

**PSYCHOPHYSICAL STUDIES OF MIXTURES OF TASTANTS**

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Cornelis de Graaf

Psychophysical Studies of Mixtures of Tastants

Proefschrift

ter verkrijging van de graad van  
doctor in de landbouwwetenschappen,  
op gezag van de rector magnificus,  
dr. C.C. Oosterlee,

in het openbaar te verdedigen

op dinsdag 19 januari 1988

des namiddags te vier uur in de aula  
van de Landbouwuniversiteit te Wageningen

Een dwaling wordt geen waarheid door veelvuldig aanprijzen en  
evenmin wordt de waarheid een dwaling omdat niemand haar ziet.

M.K. Gandhi

VOOR MIJN OUDERS  
VOOR META

## STELLINGEN

1. De zoetheidsintensiteit van een tweewaardig suikermengsel ligt tussen de zoetheidsintensiteiten van de componenten, wanneer elk van de afzonderlijke componenten en het mengsel worden vergeleken bij eenzelfde molaire concentratie.
2. De stelling dat kunstmatige zoetstoffen vele malen zoeter zijn dan suikers berust op een onjuiste interpretatie van het begrip zoetheid.
3. De conclusie die in voorafgaande studies is getrokken, al zou er sprake zijn van synergie in mengsels van zoetstoffen, berust op een onjuiste vaststelling van de smaakinteractie.

(dit proefschrift)

4. Gelijke molaire concentraties van glucose, sorbitol, mannitol en xylose, alsmede gelijke molaire concentraties van alle mogelijke mengsels van deze stoffen smaken even zoet.

(dit proefschrift)

5. Men kan kinderen niet afleren zoet lekker te vinden door hen van zoetheiden te onthouden.
6. Pogingen om voedingsgedrag te veranderen vanuit gezondheidkundige overwegingen hebben een grotere kans op succes indien de voorlichter er rekening mee houdt dat voedsel in eerste instantie smakelijk moet zijn.
7. De grote beschikbaarheid van statistische software pakketten is niet bevordelijk voor het statistisch inzicht.
8. Het beoefenen van wetenschap en het ambtenarenreglement verhouden zich als vuur staat tot water.
9. De Europese éénwording zou er bij gebaat zijn als iedere Europeaan voor een bepaalde tijd buiten Europa verblijft.
10. Met het huidige prijzeniveau is het openbaar vervoer niet meer openbaar.

Proefschrift C. de Graaf  
 Psychophysical Studies of Mixtures of Tastants  
 Wageningen, 19 januari 1988

## VOORWOORD

Vermoedelijk zijn er weinig promovendi die zich hebben mogen verheugen in een begeleiding zoals ik die heb gehad van de promotor van dit proefschrift Prof. Dr. Jan Frijters. Hij heeft me de beginselen van de psychofysica zo enthousiast bijgebracht, dat ik al gauw gefascineerd was door dit type onderzoek. Met vragen als "wat bedoel je hier nu mee", en "wat hebben we hier eigenlijk aan" werd ik steeds gedwongen om kritisch te kijken naar het perspectief en doel van elke studie en elk artikel. Ik heb veel geleerd van de vaak lange en pittige discussies die we hebben gehad. Bij deze wil ik je graag bedanken voor je enthousiaste inzet en solidariteit.

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Dit proefschrift telt vele figuren. Mijn oorspronkelijke versies hiervan werden op de Tekenkamer van het Biotechnion omgetoverd tot professionele tekeningen. Van de Tekenkamer gingen deze tekeningen naar de Fotokamer, waar ze er als prachtige foto's weer uitkwamen. Gedurende mijn onderzoek heb ik gemiddeld één keer per dag een artikel aangevraagd bij de medewerkers van de Bibliotheek van het Biotechnion. Zij weten vaak artikelen te achterhalen uit voor mij verborgen bronnen. Ik dank hen voor hun grote medewerking. Jaap Booij wil ik bedanken voor alle programma's die hij heeft geschreven. Ook de heer Woldendorp ben ik erkentelijk voor de ondersteuning van mijn onderzoek.

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**PSYCHOPHYSICAL STUDIES OF MIXTURES OF TASTANTS**  
**THESIS, WAGENINGEN AGRICULTURAL UNIVERSITY, THE NETHERLANDS,**

**JANUARI 19, 1988**

**C de Graaf**

**ABSTRACT**

The human perception of mixtures of tastants was studied with reference to three central issues, i.e., 1) the paradigm of equiratio taste substance mixtures, as an instrument to manipulate the physical composition of tastant mixtures. This paradigm also enables the construction of psychophysical functions for tastant mixtures. 2) the way how the perceived intensity of a mixture is compared with the perceived taste intensities of the mixture's unmixed components, and 3) the psychometrical properties of the response scale. Major conclusions of the studies in this thesis are 1) the sweetness intensity of a binary sugar mixture lies between the sweetness intensities of its components, when each is tasted alone and at the same total molarity as the mixture, 2) application of a functional measurement approach in combination with a two stimulus procedure yields an interval scale of perceived taste intensity, and 3) the paradigm of equiratio taste substance mixtures is a powerful instrument in the study of perceptual interaction phenomena in tastant mixtures.



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## **CHAPTER ONE**

### **GENERAL INTRODUCTION**

1. SUBJECT MATTER AND PERSPECTIVE OF THE THESIS
2. STRUCTURE OF THE THESIS

## 1. SUBJECT MATTER AND PERSPECTIVE OF THE THESIS

This thesis deals with the human perception of aqueous solutions of taste substance mixtures. The psychophysical study of taste substance mixtures involves a comparison of perceptual attributes of a mixture with the perceptual attributes of the mixture's components when tasted independently outside the mixture. This thesis is primarily concerned with one of these perceptual attributes, perceived taste intensity.

The psychophysics of taste substance mixtures is an scientific issue, which has been studied since the end of the nineteenth century. It has been studied from a variety of perspectives, and with various psychophysical methods. In the first half of this century, taste mixture phenomena were studied primarily with the help of indirect psychophysical scaling methods. In the second half of this century when a more advanced psychophysical methodology was developed direct psychophysical scaling methods were also applied for the study of taste substance mixtures.

The development of direct psychophysical scaling methods has lead to the first attempts to model taste mixture interactions. These models are primarily aimed at the prediction of the perceived taste intensity of a mixture on the basis of the perceived taste intensities of the unmixed components. However, These first attmeps were not succesful and Frijters & Oude Ophuis (1983) showed that these models were either internally inconsistent or lacked sufficient generality. In the same paper Frijters & Oude Ophuis developed the "equiratio taste mixture model". These authors showed that this model provided excellent predictions for sensory responses to the sweetness intensity of glucose-fructose mixtures.

It appeared that the concept of equiratio taste substance mixtures is a powerful tool in the study of taste interaction phenomena. This concept plays a central role in this thesis.

Assessing the taste interaction in mixtures of taste

substances involves a comparison of the perceived taste intensity of mixtures with the perceived taste intensities of the mixture's components when tasted alone outside the mixture. This comparison must occur according to a particular rule, i.e., it must be specified how the taste intensity of a mixture is being compared to the taste intensities of the unmixed components. There are a number of ways of carrying out this comparison and the description of the taste interaction depends on which comparison rule is applied.

Apart from the comparison rule used to assess the taste interaction in taste substance mixture, there is another issue that has to be considered. It appears that the psychometric properties of the response scale have a drastic influence on the description of the taste interaction.

This thesis investigates the taste interaction in taste substance mixtures whilst taking into account three central issues:

- 1) the concept of equiratio taste substance mixtures.
- 2) the rule according to which the taste intensity of mixtures is compared with the taste intensities of the unmixed components.
- 3) the psychometric properties of the response scale.

## 2. STRUCTURE OF THE THESIS

Most of the chapters in this thesis consists of material which has been or will be published as papers in scientific journals.

Chapter Two of this thesis is a review of the pre 1980 literature on the perception of taste substance mixtures. This chapter results in a description of the state of knowledge on the human perception of taste substance mixtures, as it existed at the end of the 1970's.

Chapter Three is a study of a psychophysical investigation of Beidler's mixture equation carried out with glucose-fructose

mixtures. In Chapter Four, the results of seven published studies on the sweetness intensity of binary sugar mixtures are reanalyzed, in order to assess the taste interaction in binary sugar mixtures according to the equimolar comparison rule. In Chapter Five, two recent theoretical developments are applied to assess the taste interaction between glucose and fructose. These developments are Anderson's theory of information integration (Anderson, 1981) and the concept of equiratio taste substance mixtures developed by Frijters & Oude Ophuis (1983). Chapter Six gives a general outline of different comparison rules for assessing the taste interaction in mixtures of qualitatively similar tasting substances. These comparison rules are applied to the results of an experiment on sucrose-fructose mixtures. The psychophysical methodology applied in the experiments described in Chapters Five and Six, is further investigated in Chapter Seven. This chapter deals with issues concerning judgments of "ratios" and "differences" of perceived sweetness intensity.

Chapter Eight deals with concentrations of sucrose and NaCl which are equal in perceived taste intensity. This study can be considered as a pilot study for the study in Chapter Nine. The latter chapter presents and investigates a conceptual framework for the examination of the interrelationships among the sweetness, saltiness and total taste intensity of sucrose, NaCl and sucrose/NaCl mixtures. These interrelationships are investigated in an extensive experiment.

The results of some additional analyses on the results of the various experiments and interrelationships among them are given in Chapter Ten.

The thesis ends with a general discussion (Chapter Eleven), an English and Dutch summary of each of the Chapters One to Eleven (Chapter Twelve and Thirteen).

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- Anderson, N.H. (1981) Foundations of Information Integration Theory, New York, Academic Press.
- Frijters, J.E.R., & Oude Ophuis, P.A.M. (1983) The construction and prediction of psychophysical power functions of equiratio sugar mixtures. Perception, 12, 753-767.

## CHAPTER TWO

### PSYCHOPHYSICAL STUDIES ON TASTE MIXTURES: A REVIEW UNTIL 1980

1. INTRODUCTION
2. MIXTURES OF QUALITATIVELY SIMILAR TASTING SUBSTANCES
  - 2.1. Mixture research in the tradition of indirect scaling
  - 2.2. Mixture research in the era of direct scaling
  - 2.3. Thresholds of mixtures of two qualitatively similar tasting substances: The studies of Hahn & Ulbrich (1948)
3. MIXTURES OF QUALITATIVELY DISSIMILAR TASTING SUBSTANCES
  - 3.1. The quality of mixtures of qualitatively dissimilar tasting substances
  - 3.2. Intensity of mixtures of qualitatively dissimilar tasting substances
    - 3.2.1. Specific taste intensity of a tastant in the presence of another dissimilar tasting substance
    - 3.2.2. Taste intensity of a mixture in relation to the taste intensity of the mixture's components when tasted independently.
4. SUMMARY

## 1. INTRODUCTION

Judged by the number of recently published studies, it seems that there is increasing work being done on taste mixture phenomena. This revival of interest in a long standing scientific issue has lead to a recent symposium which focused on the Perception of Complex Mixtures of Tastes and Smells (Ache et al., 1987). In recent years, investigators have applied more advanced methods, and have developed new perspectives on the phenomena which occur when two taste substances are mixed together (e.g., Curtis, Stevens & Lawless, 1984; Frank & Archambo, 1986; Frijters & Oude Ophuis, 1983; Kroeze, 1978, 1979; Lawless, 1979; Kuznicki & Ashbaugh, 1983; McBride, 1986).

The present research on taste mixtures has its roots in the earlier literature on taste mixtures, and current papers are oriented towards relatively recent Anglo-American literature. The older literature however, written mostly in German, is less frequently referred to. The purpose of this review is to discuss the older literature on taste substance mixtures.

The present review on taste mixtures focuses on studies in which the human perception of taste substance mixtures was investigated. It deals with mixtures of tastants in aqueous solutions only. This review will not address perceptual phenomena occurring when two or more stimuli are temporarily or spatially separated. It has some overlap with two recent reviews of Bartoshuk (1978) and Bartoshuk & Gent (1985), which gave a more general account of the history of taste research. Most of the publications cited below are mentioned in The Harveys Bibliography of Taste (O'Mahony & Thompson, 1975).

This review is divided into two main parts. In the first part the literature on the taste interaction between qualitatively similar tasting substances is discussed. The second part deals with mixtures of qualitatively dissimilar tasting substances. This division seems appropriate since the psychophysical study of mixtures of qualitatively dissimilar



tasting substances has been considered to be different from the psychophysical research on mixtures composed of qualitatively similar tasting substances. The reason for this difference is obvious. In mixtures of qualitatively dissimilar tasting substances, the taste qualities of the individual tastants may remain identifiable in the mixture percept. This is not the case for mixtures of substances which have a similar taste quality. As will become clear in the course of this review, identifiability of the original taste qualities has various consequences for the issues to be addressed.

The terminology that is used to describe taste interactions in mixtures is confusing. It appears that almost each author uses his own vocabulary to describe taste interactions in mixtures. In order not to disrupt the meaning and intention of each paper, we have maintained the original terminology used by each author. We also retained the original interpretation of the results of each paper. This does not necessarily imply that we agree with the conclusions formulated, and it is important to note that these conclusions are not considered in the light of the present knowledge on taste mixtures.

## 2. MIXTURES OF QUALITATIVELY SIMILAR TASTING SUBSTANCES

The taste interaction between two qualitatively similar tasting substances in mixtures seems to be characterized primarily by the relationship between the taste intensity of mixtures and the taste intensities of the mixture's constituent components when tasted alone. In order to describe some kind of taste interaction this relationship must be described according to a particular rule. Usually the taste interaction is inferred by comparing the taste intensity of the mixture with the sum of the intensities of the mixture's components. The taste intensity of a mixture containing  $x$  mol/L of substance A and a concentration of  $y$  mol/L of substance B, is compared to the sum of the intensities to  $x$  mol/L of A tasted alone, and  $y$  mol/L of B

tasted alone. This comparison rule has been applied by all but two of the studies to be discussed.

Most of the research on mixtures of qualitatively similar tasting substances has been carried out with sweet tasting substances. Some exceptions are one study carried out by Moskowitz (1974a), one study of Bartoshuk & Cleveland (1977), and an extensive report made by Hahn & Ulbrich (1948) on the thresholds of binary mixtures, which consisted of salty, sweet, sour, bitter, and alkaline tasting substances. The results of the work of Hahn & Ulbrich (1948) will be discussed in a separate paragraph.

The first part of this discussion on mixtures of qualitatively similar tasting substances will review studies, in which indirect scaling methods were used for the determination of perceived taste intensity. In most of these studies the subjective intensity of a concentration of a particular taste substance is expressed in another concentration of a particular reference substance of equal perceived taste intensity. The second part of this review will discuss studies using some form of direct scaling to assess the taste intensity of mixtures and single substances. In direct scaling methods the taste intensity is expressed in numerical ratings. These numbers may be ratings on a category scale (e.g., Schutz & Pilgrim, 1957), or ratings obtained by magnitude estimation (e.g., Stevens, 1969).

## **2.1 Mixture research in the tradition of indirect scaling**

Taste interaction phenomena in mixtures containing qualitatively similar tasting substances had not been studied before the 1920's. The first study concerning this issue was probably an investigation of Paul (1921). He determined the sweetness intensity of dulcine, saccharine and dulcine/saccharine mixtures, and expressed the sweetness intensity of these substances and mixtures in equisweet sucrose concentrations. He observed that the relative sweetness intensity of the mixtures

was equal to the sum of the intensities of the mixture's components. Although Paul (1921) found additivity, he concluded that in practice saccharine and dulcine potentiated each other. "Obwohl es sich also bei diesen Mischungen um eine additive Wirkung des Süßungsgrade des Dulcine und Saccharins handelt, wird in der Praxis doch eine Wirkung erzielt, die einer potenzierenden gleichkommt." This conclusion is not without ambiguity, and seems to be of little help in adequately describing the taste interaction between saccharine and dulcine. When discussing Paul's results, Von Skramlik (1926) gave an explanation for Paul's observations, which is essentially a chemical one. He argued that the potentiating effect between saccharine and dulcine was the result of a chemical reaction between these substances which caused them to be more dissociated in the presence of each other than when dissolved alone.

To investigate the generality of Paul's findings, Heiduschka et al. (1925) investigated whether the sweet tasting amino acids glycine and alanine also showed addition when mixed. Heiduschka et al. (1925) used one mixture only and expressed the sweetness intensity of glycine, alanine and that of the mixture in equisweet sucrose concentrations. It was observed that the sweetness intensity of the glycine-alanine mixture was less than the sum of the sweetness intensities of its components. Glycine and alanine did not show addition when mixed.

Dahlberg & Penczek (1941) noted that mixtures of glucose and sucrose were sweeter than might be expected by adding the intensities of its components. These authors explained what they called the supplemental action between glucose and sucrose and noted that "The sweetness of sucrose is quickly perceived, promptly reaches a maximum intensity, and then decreases. The sweetness of dextrose stimulates the taste sensory organs more slowly and reaches a maximum intensity later. Hence, the one sugar might be expected to supplement the other."

Cameron (1945, 1947) determined the relative sweetness of binary mixtures of sucrose-fructose, sucrose-glucose, sucrose-

lactose, glucose-galactose, glucose-lactose, sucrose-glycine, sucrose-alanine, glucose-glycine, and glycine-alanine. In sugar mixtures, Cameron (1947) found that the intensity of mixtures exceeded the sum of the intensities of its components, when the sweetness intensity was expressed in equisweet sucrose concentrations. When the sweetness intensity however, was expressed in glucose equivalents, the mixture intensity was approximately equal to the sum of the intensities of its components. Apparently the result of the comparison of the sweetness intensity of a mixture with the sum of the sweetness intensities of the mixture's components depends on the unit of sweetness intensity. The observation that two sugars show addition in terms of glucose equivalents but show enhancement in terms of sucrose equivalents can be explained by the non-linear relationship between equisweet concentrations of glucose and sucrose. Cameron (1947) noted that the supplemental action between glucose and sucrose found by Dahlberg & Penczek (1941) also changed into addition when the sweetness intensity was expressed in glucose equivalents instead of sucrose equivalents.

