (New York: John Wiley) pp 1 - 329

Stone H, Oliver S M, 1969 "Measurement of the relative sweetness of selected sweeteners and sweetener mixtures" *Journal of Food Science* **34** 215 - 222

Stone H, Oliver S M, Kloehn J, 1969 "Temperature and pH effects on the relative sweetness intensity of suprathreshold mixtures of dextrose fructose" *Perception & Psychophysics* **5** 257 - 260

Torgerson W S, 1961 "Distances and ratios in psychological scaling" *Acta Psychologica* **19** 201 - 205

Treisman M, 1964 "Sensory scaling and the psychophysical law" *Quarterly Journal of Experimental Psychology* **16** 11 - 22

Veit C T, 1978 "Ratio and subtractive processes in psychophysical judgement" *Journal of Experimental Psychology: General* **107** 81 - 107

Weiss D J, 1972 "Averaging, an empirical validity criterion for magnitude estimation" *Perception & Psychophysics* **12** 385 - 388

Yamaguchi S, Yoshikawa T, Ikeda S, Ninomiya T, 1970 "Studies on the sweet taste of some sweet substances, Part II: Interrelationship among them" *Agricultural and Biological Chemistry* **34** 187 - 197