Cameron (1947) found that taste interaction in mixtures containing either glycine or alanine was different from the taste interaction observed in mixtures of sugars. Mixtures containing either glycine or alanine were less sweet than the sum of the intensities of its components, irrespective of whether the sweetness was expressed in equivalent sucrose concentrations or in equivalent glucose concentrations. This result was in line with the observation of Heiduschka *et al.* (1925).

Vincent *et al.* (1955) concluded that "The 10:1 mixture of cyclamate sodium and saccharin sodium is sweeter than would be expected from the sum of the sugar equivalents of its components."

In an extensive study, Yamaguchi *et al.* (1970) assessed the sweetness intensities (expressed in equisweet sucrose concentrations) of all binary mixture combinations of sucrose, fructose, glucose, mannitol, sorbitol, xylitol, xylose, cyclamate, and saccharine, and also of mixtures of each of the

tastants, sucrose, glucose, cyclamate, saccharine with each of the sweet tasting amino acids glycine and DL-alanine. In addition the sweetness intensities of glycine-DL-alanine mixtures were determined. Yamaguchi *et al.* (1970) distinguished between six different types of mixture interactions of which three types were defined as additive. The other three were called the suppressing, the counteracting, and the synergistic effect. The results showed that in all mixtures, the sweeteners showed either additive or synergistic effects.

## **2.2. Mixture research in the era of direct scaling**

Kamen (1958) determined the sweetness intensity of sucrose, cyclamate, and some sucrose/cyclamate mixtures. He expressed the perceived sweetness intensity in the units of a category scale used earlier by Schutz & Pilgrim (1957). He investigated the taste interaction somewhat differently from previous investigators. He stated that "If we mix various proportions of 5 % and 10 % sucrose solutions, we will find that the perceived intensity of sweetness of the mixtures will lie between the perceived intensities of the original solutions. Specifically, the subjective intensities of the mixtures should be approximately geometrically proportional to the relative amounts of each of the original solutions that comprise the mixture. In this case, the effects of mixing the solutions are said to be additive.". Kamen (1958) thus related the taste interaction between two substances in a mixture to the apparent taste interaction within the single substances themselves. Kamen prepared sucrose and cyclamate solutions of approximately equally sweetness intensity. He also prepared two types of mixtures, one type of mixtures containing 2/3 of the original sucrose concentrations and 1/3 of the original cyclamate concentrations, and another type of mixtures containing 1/3 of the original sucrose concentrations and 2/3 of the original cyclamate concentrations. According to Kamen (1958), the results showed

that sucrose and cyclamate behaved additively when mixed at low and high sweetness levels (corresponding to the sweetness of 0.07 and 1.08 M sucrose, respectively). At intermediate sweetness levels (corresponding to the sweetness of 0.17 and 0.43 M sucrose, respectively) the sweetness intensity of the mixtures exceeded the sweetness intensities of the unmixed compounds.

Psychophysical research in the 1960's was characterized by the development and application of Stevens' method of magnitude estimation (e.g., Marks, 1974; Stevens, 1956, 1975; Stevens & Galanter, 1957). This scaling approach also had its impact on the methodology of psychophysical taste mixture research.

Magnitude estimation was applied to taste mixtures by Stone & Oliver (1969) who investigated binary mixtures consisting of some combinations of sucrose, fructose, glucose, saccharine, cyclamate, glycine, and DL-alanine. These authors observed that combinations of sucrose-fructose, sucrose-glucose, glucose-fructose, glucose-cyclamate, glucose-saccharine behaved synergistically when mixed i.e. the intensity of the mixture exceeded the intensities of the mixture's constituent components when tasted independently. Mixtures of glucose and glycine or DL-alanine behaved suppressively. In another study Stone, Oliver & Kloehn (1969) observed that the taste interaction between glucose and fructose was independent of temperature or pH.

In view of the results of the studies discussed above it is not surprising, that Pfaffmann *et al.* (1971) summarized the results of the earlier studies with the conclusion that in mixtures of two qualitatively similar tasting substances, the intensity of the mixture is equal to or greater than the sum of the intensities of its components. This conclusion was said to hold for all mixtures investigated until that year with a relatively few exceptions of mixtures containing either DL-alanine or glycine.

Psychophysical taste mixture research in the 1970's was characterized by the first attempts to explain and model taste interactions in binary mixtures. Moskowitz (1973, 1974a, 1974b)

developed two models on taste interaction which Frijters & Oude Ophuis (1983) later called the 'addition' model and the 'substitution' model.

In the addition model, it was assumed that the perceived taste intensities of two compounds are added together when the two compounds are mixed. Since Moskowitz assumed that Stevens' power law is a proper description of the relationship between concentration and intensity of a particular tastant the addition model reads:

$$R_{abij} = k_a(C_{ai})^{**n} + k_b(C_{bi})^{**m}, \quad (1)$$

where  $R_{abij}$  represent the response to a mixture of concentration  $i$  of substance A ( $= C_{ai}$ ), and concentration  $j$  of substance B ( $= C_{bi}$ ). The parameters  $k_a$ ,  $n$ ,  $k_b$ ,  $m$ , are the constants and exponents of the psychophysical power functions of substance A and substance B respectively.

In the second model the intensities rather than the concentrations were added. Moskowitz (1974b) summarizes the basis of this model as follows: "The sensory system adds together the concentrations of the mixture components, treats the sum as a higher concentration of the reference chemical, and then transforms that concentration into subjective magnitude according to an intensity function appropriate for the reference chemical.". If substance A is the reference chemical this model reads,

$$R_{abij} = k_a[C_{ai} + (k_b C_{bi}^{**n} / k_a)^{** (1/m)}]^{**m}, \quad (2)$$

and if substance B is the reference chemical the substitution model reads:

$$R_{abij} = k_b[C_{bi} + (k_a C_{ai}^{**m} / k_b)^{** (1/n)}]^{**n} \quad (3)$$

Moskowitz (1973, 1974b) tested these models for several

mixtures of sweeteners, i.e. mixtures of glucose with fructose, Na-cyclamate, Na-saccharine, and saccharine, and mixtures of either glucose or fructose with each of the substances xylose, arabinose, sorbitol, glycerol, galactose, lactose, sucrose, and maltose. Moskowitz (1974b) concluded: "Both models systematically underpredicted mixture sweetness, suggesting synergistic effects that extend beyond simple additivity.".

A few years later Moskowitz & Dubose (1977) applied a slightly adjusted version of the addition model to mixtures of fructose, glucose, and sucrose, with aspartame. It was concluded that except for the mixtures of fructose and aspartame, the mixtures showed simple additivity of sweetness.

Moskowitz (1974a) applied the same models to mixtures of acids. The models fitted better for acids than for sweeteners although some acid mixtures also showed synergism.

About the same time as Moskowitz developed his taste mixture models, Berglund et al. (1973) developed a model for the prediction of the odour intensity of mixtures of odourants. This model can be easily applied to mixtures of tastants. The mixture model of Berglund et al. (1973) treats the taste intensity of the mixture's components as vectors in a subjective space. The angle between the two vectors is supposed to represent the degree of qualitative dissimilarity between substance A and B. The vector addition model reads:

$$R_{abij} = (R_{ai}^{**2} + R_{bj}^{**2} + 2R_{ai}R_{bj}\cos\alpha)^{**0.5}, \quad (4)$$

where  $R_{abij}$  represents the response to the mixture,  $R_{ai}$  represents the response to concentration  $i$  of substance A (outside the mixture, and represented as a vector in a subjective space),  $R_{bj}$  represents the response to concentration  $j$  of substance B and  $\alpha$  represents the angle between the vector of A and the vector of B. In the case of two qualitatively similar tasting substances the value of  $\alpha$  is 0 and the cosine of  $\alpha$  becomes equal to 1, so that the vector addition model simplifies



to  $R_{abL} = R_{aL} + R_{bL}$ . This model has one serious limitation in that it cannot predict that the mixture intensity exceeds the sum of the intensities of its components. As this phenomenon has been frequently observed by several authors the vector addition model can have only a limited value in describing taste interactions in mixtures which have a similar taste quality.

A more thorough and theoretical treatment of the models of Moskowitz (1973), Berglund *et al.* (1973), has been made by Frijters & Dude Ophuis (1983).

A few years after the models of Moskowitz were developed and tested, Bartoshuk & Cleveland (1977) introduced a new approach to the study of taste mixture interactions. These authors argued that the observed taste mixture interaction (suppression, addition or synergism) could be predicted from the shapes of the psychophysical functions of the mixture's constituent components tasted separately from the mixture. The reasoning behind this new approach started with the notion that the simplest example of mixing two substances is adding a substance to itself. The apparent taste interaction of a particular substance with itself according to Bartoshuk & Cleveland (1977) is a consequence of the shape of the psychophysical function of that substance. When successive increments in concentration produce smaller increments in taste intensity, the psychophysical function is said to be compressive. In the case of a substance which has a compressive psychophysical function a mixture of a substance with itself must have a taste intensity which is less than the sum of the intensities of the "mixture's" components outside the mixture, i.e. "the mixture" shows "suppression". Similarly in the case of an expanding psychophysical function the "mixture" would show "synergism". This line of reasoning has been extended to "real" mixtures.

Bartoshuk & Cleveland (1977) tested their model in an experiment. They determined the psychophysical functions of four acids, four sweeteners, and four bitter tasting substances. Each of the psychophysical functions was constructed on the basis of

responses to four concentrations, of which the lowest concentration of each of the four substances had an about equal perceived taste intensity. The other stimuli of the unmixed substances contained two, three and four times the lowest concentration. The lowest concentrations of each substance were used to construct the six possible binary mixtures, the four possible tertiary mixtures, and the one possible quaternary mixtures. This implies that the geometric mean of the total concentrations of the six binary mixtures is equal to the geometric mean of the one to lowest concentrations of each of the four unmixed stimulus types. Similarly the geometric mean of the total concentrations of the four three component mixtures is equal to the geometric mean of the one to highest concentrations of the four unmixed stimuli. By determining and averaging the responses to each of the one-, two-, three-, and four- component "mixtures" Bartoshuk & Cleveland (1977) were able to construct a kind of psychophysical "mixture" function. This function related the number of mixture components to the mean of the responses to the four types, the 1-, 2-, 3-, and 4- component, mixtures. The results showed that the shape of the function relating the number of the components in the mixture to the mean of the responses of the mixtures was similar to the (compressed) psychophysical functions of the mixture's constituents. This conclusion held for the sweeteners, the acids, and the bitter tasting substances. The experiment with the sweeteners was replicated with another stimulus delivery procedure which changed the psychophysical functions of the single sweeteners from compression to expansion. These results showed that the same change occurred with the shape of the function relating the number of mixture components and the responses to these mixtures.

The theory and results of Bartoshuk & Cleveland (1977) explained many of the observations made in previous studies and suggested that the shapes of the psychophysical functions of single substances play an important role in observations regarding the taste interactions between two tastants in a

mixture. Most psychophysical functions obtained in the earlier studies (e.g., Moskowitz, 1973, 1974b; Stone & Oliver, 1969) were expanding. The results of Bartoshuk & Cleveland (1977) explained why these authors found "synergism" in mixtures.

### 2.3. Thresholds of mixtures of two qualitatively similar tasting substances; the studies of Hahn & Ulbrich (1948).

The experiments of Hahn and colleagues are probably the most extensive experiments carried out in the history of taste research. According to Hahn and Ulbrich (1948) they determined approximately 15,000 thresholds for 108 different tastants using 43 subjects.

Hahn and Ulbrich (1948) determined the taste thresholds of a large number of combinations of binary mixtures of salty, sweet, sour, bitter, and alkali tasting substances. These authors defined the taste interaction between two tastants as follows: Suppose that substance A has a threshold concentration of  $i$  mol/L ( $=C_{ai}$ ), and substance B has a threshold concentration of  $j$  mol/L ( $=C_{bj}$ ). Following Hahn & Ulbrich (1948), two substances show addition if the threshold concentration of a particular mixture contains  $p$  times  $i$  mol/L of A, and  $q$  ( $= 1 - p$ ) times  $j$  mol/L of B ( $0 < p < 1$ ). For instance, if the threshold concentration of A is  $i$  mol/L, and the threshold concentration of B is  $j$  mol/L, and the threshold concentration of a particular mixture contains  $1/2 i$  mol/L A, and  $1/2 j$  mol/L of B (or  $9/10 i$  mol/L A, and  $1/10 j$  mol/L B), then A and B are supposed to behave additively. If the threshold concentration of a particular mixture is less than can be expected on the basis of addition, two substances potentiate each other, and if the threshold concentration of a particular mixture is higher than can be expected on the basis of addition, two substances suppress each other. Figure 1 gives a graphical display of the categories suppression, addition, and potentiation. The additivity-line, i.e. the line connecting the point  $C_{ai}$  on the x-axis and the point  $C_{bj}$  on the y-axis, is identical to an

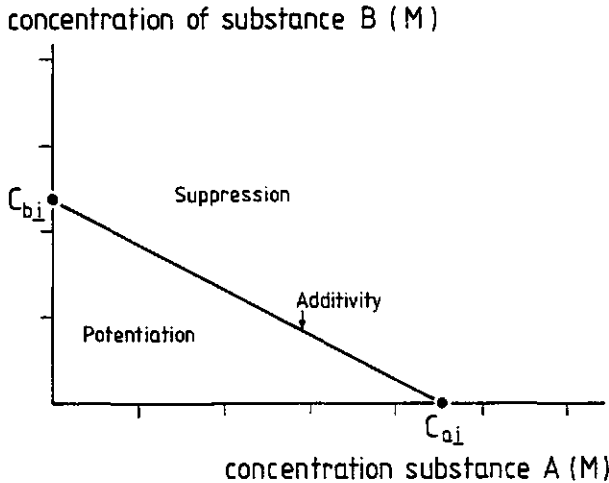


Fig. 1. Definition of the taste interaction between two qualitatively similar tasting substances at threshold levels, according to Hahn & Ulbrich (1948). The concentration  $C_{ai}$  is the threshold level of substance A, concentration  $C_{bi}$  is the threshold of substance B. If the threshold of a binary mixture of A and B is on the line connecting  $C_{ai}$  and  $C_{bi}$ , addition occurs. If the threshold mixture concentration lies above the line suppression occurs, and if the mixture threshold lies below the line A and B potentiate each other.

equation derived from Beidler's mixture model (Beidler, 1962, 1971; De Graaf & Frijters, 1986). It can be described by the following mathematical expression.

$$X + Y = \frac{C_{ai}C_{bi}}{pC_{bi} + qC_{ai}} \quad (5)$$

The sum of X and Y represents the total concentration of the mixture. X represents the concentration of substance A and Y represents the concentration of substance B. In the original derivation,  $C_{ai}$  and  $C_{bi}$  refer to those concentrations of substance A and substance B that give rise to an equal perceived taste intensity, and  $(X + Y)$  is the predicted mixture concentration of the same perceived taste intensity as the intensities elicited by  $C_{ai}$  and  $C_{bi}$ . In the present context these

figures refer to threshold concentrations.

Beidler formulated the mixture equation to describe the peripheral interaction between the molecules of two taste substances competing for adsorption at the same receptor sites. The meaning of the term "addition" used by Hahn & Ulbrich (1948) suggests that the compounds in a mixture act independently. This idea does not concur with the concept of competition introduced by Beidler (1971), because mutual competition implies mutual suppression of activity. At threshold levels however, there will be virtually no competition between the molecules of two tastants so that it seems that there is complete independence at these levels.

The results of Hahn & Ulbrich (1948) suggest that equation 5 applies for a total of some 200 combinations of salty, sweet, bitter and sour tasting substances. These combinations are given in Table 1.

**Table 1. Combinations of qualitatively similar tasting substances, which show addition at threshold level when mixed, according to Hahn & Ulbrich (1948) i.e. they concur with the prediction of equation 5, and lie on the additivity line shown in Figure 1.**

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**Salt :** NaCl- NaBr, NaCl- NaF, NaCl- NaNO<sub>3</sub>, NaCl- NaCO<sub>2</sub>CH<sub>3</sub>, NaCl- Na<sub>2</sub>SO<sub>4</sub>, NaCl- Na<sub>2</sub>CO<sub>3</sub>, NaCl- Na<sub>3</sub>PO<sub>4</sub>, all mixtures with NaCl and the 24 corresponding K, Li, and NH<sub>4</sub> salts, all 32 mixtures of CaCl<sub>2</sub> with the afore mentioned Na, K, Li, and NH<sub>4</sub> salts, NaCl- CaBr<sub>2</sub>, NaCl- Ca(NO<sub>3</sub>)<sub>2</sub>, NaCl- CaSO<sub>4</sub>, NaCl- BaCl<sub>2</sub>, and NaCl- Ba(CO<sub>2</sub>CH<sub>3</sub>)<sub>2</sub>.

**Sweet:** all 45 possible binary combinations of the sweeteners sucrose, glucose, galactose, dulcine, glycerin, glykokoll, nitrobenzol, phloroglucin, resorcine, and saccharine.

**Bitter:** all 45 possible binary combinations of the bitter tasting substances atropine-HCl, quinine-SO<sub>4</sub>, caffeine, KJ, MgSO<sub>4</sub>, morphine-HCl, picric acid, strychnine-HNO<sub>3</sub>, ureum, and a tannic acid of unknown composition. Altogether 62 out of the 100 possible combinations of ureum, quinine-HCl, KJ, and MgSO<sub>4</sub>, with each of 25 bitter tasting anorganic salts.

**Sour:** binary combinations of acetic-acid and HCl, with HCl, HBr, HJ, HNO<sub>3</sub>, H<sub>2</sub>SO<sub>4</sub>, formic acid, acetic acid, chloracetic acid, trichlor acetic acid, β-J-propionic acid, lactic acid, benzoic acid, salicylic acid, glycocholic acid, amber acid, tartaric acid, malic acid, and citric acid.

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### 3. MIXTURES OF QUALITATIVELY DISSIMILAR TASTING SUBSTANCES

This section starts with a discussion on the taste quality of mixtures with dissimilar tasting substances. It continues with a review of the literature on the taste intensity of mixtures with dissimilar tasting substances.

#### 3.1. The quality of mixtures of qualitatively dissimilar tasting substances

This discussion will focus on the taste quality of mixtures of sweet, sour, bitter, and salty taste substances. The basic issues concerning the taste quality of mixtures with dissimilar tasting substances are the relationships between the taste quality of a particular mixture and the taste qualities of the single compounds constituting the mixture.

One of the basic issues was already resolved in the middle of the nineteenth century. In a doctoral dissertation concerning the localization of the taste sense, Drielsma (1859) cited the work of Schirmer (1856) who carried out some experiments on binary mixtures of sucrose, NaCl, acetic acid, and quinine- $\text{SO}_4$ . The results of Schirmer's studies show that the individual taste qualities can be identified when particular concentrations of dissimilar tasting substances are mixed. Particular sucrose/NaCl mixtures for example taste both sweet and salty. Other taste investigators in the late nineteenth century (Kiesow, 1894, 1896; Oehrwall, 1891, 1901) and at the beginning of the twentieth century (Renqvist, 1919; Von Skramlik, 1926) have agreed with the observations of Schirmer.

Another basic issue concerning the taste quality of mixtures of qualitatively dissimilar tasting substances is the question whether or not new taste qualities emerge. The discussion on this subject matter started at the end of the nineteenth century and has continued up to the present day.

In a fierce debate Oehrwall (1891, 1901) and Kiesow (1894,

1896) discussed the issue of whether the taste sense is analytic like the auditory sense or synthetic like the visual sense (see also the reviews of Bartoshuk (1978) and Bartoshuk & Gent (1985)). One important subject in this discussion was the question of the nature of the taste quality of mixtures of dissimilar tasting substances.

Oehrwall (1891) took the position that the taste sense is analytic and one of his main arguments in favour of this position was that in mixtures of two qualitatively dissimilar tasting substances no new taste qualities emerge. Oehrwall (1891, p. 15-16) noted that "Die einfachen Geschmacksempfindungen lassen sich auch nicht wie die Farben zu neuen Empfindungen mischen, welche man nicht in ihre einfachen Bestandtheile zerlegen kann. ....Wie man auch mische, es entsteht nie ein neuer Geschmack, und noch weniger kann man etwas erhalten, das dem Weiss entspräche - das so zu sagen Qualität entbehrt."

Kiesow (1896) disagreed with Oehrwall and held the view that the taste sense is synthetic like the visual sense. One of his arguments was that the taste qualities of taste substances in a mixture may compensate each other i.e. the two taste qualities of a mixture interact in such a way that their individual identities are lost. For a few of all participating subjects, Kiesow (1896) found that a new taste quality emerges when low concentrations of sucrose and NaCl are mixed. According to Kiesow (1896, p. 266) "Die Empfindung ist nicht gleich Null, sie entspricht auch nicht völlig derjenigen des destillirten Wassers, sondern ist von so eigenartig neuer Qualität, dass sie unwissentlich schwer definirbar und eben in der angegebenen Weise am geeignetsten zu bezeichnen ist...". He called this taste quality "fade". Although he was not able to reproduce compensation of taste qualities in mixtures with another composition, Kiesow held the view that this phenomenon could occur in mixtures containing sweet-salty, sweet-sour and salty-sour tasting substances. He thought that compensation could not occur in mixtures containing a bitter component.

Oehrwall (1901, p. 256) discounted the experimental evidence of Kiesow (1896) and noted "Durch einen Versuch, nachzuweisen, dass Contrast und Compensationsphänomene zwischen den verschiedenen Geschmacksarten trotzdem wirklich vorhanden sind, hat Kiesow gemeint, einen leichten Sieg zu gewinnen und mich mit meinen eigenen Waffen zu schlagen...". In a footnote Oehrwall (1901, p. 258-259) wrote "Was die Compensationsversuche anbelangt, so ist zu bemerken, dass es Kiesow trotz aller Bemühungen nicht gelungen ist, eine Compensation zwischen den anderen Geschmacksarten zu zeigen, nur zwischen schwachen Empfindungen von Süß und Salzig; ....Dass eine zusammengesetzte Geschmacksempfindung schwer zu analysiren sein kann, ist nichts Ueberraschendes....Eine Compensation aber wird durch diese Versuche nicht bewiesen....". Oehrwall rejected the idea that two taste qualities in a mixture could compensate each other. Oehrwall (1901) however did not reject the idea, that qualitatively dissimilar tasting substances show interaction when mixed. Oehrwall (1901) thought that interaction between taste qualities in a mixtures was due to attention.

Patrick (1899) (as cited by Kiesow, 1901) was one of the few investigators who agreed with Oehrwall and noted that no new taste qualities emerge when two dissimilar tasting substances are mixed. Most investigators agreed with Kiesow (e.g. Henning, 1916; Von Tschermak, 1908).

Renqvist (1919, p. 191-192) reproduced Kiesows finding for the taste quality "fade" for mixtures of NaCl and K-Acetate, and mixtures of NaCl and HCl. In his book about the "lower" senses, Von Skramlik (1926, p. 453) noted that compensation is frequently observed, "Durch Kompensation ergeben sich sehr oft Geschmäcke, die als fade bezeichnet wurden...". Sjöström & Cairncross (1953) constructed a quaternary mixture which according to them had a "white taste". It contained 0.01 M sucrose, 0.002 M citric acid, 0.014 M NaCl, and 0.0004 M quinine-SO<sub>4</sub>. The first two substances had a concentration equal to their thresholds. The latter two substances had concentrations which were two times their



threshold concentration levels.

Henning (1916) who introduced the taste tetraëder went even further than Kiesow in suggesting analogies with the synthetic visual sense. Henning (1916, p. 217-218) held the view that a new and homogeneous (unitary) taste quality emerges when two dissimilar tasting substances are mixed. According to him it is a "psychological" error to assume that the original taste qualities still exist. "Eine durch eine chemisch einfache Substanz ausgelöste einfache Geschmacksempfindung, die gemäß ihrer Stellung in der psychischen Qualitätenreihe mehrere Ähnlichkeiten aufweist, z. B. zu süß und zu salzig, ist als sinnliches Erlebnis einheitlich und einfach; man bemerkt sinnlich ebensowenig einen Zuckergeschmack und davon getrennt einen Salzgeschmack, als man eine Orangefarbe einmal tiefrot, hernach hellgelb sieht. Liegt hingegen chemisch eine Mischung aus Kochsalz und Rohrzucker vor, so erlebe ich ein sinnlich einfaches und einheitliches Verschmelzungserlebnis, in dem eine Süßigkeit einheitlich in eine Salzigkeit einschattiert ist... Allein es ist ein psychologischer Irrtum, wenn man im Einheitserlebnis zwei nebeneinander stehende Komponenten annimmt."

Henning (1916) knew of several substances eliciting a taste quality located between the edges of the taste tetraëder. KJ and KBr for example elicit taste sensations which lie in between salty and bitter and Pb-Acetate between sweet and sour. Henning noted that the sensation elicited by a single substance is qualitatively different from the taste sensation elicited by a mixture of two substances (see the citation in the previous paragraph). The taste quality of Pb-Acetate solution cannot be equated by a mixture of sucrose and HCl for example. A few years later Von Skramlik (1922) demonstrated the contrary. Von Skramlik (1922) showed that the taste of several anorganic salts cannot be distinguished from the taste of mixtures containing two or more of the substances sucrose, NaCl, quinine-HCl, and tartaric acid.

Baryscheva (1926) suggested that the taste of 20 common food products like apples, pears, beer, coffee and tea can be

equated by particular mixtures of sucrose, oxalic-acid, quinine-HCl, and NaCl.

Von Skramlik (1926, p. 451) held the view that the degree of homogeneity or heterogeneity of the percept of a mixture depends on the nature and the concentrations of the mixture's constituents. With respect to NaCl-quinine mixtures von Skramlik noted "Wohl aber steht fest, daß bei Zufügung von immer mehr NaCl zur Chininlösung sehr bald eine Stufe erreicht wird, von der ab jede Mischung bitter und salzig schmeckt, die beiden Bestandteile also sinnlich nebeneinander bestehen, und willkürlich mit der Aufmerksamkeit festgehalten werden können." According to Von Skramlik the taste qualities sour-salt, sweet-salt and sweet-sour lead easily to the fusion of taste qualities although fusion occurs at particular concentrations only. The taste qualities bitter and sweet do not fuse well, and the taste qualities bitter-salt, and bitter-sour do not fuse at all.

In one of the first extensive and systematic studies specifically aimed at the assessment of the taste quality of mixtures, Hambloch & Püschel (1928) developed a scheme for the quality of binary taste mixtures. These authors prepared several binary mixtures of quinine-HCl, NaCl, tartaric acid and sucrose. They distinguished between five different phenomena, when two suprathreshold concentrations of two dissimilar tasting substances e.g. A and B are mixed.

- 1) The mixture has a homogeneous taste quality identical to the quality of unmixed A. The taste quality of B is completely suppressed.
- 2) The mixture has a homogeneous taste quality which is not identical to the quality of unmixed A. The taste quality of B cannot be identified however.
- 3) The mixture has a heterogeneous taste quality in which both taste qualities can be easily recognized and the attention can be switched from the quality of component A to the quality of component B and vice versa.

- 4) The mixture has a homogeneous taste quality in which the quality of A cannot be identified. The taste quality of the mixture however is not identical to that of unmixed B.
- 5) The mixture has a homogeneous taste quality identical to the quality of unmixed B, and the taste quality of A is completely suppressed.

After this study was published, three decades passed before more research on the taste quality of mixtures was done.

Gregson (1966) found that the taste quality of weak sucrose-NaCl stimuli was not always recognized as being sweet or salty, but sometimes was recognized as being sour and bitter.

Moskowitz (1972) applied the method of magnitude estimation in a study using mixtures of sweet tasting substances (glucose and fructose) with either a salty (NaCl), a sour (citric acid), or a bitter (quinine-SD<sub>4</sub>) tasting substance. He concluded that "Mixtures of sweet and salt developed an 'unblended' or 'clashing' taste, in which the components alternated in attempting to dominate the taste percept. Sweet mixed with either sour or bitter blended in almost all proportions." He in addition noted that the quality of sweetness was changed in a different way by different taste substances.

Welsh et al. (1979), cited by Schiffman & Erickson (1980), carried out an experiment in which subjects were presented with a large number of unmixed compounds and a large number of binary mixtures. They were instructed to decide whether the resulting taste quality was 'unitary', or whether they tasted a mixture. The results showed that binary mixtures were not as frequently judged as containing more than one taste quality than the unmixed stimuli. According to Schiffman & Erickson (1980) this observation shows that new taste qualities emerge when two dissimilar tasting substances are mixed together. Welsh et al. (1979) observed, that subjects often cannot identify correctly the two taste substances in a mixture.

From the literature reviewed above, it is apparent that the

question of whether new taste qualities emerge in mixtures is still not resolved. The following citation from Bartoshuk & Gent (1985) gives an indication of why this question remains unanswered "The stumbling block now, as in the day of Keesow and Oehrwall, is the meaning of "qualitatively different". Suppose we mix quinine and sucrose. We describe the mixture as "bittersweet". The description sounds analytic since it implies recognition of both the bitter and sweet components. However, one can argue that the mixture really has a new taste quality that is similar to bitter and to sweet and that we simply lack a name for the new quality...."

### 3.2. Intensity of mixtures of qualitatively dissimilar tasting substances

Questions concerning the taste intensity of mixtures with dissimilar tasting substances can be divided into three interrelated issues. The first issue is whether or not the specific taste intensity of a particular taste substance, e.g. sweetness of sucrose is altered by the presence of another taste substance with another taste quality, e.g. NaCl. The second issue concerns the relationship between the taste intensity of the mixture and the taste intensities of the mixture's constituents when they are tasted outside the mixture. In the case of sucrose-NaCl mixtures this question might be phrased; What is the relationship between the total taste of the mixture, and the sweetness of the sucrose component when tasted alone and the saltiness of NaCl when tasted alone. This issue is similar to the question which is raised, when two qualitatively similar tasting substances are mixed. A third issue focuses on the relationship between the specific taste intensities of the mixture and the total taste intensity of the mixture. What, for example, is the relationship between the total taste intensity of a sucrose-NaCl mixture, and the sweetness and saltiness of such a mixture ?

The first issue has been investigated by a large number of investigators. The second issue has been investigated less frequently, and there are no studies concerning the third issue, although several investigators have made implicit assumptions about the relationship between the specific taste intensities and the total intensity of a mixture. The literature on the second and third issue will be discussed in one paragraph.

### 3.2.1 Specific taste intensity of a tastant in the presence another dissimilar tasting substance

The first evidence collected on this issue are citations by Kiesow (1894, 1896) and Oehrwall (1891) of some general notes made by earlier nineteenth century investigators. Kiesow (1894, 1896) and Oehrwall (1891) disagreed about the interpreting the observations of these authors. Oehrwall discounted most reports, whilst Kiesow tended to take them more seriously. This work will not be discussed here, because most of these earlier general notes were anecdotal and not based on experimental observations.

One of the first experimental observations on the comparison of the specific taste intensity of a particular taste substance tasted alone with the specific taste intensity of the same substance in the presence of another comes from Zuntz (1892). He observed that a mixture of 0.35 M sucrose and a subthreshold concentration of NaCl (0.017 M NaCl) tasted just as sweet as a 0.44 M sucrose solution. Apparently the sucrose/NaCl mixture had an higher sweetness intensity than the corresponding unmixed sucrose concentration.

Kiesow (1896, p. 267) noted that in binary mixtures of dissimilar tasting substances, the specific taste intensities of both components are suppressed. Kiesow also observed that this mutual suppression was not symmetrical. "So wirkt Salz intensiver auf Süß, als umgekehrt. Im selben Sinne wirkt Salz auf einigen Stufen stärker auf Sauer und Bitter ein, als die letzteren

Qualitäten auf das Salzige. In gleicher Weise ist die Wirkung des Säuren auf Süß und namentlich auf Bitter eine intensivere, als im umgekehrten Falle, während in einer Combination von Süß und Bitter die Wirkung der beiden Componenten wenigstens auf unteren Stufen ziemlich die gleiche ist. Auf mittleren Concentrationsstufen scheint nach meinen Resultaten das Süße, auf den höchsten dagegen wieder das Bittere leicht zu Ueberwiegen".  
Kiesow (1896) did not attempt to quantify these effects.

Heymans (1899), cited by Kremer (1917) and Pangborn (1960), found that the thresholds of HCl, NaCl and sucrose were raised by the addition of suprathreshold concentrations of one of the other components.

Kremer (1917) was probably one of the first taste investigators who had numerical ratings assigned to taste intensities. Kremer (1917) being his own subject, judged the sweetness intensity of individual sucrose stimuli and of mixtures of sucrose with subthreshold concentrations of quinine-HCl, NaCl, HCl,  $H_2SO_4$ , quinine-HCl + HCl, quinine-HCl + NaCl and HCl + NaCl. He observed that salty and sour tasting substances enhance the sweet taste, when added to a sucrose solution. A subthreshold concentration of quinine suppresses the sweet taste, when added to a sucrose solution. He also reported that suppressing and enhancing substances could cancel each other's effect.

Although the investigation of Hambloch & Püschel (1928) was primarily aimed at establishing the taste quality of mixtures the results of this study suggest that the four taste qualities suppress each other. For binary mixtures of sucrose, NaCl, quinine-HCl and tartaric acid, it was shown that one component can completely suppress the intensity of the other component. They also found that one component can suppress the intensity of the other component in such a way that the specific quality of the suppressed component cannot be recognized. With respect to mixtures in which both components can be recognized, Hambloch & Püschel (1928, p. 148) noted that "Hervorzuheben ist, daß sich in den Mischungen dieses Bereiches die beide Komponenten gegenseitig

beeinflussen, so daß sie gegenüber den in gleicher Weise mit destilliertem Wasser verdünnten Bestandteilen in der Intensität geschwächt ... erscheinen."

Cragg (1937), cited by Pangborn (1960) and Von Skramlik (1962) observed the sourness of HCl was decreased by sucrose, but was unaffected by NaCl.

In an extensive study Fabian & Blum (1943) found that subthreshold concentrations of NaCl decreased the sourness of various acids but increased the sweetness of a number of sugars, e.g. sucrose, fructose, glucose, lactose and maltose. Subthreshold concentrations of HCl and acetic acid decreased the sweetness of glucose but they had no effect on the sweetness of sucrose. Sucrose sweetness was decreased by the addition of subthreshold concentrations of lactic, malic, citric, and tartaric acid. The sweetness of fructose was decreased by adding subthreshold concentrations of lactic, malic, acetic, and tartaric acid but it was not affected by the addition of subthreshold concentrations of HCl and citric acid. The addition of subthreshold concentrations of most acids increased the saltiness of NaCl. Subthreshold concentrations of the sugars decreased the saltiness of NaCl, and the sourness of acids.

In mixtures of dissimilar tasting substances, Cameron (1947) found that a mixture of 5 % (= 0.15 M) sucrose and 2 % urea was equal in perceived sweetness intensity to a 3.1 % (= 0.09 M) sucrose solution. The sucrose/urea mixture thus had a lower perceived sweetness intensity than the unmixed sucrose solution.

Sjöström & Cairncross (1953) investigated the influence of NaCl and acetic acid on the sweetness intensity of sucrose. They concluded that 0.5 % NaCl (= 0.085 M) increased the sweetness of 0.15- 0.20 M sucrose, whereas 1.0 % NaCl (= 0.17 M) decreased the sweetness of 0.09- 0.29 M sucrose. A concentration range of 0.04- 0.06 % acetic acid had no effect on 0.03- 0.15 M sucrose but decreased the sweetness of a sucrose solution containing 0.18 M sucrose or more. On the other hand, it was observed that 0.03- 0.29 M sucrose decreased the sourness of 0.04- 0.006 % acetic

acid.

Gerigk (1955), cited by Von Skramlik (1962), reported that quinine-HCl, tartaric acid and glucose depressed the saltiness of NaCl. The sourness of tartaric acid was enhanced by quinine-HCl and glucose, but depressed by NaCl. Tartaric acid and quinine-HCl depressed the sweetness intensity of glucose, but NaCl enhanced the sweetness of glucose.

In an abstract, Kamenetzky & Pilgrim (1958) noted that sucrose did not affect the saltiness of NaCl but depressed the bitterness of caffeine.

Von Skramlik (1962) published the results of some extensive investigations on how the detection and recognition thresholds of NaCl, glucose, tartaric acid and quinine-HCl are altered by the addition of suprathreshold concentrations of another component. Von Skramlik (1962) reported that the presence of one component raised both the detection as well as the recognition threshold for the other component. There were a few exceptions however. Suprathreshold concentrations of quinine-HCl lowered the detection and recognition threshold of tartaric acid and suprathreshold concentrations of tartaric acid lowered the thresholds of glucose and NaCl.

From the end of 1950's until the end of the 1960's the results of a number of extensive studies on the specific taste intensities of dissimilar tasting substance mixtures were published. Several of these papers started with noting that there was little knowledge about this subject, and that the results of previous studies also appeared to be contradictory. Beebe-Center et al. (1959) writing about the sweetness and saltiness of sucrose/NaCl mixtures, noted "The data are too limited, however, to allow any but the vaguest inferences concerning the general functions relating sweetness and saltiness of the compound solution to concentration of the two solutes..". Pangborn (1960) noted that "The early literature on the subject of taste interrelationships in aqueous solutions of pure compounds is confusing since conflicting conclusions were obtained from



similar experiments...", and Kamen et al. (1961) observed that "No systematic investigation of taste interactions at suprathreshold stimulus intensities has ever been reported.."

Unfortunately, the studies related to the question of the specific taste intensities of dissimilar tasting substance mixtures have not been able to resolve this issue. On the contrary, a rather complicated picture emerged. The results of these studies will be discussed separately for each of the possible binary combinations of sweet, salt, sour and bitter.

#### Sweet-salt

Beebe-Center et al. (1959) observed that the saltiness of sucrose/NaCl mixtures is lower than the saltiness of the corresponding unmixed NaCl solution although this difference was only marginal for mixtures with a low sucrose concentration. Pangborn's (1960, 1962) observations are in line with those of Beebe-Center et al. (1959). Kamen et al. (1961) concluded however that "Sucrose had no general enhancing or masking effects on saltiness.." Indow (1969) concluded that sucrose/NaCl mixtures are just as salty as the corresponding unmixed NaCl concentrations when tasted alone except for one specific NaCl level (0.21 M).

The sweetness of sucrose/NaCl mixtures is higher than the corresponding unmixed sucrose solution when both the NaCl and the sucrose concentration is low (Beebe-Center et al., 1959; Indow, 1969; Kamen, et al. 1961; Pangborn, 1962). At higher NaCl and sucrose levels the results are less clear. Indow (1969) found that most sucrose/NaCl mixtures are just as sweet as the unmixed sucrose solutions. However the results of the other studies suggest that the sweetness of sucrose/NaCl mixtures is lower than the sweetness of unmixed sucrose. The difference in sweetness between the sucrose/NaCl mixture and unmixed sucrose seems to increase when both the NaCl and the sucrose concentration increases (Beebe-Center et al., 1959; Kamen et al., 1961;

Pangborn, 1962).

#### Sweet-sour

Sweet-sour mixtures were investigated by Gregson & McCowen (1963), Indow (1969), Kamen *et al.* (1961), Pangborn (1960, 1961), and Stone, Oliver, & Kloehn (1969).

Gregson & McCowen (1963) investigated weak sucrose-citric acid mixtures and concluded that some subjects perceive sucrose/citric mixtures as sweeter than the corresponding unmixed sucrose solutions whereas other subjects perceive the mixture as being less sweet. Kamen *et al.* (1961) concluded that suprathreshold sucrose/citric acid mixtures are generally sweeter than sucrose tasted alone. Pangborn (1960) observed that (sub)threshold concentrations of citric acid depress the sweetness. This suppressing effect of citric acid was also found at suprathreshold levels (Pangborn, 1961). Stone, Oliver, & Kloehn (1969) reported that the sweetness of glucose, fructose, and glucose-fructose mixtures is reduced by about 50 %, when the pH of the stimuli, manipulated by citric acid, was reduced from 5.8 to 2.7. Indow (1969) found that sucrose/tartaric acid mixtures are slightly sweeter than unmixed sucrose at some concentration levels of both components.

The sourness of sweet-sour mixtures appears to be lower than the sourness of the corresponding unmixed acid (Kamen *et al.*, 1961; Pangborn, 1960). This appears to be a general rule, although some investigators found some exceptions. Gregson & McCowen (1963) obtained different results for different subjects. Indow (1969) also reported some exceptions to this rule.

#### Sweet-bitter

The complex and contradictory results of various experiments is well illustrated by a few citations on the sweetness of sucrose/caffeine or sucrose/quinine-SO<sub>4</sub> mixtures.

Pangborn (1960) observed that "Caffeine, at both threshold (0.001 M) and sub-threshold levels (0.0008 M) had a great depressing effect on the sweetness of sucrose..". With respect to the sweetness of suprathreshold sucrose/caffeine mixtures however, Kamen et al. (1961) noted that "...No variables affected sweetness other than the sucrose concentrations themselves...". Indow (1969) obtained a mixed result with mixtures of sucrose and quinine- $\text{SO}_4$ . Sucrose/quinine- $\text{SO}_4$  mixtures were less sweet than unmixed sucrose at high quinine- $\text{SO}_4$  concentrations.

The effect of sweetness upon the bitterness seems clearer. Sucrose/caffeine and sucrose/quinine- $\text{SO}_4$  mixtures are less bitter than the corresponding unmixed bitter substances (Indow, 1969; Kamen et al., 1961; Pangborn, 1960).

#### Salt-sour

According to Pangborn (1960) citric acid reduced the saltiness of NaCl. Kamen et al. (1961) concluded however that the saltiness of NaCl was generally enhanced by citric acid. Indow (1969) observed that NaCl/tartaric acid mixtures were of about the same saltiness as the unmixed NaCl stimuli except for mixtures containing a low NaCl concentration and a high tartaric acid concentration. The latter mixtures had a higher saltiness intensity than the unmixed NaCl concentration.

Pangborn (1960) found that subthreshold concentrations of NaCl reduced the sourness of citric acid. Kamen et al. (1961) obtained a rather complex result on the sourness of NaCl/citric acid mixtures. High levels of NaCl tended to enhance the sourness of lower citric acid concentrations but depressed the sourness of higher citric acid concentrations. Low NaCl concentrations appeared to depress sourness. Indow (1969) observed that one particularly concentrated NaCl solution (0.21 M NaCl) enhanced the sourness of lower and of intermediate concentrations tartaric acid. Other NaCl concentrations did not have an effect.

### Salt-bitter

Pangborn (1960) noted that subthreshold and threshold caffeine concentrations reduced the saltiness of NaCl, whereas Kamen *et al.* (1961) recorded that they found no effect. These authors noted however that high caffeine levels might enhance saltiness. Indow (1969) concluded that high levels of tartaric acid enhanced the saltiness of low concentration of NaCl.

Subthreshold and threshold concentrations of NaCl reduce the bitterness of caffeine (Pangborn, 1960). Kamen *et al.* (1961) found no effect of NaCl on the bitterness of caffeine. Indow (1969) observed that all NaCl concentrations reduced the bitterness of all but the lowest quinine-SO<sub>4</sub> concentration.

### Sour-bitter

Pangborn (1960) observed that (sub)threshold concentrations of caffeine reduced the sourness of citric acid. Kamen *et al.* (1961) obtained an opposite result, i.e. these authors found that caffeine enhanced the sourness of citric acid. To complete the picture, Indow (1969) reported that high concentrations of quinine-SO<sub>4</sub> reduced the sourness of low and high concentrations of tartaric acid. The sourness of intermediate concentration levels of tartaric acid was unaffected.

When subthreshold or a threshold concentration of citric acid is added to a caffeine solution, the bitterness is reduced (Pangborn, 1960). However, Kamen *et al.* (1961) observed that "Citric acid very markedly enhanced bitterness...". Indow (1969) observed moderate enhancement at intermediate levels of tartaric acid and lower levels quinine-SO<sub>4</sub>.

### Summary

The results may be best summarized by the notion that with almost all possible binary combinations of sweet, salt, sour and

bitter tasting substances, anything may occur. The specific taste intensities of a particular mixture may be lower, equal to, or higher than the specific taste intensities of the mixture's constituents tasted independently. There is no agreement about the effect of the addition of one particular taste component to another. There are however a few consistent observations. All studies seem to agree with the observation that sucrose/NaCl mixtures containing a low concentration of both components have a higher perceived sweetness intensity than the corresponding unmixed sucrose stimuli. Another consistent observation is that mixtures of sucrose and a bitter substance taste less bitter than the unmixed bitter component. It appears that most effects depend on the concentration levels of both substances. As Kamen *et al.* (1961) noted, "...what happened at near-threshold stimulus concentrations was not necessarily predictive of suprathreshold phenomena...". Another observation is that the frequency of suppression is higher than the frequency of enhancement.

As can be inferred from the above summary, there was some confusion in the state of knowledge on this issue at the beginning of the 1970's. The next decade did not bring clarity.

Moskowitz (1971) reported that the addition of one particular concentration of a tastant to a series of concentrations of another tastant does not affect the exponent of the psychophysical power function for the other component. Because Moskowitz (1971) did not use a standard or modulus in this experiment, the intercepts of the power functions could not be determined. It could not be established whether or not the absolute levels of the specific taste intensities were affected. In another experiment published one year later, Moskowitz (1972) observed that NaCl, citric acid and quinine- $\text{SO}_4$  functioned primarily to depress the sweetness of glucose and fructose. There were some cases however in which enhancement occurred.

Bartoshuk (1975) prepared six binary, six tertiary and one quaternary mixtures of moderately intense concentrations of sucrose, HCl, sucrose, and quinine-HCl. Subjects judged each of

the single substances and each of the mixtures simultaneously on sweetness, saltiness, bitterness, and sourness. The results showed that some of the mixtures had an higher specific taste intensity than the corresponding unmixed tastant. In most cases however the specific taste intensity was lower than the specific taste intensity of the unmixed component.

At the end of the 1970's attention shifted from actually describing the taste interactions, towards efforts to localize the taste interactions. As it was well known that two taste substances may affect each other's specific taste intensity when mixed the question now became at which phase in the transduction process these taste interactions occurred (Kroeze, 1978, 1979; Lawless, 1979). This type of research has continued until the present day. The present review does not concern itself with these developments.

### 3.2.2. Taste intensity of a mixtures in relation to taste intensities of the mixture's components when tasted independently.

The relationship between the taste intensity of a mixture of dissimilar tasting substances and the taste intensities of the unmixed components can be studied in a way similar to studying such relationship in mixtures of similar tasting substances. In the discussion on the taste interaction between similar tasting substances, it was noted that the taste interaction in these type of mixtures was usually described by a comparison of the taste intensity of the mixture with the sum of the taste intensities of the mixture's components when tasted independently. The same holds for the relationship between the taste intensity of a mixture of dissimilar tasting substances and the taste intensities of it's unmixed components. It is usually described by a comparison of the taste intensity of a mixture with the sum of the taste intensities of the mixture's unmixed components.

Although this issue had received attention from Kissew (1896), only a few investigators have addressed it again.

relationship between the total taste intensity of mixtures with dissimilar tasting substances and the specific taste intensities of these mixtures.

#### 4. SUMMARY

A brief outline is given here of the state of knowledge of the psychophysics of taste mixtures as it was at the end of the 1970's. Although the amount of energy devoted to taste mixtures is impressive the same cannot be said from the state of knowledge in this area. The issues addressed in taste mixture research are less simple than is apparent at first sight.

With respect to mixtures of qualitatively similar tasting substances, in virtually all studies it has been reported that the taste intensity of a particular mixture is equal to or more than the sum of the taste intensities of the mixture's constituent components when tasted alone. However, most of these results can be explained on the basis of the psychophysical mixture model introduced by Bartoshuk & Cleveland (1977). According to this model the taste interaction between two taste substances can be predicted by the forms of the psychophysical functions of the mixture's constituent components.

Research on mixtures of qualitatively dissimilar tasting substances focused on two main issues; the taste quality of those mixtures, and their taste intensity.

With respect to the assessment of the taste quality of mixtures of qualitatively dissimilar tasting substances little progress has been made since the end of the nineteenth century. At that time it was already known, that the taste qualities of individual taste substances can be identified in mixtures. The debate is still going on, on whether or not new taste qualities emerge (McBurney & Gent, 1979; Schiffman & Erickson, 1980).

In mixtures of two qualitatively dissimilar tasting substances the specific taste intensities may be lower than, equal to, or greater than the the specific taste intensities of

Kiesow (1896, p. 265) noted that "Die Intensität einer Mischempfindung entspricht somit nicht einer Summe der Stärkegrade der in sie eingehenden Empfindungselemente..". He did not attempt to quantify this statement.

It took about 75 years before this issue was again considered. Pfaffmann *et al.* (1971) obtained a similar conclusion to Kiesow, "When two substances are mixed, the intensity of the mixture is less than the intensity of the components tasted independently..". Pfaffmann *et al.* (1971) drew this conclusion on the basis of the results of Beebe-Center *et al.* (1959) on the specific taste intensities of sucrose/NaCl mixtures.

Moskowitz (1972) drew a similar conclusion for mixtures of each of the sweeteners glucose and fructose with each of the substances NaCl, citric acid and quinine- $\text{SO}_4$ . He concluded that the total taste intensities of the mixtures was about 50 % of the sum of the specific taste intensities of the mixtures' unmixed components.

Bartoshuk (1975) also arrived at a similar conclusion for binary, tertiary and quaternary mixtures of sucrose, NaCl, quinine-HCl and HCl.

When the line of reasoning of the three latter studies is examined more closely, it becomes apparent that in each of them one untested assumption is made. The total taste intensity of a mixtures must be equal to the sum of the specific taste intensities of that mixture. Pfaffmann *et al.* (1971) assume for example that the total taste intensity of a sucrose/NaCl mixture is the sum of the sweetness and saltiness of that mixture. Moskowitz (1972) and Bartoshuk (1975) follow this same line of reasoning. Although this assumption might be valid there is no experimental evidence that the total taste intensity of a heterogeneous taste percept is equal to the sum of its specific taste intensities. This implies that the conclusions of the latter studies may or may not be valid depending on the validity of the underlying assumption.

It will now be clear that no research has been done on the



the unmixed components. Which effect occurs depends on the nature, concentrations and composition of the mixture's components. There have been a few consistent observations, in what is otherwise a substantial amount of contradictory results. One consistent observation is that the sweetness of sucrose/NaCl mixtures with low concentration of both substances are sweeter than the sweetness of the corresponding unmixed sucrose concentration. Two other consistent observations are that the sourness of sweet-sour mixtures, and the bitterness of sweet-bitter mixtures is lower than the corresponding unmixed sour and bitter components.

The relationship between the total taste intensity of a mixture and the specific taste intensities of the unmixed components is unknown. The same applies to the relationship between the total taste intensity of a mixture and the specific taste intensities of the mixture itself.

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### CHAPTER THREE

#### A PSYCHOPHYSICAL INVESTIGATION OF BEIDLER'S MIXTURE EQUATION

Cees De Graaf & Jan E.R. Frijters

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## A psychophysical investigation of Beidler's mixture equation

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**Abstract.** Beidler's mixture equation (1971) describes the relationship between the concentration and composition of a binary mixture and the magnitude of the neural response. Later this equation was generalized to a psychophysical level. The purpose of the present study is to show that Beidler's mixture equation can be tested appropriately with indirect psychophysical methods, without the necessity of making assumptions about the magnitude of the maximum responses to the single compounds which constitute the mixture. Experiments were carried out using glucose and fructose as tastants. Concentrations of fructose and three equiratio mixture types containing glucose and fructose were matched in perceived sweetness intensities to five different glucose concentrations using the method of constant stimuli. The results showed that Beidler's mixture equation describes accurately the taste interaction between glucose and fructose at low sweetness levels. At high sweetness levels the taste system is more efficient, as could be expected on the basis of Beidler's mixture equation, because the experimentally determined mixture concentrations were lower than those predicted by the mixture equation. The findings suggest that glucose and fructose share common receptors, but that either one or both have additional secondary binding mechanisms.

### Introduction

In his theory of taste stimulation, Beidler (1954) postulated that the adsorption of stimulus molecules to receptor sites elicits a neural response of a magnitude proportional to the number of occupied receptor sites. Because the number of receptor sites is limited, the response magnitude approaches asymptotically to a maximum response at very high stimulus concentrations. According to Beidler's occupation theory, the quantitative relationship between the neural response and stimulus concentration can be described by the following equation:

$$R = \frac{KCR_s}{1 + KC} \quad (1)$$

where  $R$  = magnitude of the response, in most electrophysiological studies, this is the integrated whole nerve *chorda tympani* response;  $R_s$  = maximum response at very high stimulus concentrations;  $C$  = stimulus concentration;  $K$  = association constant reflecting the strength of binding between stimulus molecules and receptor sites.

Beidler's taste equation adequately describes electrophysiological responses obtained with various taste substances for several species, for example, for sodium salts in the rat, the hamster (Beidler, 1953, 1954; Kimura and Beidler, 1961), and the primary taste receptor in the blowfly (Evans and Mellon, 1962); for sucrose in the rat (Hagström and Pfaffmann, 1959; Tateda and Hidaka, 1966; Hiji and Imoto, 1980), hamster (Beidler *et al.* (1955), gerbil (Jakinovich, 1976; Jakinovich and Goldstein, 1976; Jakinovich and Oakley, 1976), and the labellar sugar receptor in the fleshfly (Morita and Shiraishi, 1968). According to Jakinovich and associates, Equation 1 adequately describes the concentration-neural response relationship in the gerbil for various disaccharides (Jakinovich, 1976), monosaccharides (Jakinovich and Goldstein, 1976), sugar alcohols (Jakinovich and Oakley, 1976), methyl esters of glycopyranosides (Jakinovich, 1985)

and saccharine (Jakimovich, 1982). However, electrophysiological responses to glucose and fructose obtained from the labellar sugar receptor of the fleshfly (Morita and Shirai-shi, 1968), and from the rat's *chorda tympani* (Tateda and Hidaka, 1966; Hiji and Imoto, 1980) did not concur with Beidler's taste equation. This was also the case for data from the gerbil's *chorda tympani* response to fructose (Jakimovich and Goldstein, 1976).

Although Beidler's theory accounts for a large amount of experimental data, this theory does not account for several phenomena related to the time course of the neural response to taste stimuli. Beidler's theory predicts the steady state response to taste stimuli. It does not contain a parameter or parameters related to the initial high-rate transient response observed in the neural recording of the taste response (Faull and Halpern, 1972; Smith *et al.*, 1975; Kashiwagura *et al.*, 1980). Marowitz and Halpern (1977) and Bealer (1978) suggested that the initial transient response is essential for intensity discrimination between taste stimuli. To account for this phenomenon other more detailed models have been developed (Heck and Erickson, 1973; Smith *et al.*, 1975; Kamo *et al.*, 1980).

There is only one analysis, carried out by Beidler (1961) himself, in which the taste equation has been applied to human psychophysical data. His findings suggest that the taste equation concurs with an accumulated JND-scale constructed by Lemberger (1908).

In addition to the equation for single compounds, Beidler (1962, 1971) proposed a mixture equation to describe the peripheral interaction of two taste substances under the condition that the stimulus molecules of both substances compete for adsorption at the same receptor sites. According to this mixture model, the magnitude of the response to a mixture of concentration  $i$  of substance A ( $=C_{ai}$ ), and concentration  $j$  of substance B ( $=C_{bj}$ ) is given by:

$$R_{abij} = \frac{K_a C_{ai} R_{sa} + K_b C_{bj} R_{sb}}{1 + K_a C_{ai} + K_b C_{bj}} \quad (2)$$

where  $R_{abij}$  = response to the mixture;  $R_{sa}$ ,  $R_{sb}$  = maximum responses to substances A and B, respectively;  $K_a$ ,  $K_b$  = association constants of substances A and B, respectively.

This mixture equation has been tested in five electrophysiological studies. The results obtained in two studies, one with sorbitol-sucrose mixtures (Jakimovich and Oakley, 1976), and one with mixtures of sucrose and methyl  $\alpha$ -D-glycopyranoside (Jakimovich and Goldstein, 1976) were in agreement with the mixture equation. The data obtained in an experiment on sucrose-saccharine mixtures were not in agreement with the mixture equation (Jakimovich, 1982). According to Jakimovich, the reason for such failure is that sucrose and saccharine have different independent receptor sites. In two other experiments the data obtained also did not concur with the predictions from the mixture equation (Tateda and Hidaka, 1966; Morita and Shiraiishi, 1968). However, in these latter studies, the responses to the unmixed compounds deviated from the function fitted on the basis of Beidler's equation for single compounds. The results of studies investigating mixtures of these deviating substances can therefore not be accepted as valid tests of the mixture equation.

Not only electrophysiological research has been carried out. Curtis *et al.* (1984) evaluated the mixture equation in a psychophysical experiment using the method of magnitude estimation (Stevens, 1975). They concluded that Beidler's mixture equation provides

'... an excellent description of the psychophysical relation for mixture data, if it is assumed that a non-linear response transformation is introduced in judgement'. Unfortunately, the shape of such a non-linear response output transformation is generally not known (Veit, 1978; Rule and Curtis, 1980; Birnbaum, 1980). A non-linear response output function implies that the responses obtained are not linear with perceived taste intensity; even if the relationship between a tastant's concentration and its perceived intensity could in principle be described by Beidler's taste equation, a psychophysical power function obtained by magnitude estimation obscures this relationship.

Another problem also encountered when attempting to test Beidler's mixture equation in a psychophysical experiment is the experimental determination of the maximum response to a particular substance. For example, sweet substances have side tastes (Cameron, 1947; Schiffman *et al.*, 1979; Kuznicki and Ashbaugh, 1979), which are more pronounced at high intensities than at low intensities (McBurney, 1978), and these side tastes may interfere with the maximum response to sweetness itself. In addition, the increased viscosity at high concentrations may affect the sweetness response (e.g. Christensen, 1980; Izutsu *et al.*, 1981).

The present paper reports a different type of psychophysical test of Beidler's mixture equation. The methodology was developed with the specific aim in mind of bypassing the two serious problems referred to above, i.e. the unknown relationship between perceived taste intensity and observable response, and the necessity of the experimental determination of the maximum response.

The fundamental question may arise whether a structure-activity theory can be generalized to the level of sensory perception. As Beidler (1961) and Curtis *et al.* (1984) have already done, we take this philosophical issue for granted. Although many events intervene between stimulus binding at the receptor level and elicitation of sensation at a central level, we assume that there is a linear relationship between these two levels. In electrophysiological studies a similar linear correspondence between receptor activity and the whole nerve *chorda tympani* response is assumed. Generalization of Beidler's theory to the psychophysical level is one step further. This extension of the theory seems to be warranted since several studies (Erickson, 1963; Diamant *et al.*, 1965; Borg *et al.*, 1967; Ganchrow and Erickson, 1970; Stevens, 1970; Smith, 1974) have demonstrated that there is a simple functional relationship between neural and behavioural responses. However, we agree with Beidler (1978), that '... the success of the taste equation is not necessarily evidence that the theory on which is based is correct ...'.

## Theory

In this section, it is shown logically that Beidler's mixture equation leads to simple and testable predictions of the intensity of mixtures of two substances. Since these predictions can be tested with indirect instead of direct psychophysical methods, possible artefacts resulting from an unknown response transformation are excluded. Moreover, as follows from the derivations made below, predictions of mixture intensities are independent of the maximum responses to the mixture's constituent components. Therefore, assumptions about the magnitude of the maximum responses to the single compounds are unnecessary.

Analogously to Beidler (1954), let the concentration-sensory response relationships

for the substances A and B be given by:

$$R_{ai} = \frac{K_a C_{ai} R_{sa}}{1 + K_a C_{ai}} \quad (3)$$

and

$$R_{bj} = \frac{K_b C_{bj} R_{sb}}{1 + K_b C_{bj}} \quad (4)$$

where  $R_{ai}$ ,  $R_{bj}$  = the response to concentration  $i$  of substance A ( $= C_{ai}$ ), and concentration  $j$  of substance B ( $= C_{bj}$ ), respectively;  $R_{sa}$ ,  $R_{sb}$  = maximum responses to substance A and B, respectively;  $K_a$ ,  $K_b$  = association constants of substances A and B, respectively.

According to Equation 2, the response to a mixture containing a particular concentration  $X$  of substance A ( $= X$ ) and a particular concentration  $Y$  of substance B ( $= Y$ ) is given by:

$$R_{abXY} = \frac{K_a X R_{sa} + K_b Y R_{sb}}{1 + K_a X + K_b Y} \quad (5)$$

Assume that a particular concentration  $i$  of substance A ( $= C_{ai}$ ) evokes a response of the same magnitude as the response to concentration  $j$  of substance B ( $= C_{bj}$ ), i.e.  $R_{ai} = R_{bj}$ . The question may now arise as to what is the total concentration and composition of possible mixtures of A and B, which give rise to a response identical to  $R_{ai}$  and  $R_{bj}$ . Inferences made from Beidler's mixture equation provide a general, but simple answer to this question.

Expressed in terms of Equation 5, this question can be stated as follows: what mixtures composed of a certain concentration  $X$  of substance A and a certain concentration  $Y$  of substance B give rise to a response equal in magnitude to responses to  $C_{ai}$  ( $= R_{ai}$ ) and to  $C_{bj}$  ( $= R_{bj}$ ), provided that  $R_{ai} = R_{bj}$ ?

The condition that the responses to  $C_{ai}$  and to  $C_{bj}$ , and to each mixture of a series of mixtures of substances A and B, containing the concentration  $X$  (of A) and  $Y$  (of B) are equal to a response magnitude  $R$ , can be expressed as:

$$R = R_{ai} = R_{bj} = R_{abXY} \quad (6)$$

If the parameter  $R_{ai}$  in Equation 3 is substituted by  $R$  using Equation 6, then the parameter  $K_a$  in Equation 3 can be expressed as follows:

$$K_a = \frac{R}{C_{ai}(R_{sa} - R)} \quad (7)$$

Analogously,  $K_b$  in Equation 4 can be written as:

$$K_b = \frac{R}{C_{bj}(R_{sb} - R)} \quad (8)$$

If the right-hand side of Equations 7 and 8 are substituted in Equation 5, thereby eliminating the constants  $K_a$  and  $K_b$ , the following equation is obtained (see Appendix 1):

$$X = C_{ai} - \frac{C_{ai} Y}{C_{bj}} \quad (9)$$

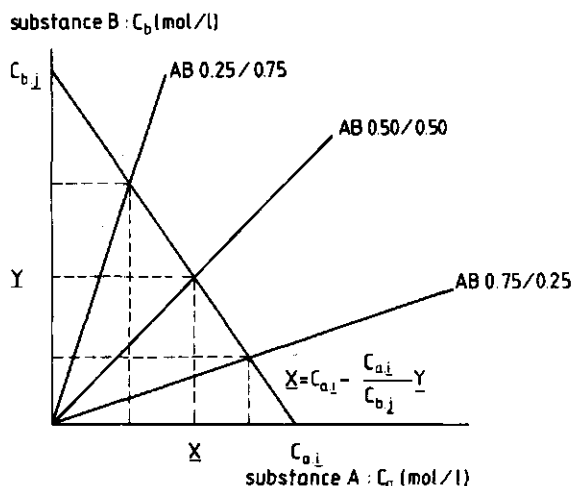


Fig. 1. Predictions derived from Beidler's mixture equation. The concentration  $C_{ai}$  of substance A gives rise to a response equal in magnitude to the response to concentration  $C_{bj}$  of substance B. According to Beidler's mixture equation, the straight line connecting  $C_{ai}$  or  $C_{bj}$  represents the series of mixtures of the substances A and B, each of which gives rise to a response equal in magnitude to the response to  $C_{ai}$  or  $C_{bj}$ . The lines from the origin represent three types of equiratio mixtures. Intersections of the lines representing the equiratio mixtures with the line connecting  $C_{ai}$  and  $C_{bj}$  define the total concentration and composition of mixtures equal in intensity to the single compound solutions. For example, the 0.50/0.50 mixture of AB that should produce a response equal to the response to  $C_{ai}$  or  $C_{bj}$  contains X M of substance A and Y M of substance B. The illustration shows that X and Y are mutually dependent, and vary with the ratio of A and B in a particular mixture. The broken lines are three examples of different mixture ratios.

Equation 9 is illustrated graphically in Figure 1, showing that this equation describes the straight line connecting  $C_{ai}$  and  $C_{bj}$ . All possible mixtures predicted to give rise to a response magnitude identical to  $R_{ai}$  and  $R_{bj}$  ( $= R$ ) are represented by the points on this line.

As shown earlier by Frijters and Oude Ophuis (1983), a mixture of X and Y can also be conceived as a solution of total concentration  $(X + Y)$  containing the fraction  $p = X/(X + Y)$  of substance A and the fraction  $q = Y/(X + Y)$  of substance B ( $p + q = 1$ ).

These authors developed the concept of 'equiratio mixture type', i.e. a series of mixtures in each of which the ratio of the constituent components is constant; a specific type of equiratio mixture is defined by the values of p and q. Making use of this concept and rearranging the terms in Equation 9 yields:

$$X + Y = \frac{C_{ai}C_{bj}}{pC_{bj} + qC_{ai}} \quad (10)$$

Equation 10 is a simple formula resulting from Beidler's mixture equation that predicts the total concentration of AB mixtures containing X (of A) and Y (of B), which produce the same response magnitude as that to  $C_{ai}$  and to  $C_{bj}$  (i.e.  $R_{ai} = R_{bj} = R_{abXY} = R$ ). In Figure 1, three equiratio mixture types with different values of p and q are represented by the lines drawn from the origin. The points at which these lines intersect with the line representing Equation 9 gives the predicted concentrations X and Y.

Equations 9 and 10 do not contain the parameters  $R$ ,  $R_{sa}$ ,  $R_{sb}$ ,  $K_a$  and  $K_b$ . This is meritorious from an experimental point of view, since elimination of these parameters makes it possible to test Beidler's mixture equation at an arbitrary level of sensory intensity, independent of the maximum responses to the single compounds. These predictions can be tested easily using indirect psychophysical scaling methods.

It should be borne in mind that there are certain limitations to the applicability of Beidler's mixture equation, and consequently restrictions on the validity of the equations derived above. As Beidler's mixture model aims to describe the peripheral interaction between two taste substances, it does not account for interactions at a higher level in the transduction process. When two qualitatively different taste substances are mixed, the intensity of the single taste qualities is affected (e.g. Beebe-Center *et al.*, 1959; Pangborn, 1961, 1962; Bartoshuk, 1975). The interaction between two qualitatively different taste qualities is not necessarily located only at the receptor level of the taste system. Smith (1974) and McBurney and Bartoshuk (1973) found no evidence for the interaction of sucrose and NaCl at the receptor site. Kroeze (1978, 1979) has shown that the interaction of sweet and salty taste occurs not at the periphery, but at a higher level in the transduction process. A similar conclusion was drawn by Lawless (1979) for bitter-sweet mixtures. Therefore, the potential validity of the above derivations is limited to mixtures of taste substances of similar taste qualities.

### Aim of the experiment

The purpose of the present study was to test the validity of Equation 9 and 10 in a psychophysical experiment. This requires the experimental determination of concentrations of the two substances (used for mixture composition), and concentrations of mixtures of these substances, all of which are perceived of as being equally intense. When the concentrations of the two unmixed compounds which give rise to an identical perceived intensity have been experimentally determined, then Equation 10 can be used to predict the concentration and composition of mixtures, which by Beidler's mixture model should give rise to identical perceived taste intensities. Evaluation of Beidler's mixture equation then consists of comparing the experimentally determined mixture concentrations (each of which has a perceived intensity equal to those of the particular concentrations of the unmixed components) with the predicted mixture concentrations (each of which according to Beidler's mixture equation should have a perceived intensity equal to those of the single compound solutions).

### Methods and materials

In this study, fructose and three equiratio mixture types of glucose and fructose (denoted by 'comparison stimuli') were matched in perceived sweetness intensity to glucose (denoted by 'reference stimulus'). Use was made of the method of constant stimuli (Guilford, 1954). Since the validity of Equations 10 and 11 may depend on the level of taste intensity, these equations were tested at five different levels. In order to obtain as precise results as possible, and to avoid range biases (Poulton, 1979) a preliminary experiment was carried out to determine the concentration levels and ranges to be used. In order to check for possible biases in the method, 10 control experiments were incorporated in the study; glucose was matched to itself at the five standard levels, and fruc-

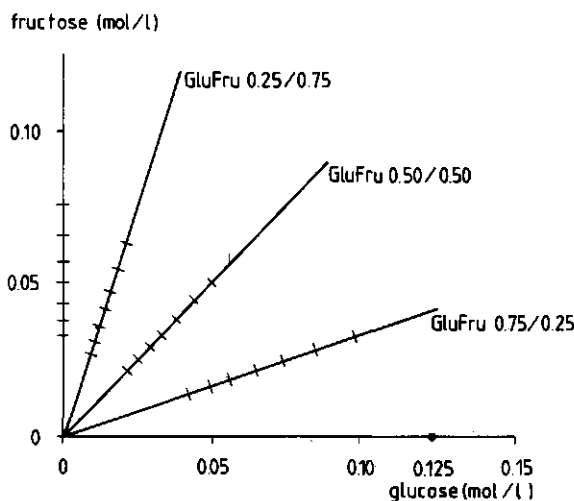


Fig. 2. Concentrations of the comparison stimuli (—) and the standard stimulus (●) in the experiments at the sweetness level corresponding to 0.125 M glucose.

tose was also matched to itself at the five levels equal in perceived sweetness intensity to the glucose standards. Thus, the entire study encompassed 30 identically designed experiments. Each of the four types of comparison stimuli were matched in perceived sweetness intensity to each of the five levels of the glucose reference ( $4 \times 5$  experiments). In addition there were the 10 control experiments.

### Subjects

The subjects were 10 paid volunteers (six men and four women) whose ages ranged from 18 to 26 years, and who were either graduate or undergraduate students of the Agricultural University. Some subjects had had previous experience with psychophysical tasks, but all were naive with respect to the substances used and the purpose of the study.

### Stimuli

The stimuli were solutions of glucose (Merck: 15639), fructose (Merck: 5321) and three equiratio mixture types (Frijters and Oude Ophuis, 1983) in demineralized water. The three equiratio mixture types were: mixtures containing three times as much glucose as fructose (GluFru 0.75/0.25); mixtures with an equal concentration of both substances (GluFru 0.50/0.50); and mixtures containing three times as much fructose as glucose (GluFru 0.25/0.75). Solutions were prepared at least 24 h before tasting.

The five concentrations used as reference stimuli were 0.125, 0.250, 0.50, 1.00 and 2.00 M glucose per litre of solution. Figure 2 illustrates the basic experimental design; it shows the concentrations of the comparison stimuli in the experiments at the sweetness level corresponding to 0.125 M glucose. The designs for the experiments at the other sweetness levels (0.25, 0.50, 1.00 and 2.00 M glucose as standard) were identical. Each standard glucose solution was compared with a series of seven geometrically spaced comparison stimuli. The middle stimulus of each series of comparison stimuli was determined from the data of the pilot experiment, and was selected so that it could be ex-



**Table I.** Middle concentrations of the series of seven comparison stimuli matched to glucose

Glucose concentration (M)	Type of comparison stimulus (M)			
	GluFru 0.75/0.25	GluFru 0.50/0.50	GluFru 0.25/0.75	Fructose
0.1250	0.0860	0.0660	0.0550	0.0500
0.2500	0.1700	0.1400	0.1200	0.1000
0.5000	0.3600	0.3200	0.2800	0.2400
1.0000	0.7300	0.6700	0.5700	0.5500
2.0000	1.6700	1.4400	1.3600	1.3100

pected to result in 50% of 'sweeter than the standard' responses. The concentrations of the middle stimulus of each of the 20 ranges are given in Table I. The width of geometric spacing within each series of comparison stimuli was also determined in the pilot study. On the basis of these preliminary data, the weakest and strongest stimulus of each series could be expected to result in 10 and 90%, respectively, of 'sweeter than the standard' responses. The width of spacing was kept constant for the four series of comparison stimuli at each level of the standard, but was varied between each of the five levels. The difference in concentration between two adjacent stimuli within each series of comparison stimuli at the sweetness level corresponding to 0.125 M glucose was 15%. Thus, as shown in Figure 2, the concentrations of pure fructose solutions compared with 0.125 M glucose were 0.0329, 0.0378, 0.0435, 0.0500, 0.0575, 0.0660 and 0.0760 M fructose. Similarly, the difference in concentration between two adjacent stimuli at the sweetness level of 0.25 M glucose was 12%; at 0.50 M glucose, 10%; at 1.00 M glucose, 8%; and at 2.00 M glucose, 15%.

The concentrations of the middle stimulus of each series of comparison stimuli in the 10 control experiments were identical to the concentrations of the reference stimuli themselves. The width of spacings for the sweetness levels varied in the same way as in the other experiments.

### *Procedure*

The method of constant stimuli was used (Guilford, 1954). The subjects were instructed to identify the sweeter stimulus of each pair, and when in doubt to guess. The subjects rinsed their mouths thoroughly with demineralized water after tasting each pair of stimuli. The instructions emphasized that only the sweetness intensity was to be judged, and that the pleasantness or unpleasantness and side tastes were to be disregarded.

The stimuli were presented at room temperature, in pairs of polystyrene medicine cups, each containing about 10 ml solution. For each level of the standard and each type of comparison stimulus, there were 14 possible pairs, i.e. seven times the standard tasted firstly and the comparison stimulus tasted secondly, and seven times in the reverse order of tasting. The 14 pairs were presented in a random order, and in a different order for each subject. The interval between pairs was 70 s.

The subjects tasted each series of 14 pairs three times. They participated in 30 1-h sessions, and tasted three series of 14 pairs at each session. The three series within each session were always of a different level and/or type of comparison stimulus.

**Table II.** Calculation procedure after Bock and Jones (1968) to determine the concentration of GluFru 0.50/0.50 mixture type (and 95% confidence interval) equal in perceived sweetness intensity to 0.50 M glucose

Concentration of comparison stimulus (M)	Natural log. of the concentration (x)	Proportion of responses 'sweeter than the standard' (= 0.50 M glucose) (N = 60)	z-score corresponding to proportion in col. 3 (y)	z-score predicted by unweighted regression ( $y_p$ ) <sup>a</sup>	Müller-Urban weight based expected z-score (col. 5) (W)
0.2404	-1.4255	0.017	-2.12	-1.93	0.1474
0.2645	-1.3299	0.150	-1.04	-1.23	0.3600
0.2909	-1.2348	0.333	-0.43	-0.53	0.5745
0.3200	-1.1394	0.533	0.08	0.18	0.6291
0.3520	-1.0441	0.783	0.78	0.88	0.4780
0.3872	-0.9488	0.967	1.84	1.58	0.2435
0.4259	-0.8536	0.983	2.12	2.29	0.0773

<sup>a</sup>Solution of unweighted regression analysis:  $y_p = 8.583 + 7.379x$ .

General solution for weighted regression analysis:

$y = \hat{a} + \hat{b}x$ , where  $\hat{b} = S_{xy}/S_{xx} = (\sum Wxy - \bar{x}\sum Wy)/(\sum Wx^2 - \bar{x}\sum Wx)$ , and  $\hat{a} = y - \hat{b}x$ .

The solution obtained is:  $y = 8.457 + 7.256x$ , so  $x = -1.1655$ , when  $y$  is set equal to zero. Taking the antilogarithm of  $-1.1655$  yields 0.3118, which is the PSE in M. The standard error around  $\ln(\text{PSE})$  is estimated by:  $[(1/b^2)(1/N\sum W) + (\bar{y}/b^2)^2(1/NS_{xx})]^{1/2}$ , in this case it is equal to 0.01125. The 95% confidence interval of  $\ln(\text{PSE})$  is then  $-1.1876 < \ln(\text{PSE}) < -1.1434$ . Taking antilogarithms yields the 95% confidence interval for the PSE in M, i.e.  $0.3050 < \text{PSE} < 0.3187$ .

## Data analysis and results

The data analysis had to result in concentrations of the comparison stimuli at each of the five levels having perceived intensities equal to those of the glucose standards. In addition, the mixture concentrations predicted by Beidler's mixture equation had to be determined, in order to compare them with the experimentally determined mixture concentrations.

On the basis of 60 responses to each comparison stimulus, the proportions of 'sweeter than the standard' responses were determined, and converted into normal deviates (z-score, Table II Col. 4). Those stimuli with a proportion of responses equal to zero or one were excluded from the analyses.

The concentrations of the points of subjective equality (i.e. experimentally determined PSEs) were obtained by applying Urban's solution for the method of constant stimuli as described by Bock and Jones (1968). This weighted linear regression analysis, which enabled the determination of confidence intervals around the PSEs, was carried out with the natural logarithm of the concentrations of the comparison stimuli as the independent variable and the z-score obtained as the dependent variable. The same computational procedure was followed for each of the 30 experiments, and it is illustrated in Table II with the data obtained for the GluFru 0.50/0.50 mixture compared with 0.50 M glucose. The Müller-Urban weights were based on the expected normal deviates calculated from a preliminary unweighted regression analysis on the same data. As the regression procedure was used with the logarithms of the concentrations, the concentration of the PSE was calculated by taking the antilogarithm of the value of the independent variable corresponding to an expected z-score of zero. This calculation

**Table III.** Concentrations of comparison stimuli equal in perceived sweetness intensity to five glucose levels; a comparison between PSEs experimentally determined and PSEs predicted by Beidler's mixture equation

Glucose concentration (M)	Type of comparison stimulus	PSE experimentally determined (M)	PSE predicted by Beidler's model (M)	Difference (%) $\frac{(PSE_{exp} - PSE_{model})}{PSE_{model}}$	95% confidence interval of PSE <sub>exp</sub>	Interval of uncertainty of PSE <sub>model</sub>
0.1250	GluFru 0.75/0.25	0.0873	0.0896	-2.6	0.0841-0.0907	0.0880-0.0912
0.1250	GluFru 0.50/0.50	0.0666	0.0699	-4.7	0.0640-0.0693	0.0679-0.0719
0.1250	GluFru 0.25/0.75	0.0558	0.0573	-2.6	0.0539-0.0580	0.0553-0.0592
0.1250	Fructose	0.0485	-	-	0.0466-0.0504	-
0.2500	GluFru 0.75/0.25	0.1817	0.1840	-1.3	0.1762-0.1873	0.1810-0.1866
0.2500	GluFru 0.50/0.50	0.1439	0.1456	-1.2	0.1388-0.1491	0.1418-0.1489
0.2500	GluFru 0.25/0.75	0.1206	0.1204	+0.2	0.1174-0.1239	0.1166-0.1238
0.2500	Fructose	0.1027	-	-	0.0990-0.1060	-
0.5000	GluFru 0.75/0.25	0.3639	0.3917	-7.1 <sup>a</sup>	0.3558-0.3722	0.3879-0.3954
0.5000	GluFru 0.50/0.50	0.3118	0.3219	-3.1	0.3050-0.3187	0.3168-0.3271
0.5000	GluFru 0.25/0.75	0.2682	0.2733	-1.8	0.2626-0.2738	0.2678-0.2788
0.5000	Fructose	0.2374	-	-	0.2319-0.2430	-
1.0000	GluFru 0.75/0.25	0.7729	0.8461	-8.7 <sup>a</sup>	0.7586-0.7874	0.8391-0.8532
1.0000	GluFru 0.50/0.50	0.6550	0.7334	-10.7 <sup>a</sup>	0.6413-0.6689	0.7229-0.7440
1.0000	GluFru 0.25/0.75	0.5928	0.6471	-8.4 <sup>a</sup>	0.5801-0.6058	0.6349-0.6595
1.0000	Fructose	0.5790	-	-	0.5660-0.5923	-
2.0000	GluFru 0.75/0.25	1.6310	1.7992	-9.3 <sup>a</sup>	1.5816-1.6819	1.7748-1.8231
2.0000	GluFru 0.50/0.50	1.4552	1.6351	-11.0 <sup>a</sup>	1.4054-1.5068	1.5952-1.6749
2.0000	GluFru 0.25/0.75	1.4007	1.4984	-6.5 <sup>a</sup>	1.3579-1.4448	1.4486-1.5490
2.0000	Fructose	1.3828	-	-	1.3268-1.4407	-

<sup>a</sup>Significant at  $P < 0.05$  level.

**Table IV.** Results of control experiments; PSEs of glucose when matched to itself at five levels, and the PSEs of fructose matched to itself at the corresponding sweetness levels (the sweetness intensity of 0.0485 M fructose is equal to the sweetness intensity of 0.125 M glucose, etc.)

Concentration and type of standard solution (M)		PSE (M)	95% confidence interval of PSE (M)	Error: (PSE - Conc. stand.) Conc. stand. (%)
Glucose	0.1250	0.1240	0.1196-0.1285	-0.80
Glucose	0.2500	0.2480	0.2411-0.2551	-0.80
Glucose	0.5000	0.4924	0.4820-0.5030	-1.52
Glucose	1.0000	1.0016	0.9847-1.0188	+0.16
Glucose	2.0000	1.9918	1.9385-2.0466	-0.41
Fructose	0.0485	0.0486	0.0468-0.0504	+0.20
Fructose	0.1027	0.1025	0.0996-0.1055	-0.19
Fructose	0.2374	0.2401	0.2341-0.2462	+1.14
Fructose	0.5790	0.5841	0.5727-0.5957	+0.88
Fructose	1.3828	1.3782	1.3364-1.4213	-0.33
Mean absolute error: 0.64%				

procedure also implies that the confidence interval is geometrically spaced around the PSE.

The experimentally determined PSEs and their confidence intervals are given in Table III, columns 3 and 6, respectively.

The results of the 10 control experiments given in Table IV show that the error in the PSEs in the control study varied between -1.5 and +1.1% with a mean absolute error of 0.6%. These results confirm the reliability of the experimental data.

Because the concentrations of glucose and fructose which give rise to an equal response magnitude are known (Table III), the derivations from Beidler's mixture equation can now be used to predict the concentrations of the mixtures that must have a perceived intensity equal to the corresponding glucose and fructose solutions. These predicted mixture concentrations (i.e. predicted PSEs) were calculated using Equation 10, and are given in Table III, column 4. As the PSEs of fructose (one of the parameters of Equation 10) have some degree of uncertainty defined by their confidence intervals, the predicted PSEs also have a certain degree of uncertainty. The lower and upper limits of these 'intervals of uncertainty' were calculated by inserting the lower and upper confidence limits of the experimentally determined PSEs of fructose into Equation 10. The 'intervals of uncertainty' of the predicted PSEs are given in Table III, column 7.

A difference between an experimentally determined and a predicted PSE was considered to be significant if the 95% confidence interval of the experimentally determined PSE did not overlap the interval of uncertainty of the predicted PSE.

Inspection of Table III reveals that at the lowest sweetness levels there were only minor deviations between experimentally determined and predicted PSEs. This was also the case for the concentrations of the GluFru 0.50/0.50 and the GluFru 0.25/0.75 mixture types of equal perceived sweetness intensity to 0.50 M glucose. However, the concentration of the GluFru 0.75/0.25 mixture type of equal perceived sweetness intensity to 0.50 M glucose was significantly lower than predicted by Beidler's mixture equation. The same holds for the experimentally determined PSEs of all three equiratio

mixture types equal in perceived sweetness intensity to 1.00 and 2.00 M glucose, respectively.

## Discussion

At low sweetness levels (0.125 and 0.25 M glucose), Beidler's mixture equation appears to predict the taste interaction between glucose and fructose with great precision; the deviation between experimentally determined and predicted PSEs was on average about -2%. However, at high sweetness levels (1.00 and 2.00 M glucose), the experimentally determined mixture concentrations were significantly lower (mean deviation was about -9%) than those predicted by Beidler's mixture equation. At the sweetness levels corresponding to 0.50 M glucose, the results were intermediate, the mean deviation being -4%.

One possible explanation for the concurrence of low sweetness levels and the discrepancy at high sweetness levels is that the conditions imposed by Beidler's mixture model are satisfied at low sweetness levels only, but not at high sweetness levels. As stated in the Introduction and Theory sections, these conditions are that the constituent components of the mixture have similar taste qualities, and that the molecules of both substances compete for the same receptor sites.

With respect to the taste qualities of glucose and fructose, a few considerations are in order. It is well established that the taste quality of a substance may change as a function of its concentration (Renqvist, 1919; Dzendolet and Meiselman, 1967; Cardello and Murphy, 1977; Bartoshuk *et al.*, 1978). Data of Kuznicki and Ashbaugh (1979) suggest that low concentrations of glucose and fructose have indeed similar taste qualities, but that taste quality differences between these substances emerge at high concentrations. Consequently, the condition that the mixture substances must have similar taste qualities seems to have been satisfied at the low concentrations of glucose and fructose used in the present experiment, but not at the high concentrations. As shown by Kroeze (1978, 1979) for sweet-salt mixtures, and by Lawless (1979) for bitter-sweet mixtures, mixing two qualitatively different substances leads to central suppression of the original taste qualities. Thus, central suppression may have occurred in the mixtures of glucose and fructose at the high sweetness levels used in this experiment. If, however, the other condition implied by Beidler's mixture model (i.e. mutual competition for the same receptor site) was met, then the occurrence of mixture suppression must have resulted in a mixture concentration higher than predicted, and not lower as was found in this experiment. Thus, the logical consequence of the explanation in terms of mixture suppression conflicts with the experimental finding that the mixture concentrations of glucose and fructose equal in sweetness intensity to 1.00 and 2.00 M glucose are lower than predicted by Beidler's mixture model. Therefore, although mixture suppression may have occurred, differences in taste quality between glucose and fructose at high sweetness levels do not explain the discrepancy observed.

The second condition imposed by Beidler's mixture equation is that the substances in a binary mixture compete mutually and exclusively for the same receptor sites. If, however, these substances stimulate other receptor sites in addition to their common receptor site, then the adsorption of one substance is less suppressed by the presence

of the other substance (and vice versa) than in the case of complete competition. Consequently, if glucose and fructose do not only compete for the same receptor sites, but either one or both also have additional independent receptor sites, then the mixture concentration necessary to elicit a response of the same magnitude as those of the single compound solutions must be lower than those predicted by Beidler's mixture equation. The experimental results are in accordance with this conclusion at the two highest sweetness levels, but not at the two lowest sweetness levels. It seems that competition at low sweetness levels, but absence of complete competition at high sweetness levels accounts for the results obtained. This explanation leads to the hypothesis that glucose and fructose share one common receptor site, but that either one or both substances have additional and different secondary binding mechanisms. The observation that glucose and fructose have similar taste qualities at low sweetness levels, but show quality differences at high sweetness levels (Kuznicki and Ashbaugh, 1979) is in line with this hypothesis. Further development of this idea requires two additional assumptions, i.e. the existence of more than one receptor site for glucose and for fructose, and a multi-molecular stimulus-receptor site interaction.

There is some experimental evidence to support the potential validity of the first assumption. Three psychophysical studies have demonstrated the existence of more than one receptor site for sweeteners (Faurion *et al.*, 1980; Schiffman *et al.*, 1981; Lawless and Stevens, 1983). The involvement of more than one type of receptor site could be concluded from absence of mutual cross-adaptation between substances (e.g. Meiselman, 1968, 1972; McBurney, 1972; McBurney *et al.*, 1972). In spite of the substantial number of cross-adaptation studies, no data for glucose and fructose are available, so that definite conclusions regarding this issue cannot be drawn.

The potential validity of the second assumption, i.e. multi-molecular interaction between receptor sites and a particular taste substance, has also been documented in the literature. Tateda and Hidaka (1966), Morita and Shiraishi (1968) and Hiji and Imoto (1980) suggested for the particular cases of glucose and fructose that more than one molecule must be adsorbed to a receptor site in order to elicit a response. Jakinovich and Goldstein (1976) obtained results from the gerbil's *chorda tympani* responses to fructose that are consistent with this idea. These observations indicate that glucose and fructose have Hill coefficients greater than one. In order to handle this situation, Beidler (1978) modified his original taste equation (which assumes a mono-molecular interaction) for a single substance, so as to include a taste substance having a Hill coefficient unequal to one. A general mixture model for mixtures of taste substances having Hill coefficients unequal to one has not yet been developed.

In the four above-mentioned studies, it was shown that sucrose has a Hill coefficient of one. Since it could be concluded from the results of these studies that glucose and fructose must have Hill coefficients greater than one, the dose-response relationships for glucose and fructose should exhibit a steeper slope than that of sucrose (Maes, 1985). This conclusion is reinforced by the results of various psychophysical experiments in which it was shown that the slope of the psychophysical function of glucose is greater than that of sucrose (e.g. Cameron, 1947; Yamaguchi *et al.*, 1970; McBride, 1983).

Although a number of arguments have been presented in favour of the hypothesis, proof of a multi-molecular interaction is still required.

### Alternative models

As noted in the Introduction, Beidler's theory does not take into account the time course of the neural response to a taste stimulus. To rectify this situation more detailed models, mainly extensions of Beidler's theory, have been developed. As some of these models may be seen by other investigators as potential candidates for the explanation of the present results, some of these models are discussed in the light of our results.

Dzendolet (1967) noted that Beidler's equation for single compounds assumes that the concentration of stimulating substance remains constant, despite an actual decrease due to binding of some of the molecules to receptor sites. In his alternative equation, the concentration term of Equation 1 is corrected for the amount of substance bound. Dzendolet (1967) argued that this correction factor is of greater influence at low concentrations than at high concentrations. Contrary to what may be expected on the basis of Dzendolet's argument, our results show that the predictions of Beidler's mixture equation are more accurate for low concentrations than for high concentrations. Therefore, it seems that the observed discrepancies between predictions and data cannot be attributed to concentration changes during stimulation.

The rate theory of Heck and Erickson (1973), an extensive modification of Beidler's theory, predicts that the magnitude of the neural response after application of a taste stimulus shows an initial high-rate transient response, after which the response declines to a steady state level. Although Heck and Erickson did not propose a binary mixture model, it can in principle be constructed analogously to the development of Beidler's original mixture equation. The present authors derived two variations of such a mixture model, one for the magnitude of the transient response ( $t \rightarrow 0$ ), and the other for the magnitude of the response at a steady state level ( $t \rightarrow \infty$ ). These derivations, specified in Appendix 2, show that both mixture models based on Heck and Erickson's theory lead to the same predictions. Interestingly, and quite unexpectedly, these predictions are identical to those evolving from Beidler's original mixture equation.

These derivations do not apply to the magnitude of the response to a mixture at a specified time in between the transient and steady state phases ( $t \neq 0, \infty$ ). A similar derivation at a specific time requires *a priori* specification of the values of several other parameters in Heck and Erickson's model. However, we do not consider such a specification to be feasible.

In conclusion, the distinction between Beidler's occupation theory and Heck and Erickson's rate theory (under two specified conditions) does not clarify the results obtained, because both appear to lead to similar predictions.

The model developed by Smith *et al.* (1975) gives a detailed description of the time course of the neural response. Although it contains two parameters depending on the concentration it does not contain the concentration itself as a parameter. Hence, no mixture model can be derived from this model.

The theory of Kamo *et al.* (1980) is an extension of Beidler's theory. It distinguishes between an active and inactive molecule-receptor site complex. Interpretation of this theory and derivation of a testable mixture model requires knowledge of the ratio between active and inactive stimulus-receptor site complexes. The value of this ratio cannot be obtained from the present data, and there are no other sources or means by which it can be estimated. This is the main reason why at present no mixture model can be derived from this theory.

## Conclusion

The methodology developed in this study permitted Beidler's mixture equation to be tested at specified levels of perceived sweetness. The predicted molecular concentrations of the glucose-fructose mixtures that should have a sweetness of equal intensity as certain concentrations of the unmixed compounds appeared to be almost correct at low sweetness levels. At the high sweetness levels the taste system appeared to be more efficient than predicted; a lower concentration than predicted was needed to obtain a certain sweetness intensity. This result suggests that glucose and fructose share common receptors, but either one, or both, has additional binding mechanisms.

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## Appendix 1

### Derivation of predicted mixture concentrations

In this appendix it is shown how Equation 9 is derived. This derivation starts from the text under Equations 7 and 8 in the Theory section.

Substitution of the right-hand sides of Equations 7 and 8 in Equation 5 yields:

$$R = \frac{\frac{R}{C_{ai}(R_{sa} - R)} X R_{sa} + \frac{R}{C_{bj}(R_{sb} - R)} Y R_{sb}}{1 + \frac{R}{C_{ai}(R_{sa} - R)} X + \frac{R}{C_{bj}(R_{sb} - R)} Y}$$

In the above expression, both the left-hand and right-hand side can be divided by  $R$ :

$$1 = \frac{\frac{X R_{sa}}{C_{ai}(R_{sa} - R)} + \frac{Y R_{sb}}{C_{bj}(R_{sb} - R)}}{1 + \frac{X R}{C_{ai}(R_{sa} - R)} + \frac{Y R}{C_{bj}(R_{sb} - R)}}$$

Since this fraction is equal to one, the numerator and denominator are equal, so that:

$$\frac{XR_{sa}}{C_{ai}(R_{sa} - R)} + \frac{YR_{sb}}{C_{bj}(R_{sb} - R)} = 1 + \frac{XR}{C_{ai}(R_{sa} - R)} + \frac{YR}{C_{bj}(R_{sb} - R)}$$

Rearranging the terms yields:

$$\frac{X(R_{sa} - R)}{C_{ai}(R_{sa} - R)} + \frac{Y(R_{sb} - R)}{C_{bj}(R_{sb} - R)} = 1$$

or

$$\frac{X}{C_{ai}} + \frac{Y}{C_{bj}} = 1$$

Expressing  $X$  in the other parameters of the above equation results in:

$$X = C_{ai} - \frac{C_{ai}}{C_{bj}} Y \quad (9)$$

The above Equation 9 is given in the Theory section. It is illustrated in Figure 1.

## Appendix 2

### *A mixture model for the rate theory of Heck and Erickson (1973)*

According to the rate theory of Heck and Erickson (1973), the magnitude of the neural response to a particular taste stimulus is proportional to the rate of adsorption of stimulus molecules to receptor sites. The neural response as a function of the time is given by the following formula:

$$R = \frac{d[CS]}{dt} = K_1 [C] [S_t] - K_1 [C] [CS]_{eq} \{1 - \exp -(K_1 [C] + K_2)t\} \quad (A1)$$

where  $R = d[CS]/dt$  = rate of formation of stimulus-receptor site complexes;  $[C]$  = concentration of the stimulus;  $[CS]_{eq}$  = concentration of adsorbed stimulus in a steady state;  $[S_t]$  = total number of receptor sites available;  $K_1$  = forward rate constant, reflecting the rate of adsorption;  $K_2$  = reverse rate constant, reflecting the rate of desorption;  $K_{eq} = K_1/K_2$  = equilibrium constant (equivalent to Beidler's association constant);  $t$  = time.

The magnitude of the transient response, when  $t \rightarrow 0$  is given by:

$$R = K_1 [C] [S_t] \quad (A2)$$

The magnitude of the response at a steady state level, when  $t \rightarrow \infty$ , is given by:

$$R = K_1 [C] [S_t] - K_1 [C] [CS]_{eq} \quad (A3)$$

Two mixture models, one for the response to a mixture at the transient phase, and the other for the response to a mixture at the steady state level, can be constructed analogously to the development of Beidler's original mixture equation (Equation 2 in the Introduction).

### *The initial transient response*

The magnitude of the transient response for concentration  $i$  of substance A is given by:

$$R_{ai,t} - 0 = K_{a1} [C_{ai}] [S_{ar}] \quad (A4)$$

A similar formula applies for the magnitude of the transient response to concentration  $j$  of substance B:

$$R_{bj,t} - 0 = K_{b1} [C_{bj}] [S_{br}] \quad (A5)$$

The magnitude of the transient response to a mixture of concentration  $X$  of substance A and concentration  $Y$  of substance B is given by:

$$R_{abXY,t} - 0 = K_{a1} [X] [S_{ar}] + K_{b1} [Y] [S_{br}] \quad (A6)$$

The question now arises as to what is the total concentration and composition of possible mixtures of A and B, which give rise to a transient response identical to  $R_{ai,t} - 0$  and  $R_{bj,t} - 0$ . The determination of these concentrations is similar to the derivations in the Theory section. The condition that the transient responses to  $C_{ai}$  and  $C_{bj}$  are equal to the transient response to  $C_{abXY}$  can be formally expressed as:

$$R = R_{ai,t} - 0 = R_{bj,t} - 0 = R_{abXY,t} - 0 \quad (A7)$$

From Equations A4 and A7 it follows that:

$$K_{a1} = \frac{R}{[C_{ai}] [S_{ar}]} \quad (A8)$$

Similarly, from Equations A5 and A7 it follows that:

$$K_{b1} = \frac{R}{[C_{bj}] [S_{br}]} \quad (A9)$$

Substitution of the right-hand side of Equation A8 and the right-hand side of Equation A9 into Equation A6 yields:

$$R = \frac{[X]R[S_{ar}]}{[C_{ai}] [S_{ar}]} + \frac{[Y]R[S_{br}]}{[C_{bj}] [S_{br}]}$$

or,

$$1 = \frac{[X]}{[C_{ai}]} + \frac{[Y]}{[C_{bj}]}$$

Rearranging the terms in the above equation yields Equation 9 in the Theory section.

### *The steady state response*

The magnitude of the steady state response to concentration  $i$  of substance A is given by:

$$R_{ai,t} - \infty = K_{a1} [C_{ai}] [S_{ar}] - K_{a1} [C_{ai}] [CS_{ai}]_{eq} \quad (A10)$$

The above equation can be written as (see Heck and Erickson, p. 712):

$$R_{ai,t} - \infty = \frac{K_{a,eq} [C_{ai}] [S_{ar}]}{1 + \frac{K_{a,eq}}{K_{a2}} [C_{ai}]} \quad (A11)$$

A similar formula applies for the magnitude of the steady state response to concentration  $j$  of substance B:

$$R_{bj,t \rightarrow \infty} = \frac{K_{b,eq}[C_{bj}] [S_{br}]}{1 + \frac{K_{b,eq}}{K_{b2}} [C_{bj}]} \quad (A12)$$

The magnitude of the steady state level of a mixture of concentration  $X$  of substance A and concentration  $Y$  of substance B is given by the following formula:

$$R_{abXY,t \rightarrow \infty} = \frac{K_{a,eq}[X] [S_{ar}] + K_{b,eq}[Y] [S_{br}]}{1 + \frac{K_{a,eq}}{K_{a2}} [X] + \frac{K_{b,eq}}{K_{b2}} [Y]} \quad (A13)$$

Again, the question now arises as to what is the total concentration and composition of possible AB mixtures, which give rise to a steady state response identical to  $R_{ai,t \rightarrow \infty}$  and  $R_{bj,t \rightarrow \infty}$ . The determination of the concentrations is similar to the derivations in the Theory section. The condition that the steady state responses to  $C_{ai}$  and  $C_{bj}$  are equal to the steady state response to  $C_{abXY}$  can be formally expressed as:

$$R = R_{ai,t \rightarrow \infty} = R_{bj,t \rightarrow \infty} = R_{abXY,t \rightarrow \infty} \quad (A14)$$

A similar derivation, as was carried out for the transient response and for Beidler's original mixture equation, yields an identical result. To obtain this result, the parameters  $K_{a,eq}$  and  $K_{b,eq}$  have to be expressed in the other parameters of Equations A11 and A12, respectively. The right-hand sides of the equations obtained can be substituted into Equation A13. Rearranging the terms in that equation results in the elimination of  $K_{a2}$ ,  $K_{b2}$ ,  $[S_{ar}]$ ,  $[S_{br}]$  and  $R$ , and so the same result as in the derivation in Appendix 1 is obtained.

## CHAPTER FOUR

**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**

Cees De Graaf & Jan E.R. Frijters

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## 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

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**Abstract.** The taste interaction between two taste substances in a mixture can be assessed in different ways. In the usual approach, the response to a mixture is compared with the sum of the responses to the mixture's components (i.e. 'the summated response comparison'). This approach has led to a large variety of classifications and descriptions of the taste interaction. An alternative way of assessing taste interaction is by comparing the intensity of a mixture with the intensities of the single compounds at those particular concentrations, where the mixture and each of the single compounds have equal molarities (i.e. 'the equimolar comparison'). This approach follows from the concept of equiratio taste substance mixtures. In the present study, the data of seven experiments on binary sugar mixtures were re-analysed in order to enable a comparison at equimolar concentrations. The outcomes of these analyses showed that the taste interaction between any two sugars in a binary mixture follows two general rules. Firstly, the sweetness intensity of a binary sugar mixture is intermediate to the sweetness intensities of its components, when each is tasted alone and at the same total molarity as the mixture. Secondly, as the proportion of the sweetest sugar in the mixture increases, the sweetness intensity of that mixture gets near the sweetness intensity of the sweetest substance, tasted alone and at the same total molarity as the mixture.

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### Introduction

The taste interaction between two taste substances in a mixture is usually investigated by comparing the perceived taste intensity of a mixture with the sum of the perceived taste intensities of the mixture's constituents in isolation (e.g. Stone and Oliver, 1969; Moskowitz, 1973, 1974a,b; Rifkin and Bartoshuk, 1980; Curtis *et al.*, 1984; Munton and Birch, 1985). This means that the taste intensity of an AB mixture is compared to the sum of the intensities of the tastants A and B under the condition that the concentrations of each of the two components in the mixture are the same as when tasted alone outside the mixture. The logic of this approach is straightforward and plausible. By comparing mixture and single compound intensities in this way, it can be determined, whether two substances in a mixture suppress each other, show additivity or show synergism (meaning, respectively, that the sum of the perceived taste intensities of the components is less than, equal to, or greater than the taste intensity of the mixture). However, interpretation of the result of such a comparison is less simple than one would suspect. Bartoshuk (1975, 1977) and Bartoshuk and Cleveland (1977) argued and showed that the observed interaction (suppression, addition or synergism) relies heavily on the forms of the psychophysical functions of the mixture's components. According to Bartoshuk, suppression takes place if the psychophysical functions of the constituents are negatively accelerating, and synergism occurs if these functions are positively accelerating. Since the shape of the psychophysical taste functions can be manipulated by change of stimulus delivery procedure (Meiselman, 1971), or by varying other ex-

perimental factors (e.g. Stevens and Galanter, 1957; Parducci, 1974; Mellers and Birnbaum, 1982), conclusions about taste interaction phenomena are not only specific for the compounds in the mixture, but depend to a large extent on several (arbitrary) experimental factors. The instability of psychophysical taste functions (cf. Meiselman, 1972) may ultimately result in inconsistent conclusions about the sensory interaction between two compounds in a mixture.

Frijters and Oude Ophuis (1983) introduced a new approach to the study of taste mixtures. They developed the concept of 'equiratio mixture type', and defined it as a series of taste substance mixtures with different concentrations, but in each of which the ratio of the constituent components is constant. They additionally showed that psychophysical functions of equiratio mixture types can be determined in the same way as for single substances. The comparison procedure between mixture and single compound intensities resulting from the equiratio mixture approach, is different from the comparison procedure elucidated above. Frijters and colleagues (Frijters and Oude Ophuis, 1983; Frijters *et al.*, 1984; De Graaf *et al.*, 1987) compare mixture and single compound intensities at those particular concentrations, where each of the mixtures and single compounds have equal molar concentrations. The concentration of a particular mixture is expressed in the total molarity of the mixture, that is, the sum of the molarities of the mixture's components. This implies that all solutions, to be compared with respect to perceived taste intensity, contain an equal number of molecules. The main argument in favour of molarities is that molecules are the active agents for stimulation of a taste receptor (although a measure for activity or 'effective' concentration would even be better).

Figure 1 illustrates the difference between the usual approach for assessing the taste interaction, and the approach evolving from the equiratio mixture approach. It shows hypothetical psychophysical functions for substance A, substance B, and the equiratio mixture type containing equal molarities of A and B (AB 0.50/0.50). In the usual approach the sum of the responses to concentration  $x$  M of substance A ( $= R_{ax}$ ) and concentration  $x$  M of substance B ( $= R_{bx}$ ) is compared to the response of a mixture containing  $x$  M of A and  $x$  M of B ( $= R_{abxx}$ ). We call this the summated response comparison. The total concentration of that mixture is twice the concentration of each of the single compounds. The concept of 'mixing' means in this approach adding a particular concentration of one component to a particular concentration of the other component. According to Bartoshuk and Gent (1985), this method of mixture construction originates from Kiesow. This means that mixing does not take place in the literal sense, that is, the addition of two single compound solutions to yield a mixture solution with a volume equal to the sum of the volumes of the single compound solutions. In effect, each component concentration is diluted upon mixing in the literal sense.

In the comparison procedure evolving from the equiratio mixture approach,  $R_{ax}$  and  $R_{bx}$  are not compared to  $R_{abxx}$ , but to the response to a mixture containing  $1/2 x$  M of A and  $1/2 x$  M of B ( $= R_{ab1/2x1/2x}$ ). The total concentration of this mixture is  $x$  M, which is equivalent to the molar concentrations of each of the single component solutions. Thus, the mixture intensity is not compared to the sum of the component intensities, but it is compared to the component intensities themselves. The concept of 'mixing' in this approach is interpreted in the literal sense. If a  $x$  M solution of substance A ( $= C_{ax}$ ) is physically mixed with a  $x$  M solution of substance B ( $= C_{bx}$ ), this results



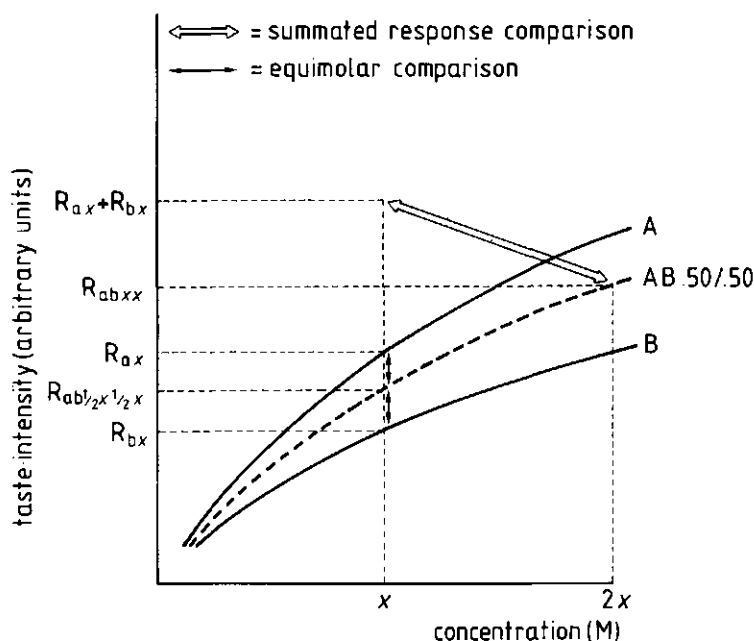
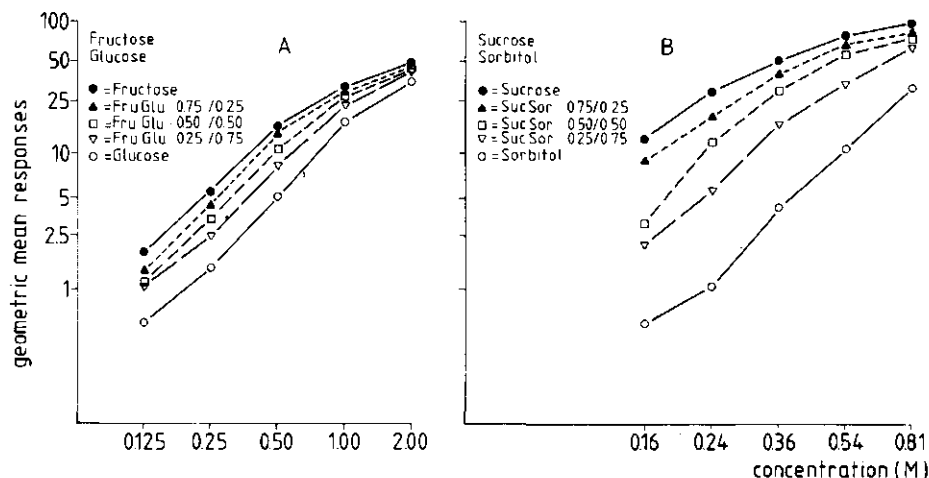


Fig. 1. Hypothetical psychophysical functions of substance A, substance B and the AB 0.50/0.50 mixture. The taste interaction between A and B is assessed by two different comparison procedures, i.e. the 'summed response comparison' ( $\longleftrightarrow$ ) or the 'equimolar comparison' ( $\rightarrow$ ). Usually, the responses to a mixture containing  $x$  of A and  $x$  of B ( $= R_{abxx}$ ) is compared to the sum of the responses to the mixture's constituents ( $= R_{ax} + R_{bx}$ ). The equiratio mixture approach to taste mixtures offers an alternative method of assessing taste interaction. It compares taste intensities of mixtures and single substances at those particular concentrations, where each of the components and the mixture have an equal total molarity. Thus, the single compound intensities ( $R_{ax}$  and  $R_{bx}$ ) are not compared to  $R_{abxx}$ , but they are compared to  $R_{ab1/2x1/2x}$ .

in a solution with a  $1/2 x$  M of A, and a  $1/2 x$  M of B ( $= C_{ab1/2x1/2x}$ ).

The potential conclusions to be drawn from the equimolar comparison are not dependent on the (arbitrary) shapes of the psychophysical functions, or of the properties of the scale used for the assessment of perceived taste intensity. There are two reasons for this. The first is that the comparison between the responses to the components and the response to the mixture can be carried out at an ordinal level of assessment ( $<$  or  $>$ ). The second reason is that the equimolar comparison does not involve an arithmetic operation; the response to a mixture is directly compared to the responses to the single compounds.

In the summed response comparison, the response to a mixture is compared with the sum of the single compound intensities (+). Since an arithmetic operation is included, the scale used for expressing the perceived taste intensity, can have a drastic effect on the ultimate conclusion. This can be illustrated by the following three examples on data of fructose-glucose mixtures, all evaluated with the summed response comparison rule. Stone and Oliver (1969), who used magnitude estimation, concluded that fructose and glucose show synergism when mixed. McBride (1986), using a category scale, concluded that fructose and glucose show addition at low sweetness levels, but suppress each other at high sweetness levels. Yamaguchi *et al.* (1970b) who expressed



**Fig. 2.** Results of two studies on the equiratio mixture model, one from Frijters and Oude Ophuis (1983) on fructose-glucose mixtures (**panel A**), and one from Frijters *et al.* (1984) on sucrose-sorbitol mixtures (**panel B**). The data were obtained using the method of magnitude estimation with a fixed standard (0.25 M FruGlu 0.50/0.50, and 0.24 M SucSor 0.50/0.50, respectively), which had an assigned value of 10 in each case.

perceived sweetness intensity in equisweet sucrose concentrations, concluded that fructose and glucose show addition, but that glucose is dominant over fructose. It is evident that on the basis of these studies no consistent conclusions can be drawn about the taste interaction between fructose and glucose. In contrast, the outcomes of two other experiments with fructose-glucose mixtures, evaluated according to the equimolar comparison rule were in broad agreement. Frijters and Oude Ophuis (1983), who used magnitude estimation, concluded that the psychophysical functions of equiratio mixtures of glucose and fructose are intermediate to the psychophysical functions of the single compounds. The same conclusion was obtained by De Graaf *et al.* (1987), who presented the same stimuli, but used functional measurement (e.g. Anderson, 1981; Birnbaum, 1982) for the assessment of the perceived taste intensities.

In another study involving equiratio mixtures of sorbitol and sucrose, Frijters *et al.* (1984) also showed that the psychophysical functions of equiratio mixtures were in between the psychophysical functions of the single compounds. Figure 2 depicts the results of the two equiratio mixture studies.

It is apparent from Figure 2 that the perceived sweetness intensities of glucose-fructose mixtures and of sorbitol-sucrose mixtures lie in between the perceived sweetness intensities of the equimolar concentrations of the single compounds constituting the mixture. The second point to be noted is that the sweetness intensity of the mixture approaches the sweetness intensity of an equimolar concentration of the sweetest substance when the proportion of the sweetest substance in the mixture increases (fructose in the glucose-fructose experiment and sucrose in the sorbitol-sucrose experiment).

McBride (1986) challenged the generality of the above observations, and noted that '... the equiratio mixture model rests upon the substitutability assumption ...', and that for '... substitutability to hold, the sweetness intensity of a mixture would always

have to lie in between the sweetness intensities of equivalent concentrations of its components. . . . According to the same author, this is not so in the case of sucrose-fructose mixtures. McBride found that the sweetness intensity of some sucrose-fructose mixtures exceeded the intensity of each of the components. However, this observation is at least partially based on the use of weight/volume as concentration unit. When his data (McBride, 1986; Figure 7) are replotted with M as the unit of concentration, his conclusion appears to be doubtful (see Figure 9, this paper). This matter is further considered in Results.

On the basis of the evidence for fructose-glucose and sorbitol-sucrose mixtures, and other evidence, we postulate the general rule that the sweetness intensity of a binary sugar (alcohol) mixture lies in between the intensities of their components, when each is tasted alone and at the same total molarity as the mixture. In order to further substantiate this hypothesis we recalculated published mixture data of other authors in such a way, that the mixture and single compound intensities are compared at equimolar concentrations. The data were taken from the results of seven experiments with sugar mixtures. These are: Cameron (1947), Stone and Oliver (1969), Stone *et al.* (1969), Yamaguchi *et al.* (1970a,b), Curtis *et al.* (1984), Munton and Birch (1985) and McBride (1982, 1983a,b, 1986). Similar recalculations could not be performed for certain other mixture studies (Moskowitz, 1973, 1974b; Bartoshuk and Cleveland, 1977; Van der Heijden *et al.*, 1983) since some details of these experiments, that were essential for our analyses, were not reported.

## Results

The recalculated data are derived from seven mixture studies, and comprise data on the perceived sweetness intensity of 27 different combinations of sweet-tasting disaccharides, monosaccharides and sugar alcohols in binary mixtures. A brief summary of the applied methodology, and a graphical display of the results of each of these seven studies are given in seven separate sections.

The sweetness intensities of mixtures and single compounds are compared at equimolar concentration levels (see Figures 1 and 2). All figures contain the following elements: (i) a plot of each of the two psychophysical functions of the mixture's components, and (ii) the sweetness intensities of the mixtures investigated. Data points representing the intensities of two or more mixture concentrations having an equal ratio of its constituents (i.e. equiratio mixture types) are connected with dashed lines. In some cases, not all the mixture data from the original publication are included because too many points would confuse the picture; it appeared that the data in some studies have nearly identical concentration-response coordinates. The structure of the data excluded shows no essential deviance from the picture that emerges from the data included. The concentrations of both single compounds and mixtures are expressed in mol substance/litre solution. The concentration of a particular mixture is defined as the sum of the molarities of the mixture's components. The units in which the perceived taste intensities are expressed are identical to the units used in the original publications.

### *Cameron (1947)*

Cameron determined the sweetness of various sugars and other sweet substances using a variation of the method of constant stimuli (Guilford, 1954). Figure 3, panels A-D,

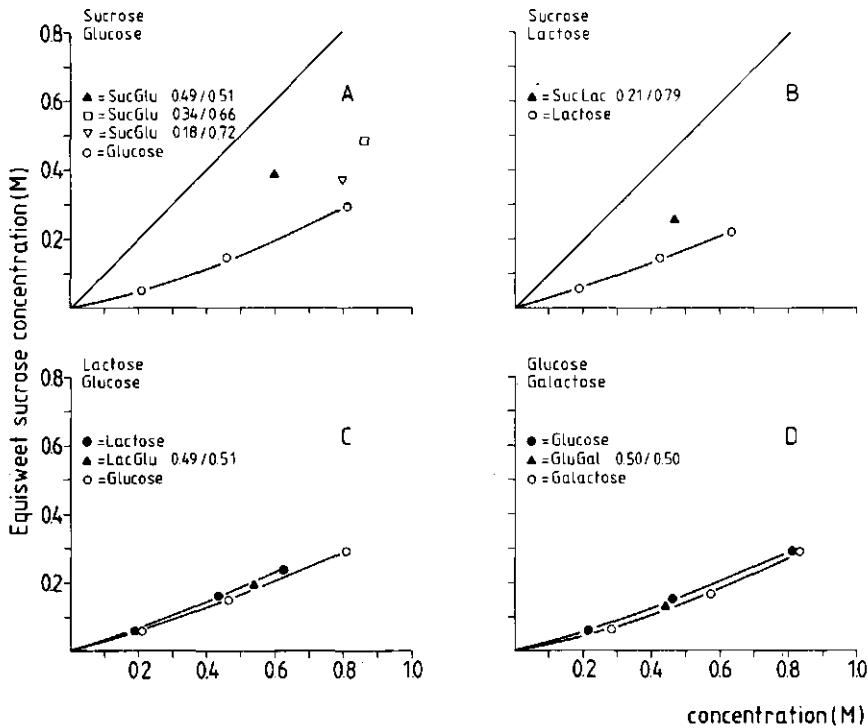


Fig. 3. Results of the study of Cameron (1947). Sweetness intensities of mixture and single substances were assessed using a variation of the method of constant stimuli. Sweetness intensities are expressed in equisweet sucrose concentrations.

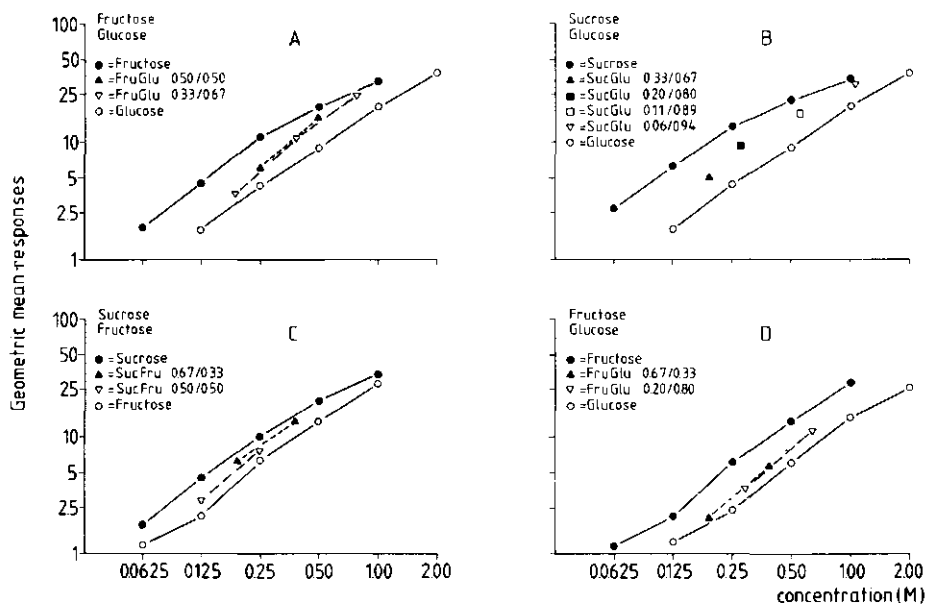
shows the results of the experiments with binary sugar mixtures (the data on fructose-glucose mixtures are excluded; various other elaborate data sets on fructose-glucose mixtures are presented further on in this paper). The sweetness intensity is expressed in equisweet sucrose concentrations.

From all four panels, the same picture emerges. The sweetness intensity of sucrose-glucose mixtures lies in between the sweetness intensity of sucrose and of glucose; the sweetness intensity of sucrose-lactose mixtures is intermediate to the sweetness intensity of sucrose and lactose. The same rule applies for lactose-glucose and glucose-galactose mixtures.

#### Stone and Oliver (1969)

The sweetness intensities of glucose, fructose, sucrose and binary mixtures of these substances were assessed using the method of magnitude estimation (Stevens, 1975). The sweetness intensities of binary mixtures and single compounds were judged relative to 0.5 M glucose, and 0.25 sucrose, both having an assigned value of 10 in the separate experiments.

Figure 4, panels A-D, shows that the sweetness intensities of the mixtures investigated are intermediate to the sweetness intensities of equimolar concentrations of the single compounds.



**Fig. 4.** Results of the study of Stone and Oliver (1969) on binary mixtures of sucrose, fructose and glucose. **Panels A and B** represent the responses for fructose-glucose and sucrose-glucose mixtures, respectively. The sweetness intensities of these mixtures were judged relative to the sweetness intensity of 0.5 M glucose which had an assigned value of 10. **Panels C and D** represent the responses to sucrose-fructose and fructose-glucose mixtures, respectively, judged relative to the sweetness intensity of 0.25 M sucrose which also had an assigned value of 10.

With respect to the second rule hypothesized, i.e. that the sweetness intensity of a mixture approaches to the sweetness intensity of the sweetest component as the proportion of that sweetest component increases, the results are less straightforward. This rule appears to be valid in panels A, C and D, but panel B does not allow for a definite conclusion.

#### *Stone et al. (1969)*

Stone *et al.* determined the sweetness intensities of glucose, fructose and mixtures of these substances at three different temperatures (5, 22 and 50°C), and three different pHs (2.7, 4.0 and 5.8). These authors used the method of magnitude estimation, where the sweetness intensity of all stimuli was judged relative to the sweetness intensity of 0.25 M sucrose at a temperature of 22°C and pH 5.8. This standard stimulus was designated as 10.

Figure 5, panels A-E, shows the results. All panels in this figure show that the sweetness intensity of glucose-fructose mixtures lie in between equimolar concentrations of its components.

However, panel A does not confirm the second rule. The sweetness intensities of the mixtures, which contained the highest proportion of fructose, lie closer to the glucose curve than the other mixtures which contained relatively less fructose. Panels B and C also do not give unequivocal support for the second rule. This result is not in line with the results of Stone and Oliver (1969), Frijters and Oude Ophuis (1983) and De

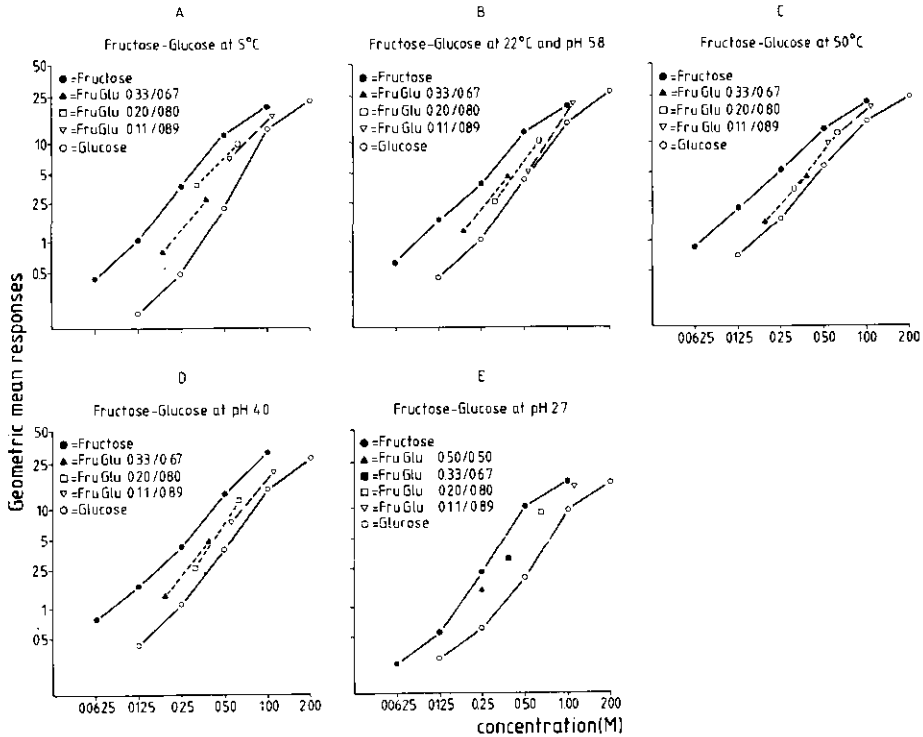


Fig. 5. Results of the study of Stone *et al.* (1969) on the sweetness intensities of fructose, glucose and their mixtures at three different temperatures and at three different pHs. All judgements were made relative to the sweetness intensity of 0.25 M sucrose (designated as 10), at a temperature of 22°C and pH 5.8.

Graaf *et al.* (1987). These deviances might reflect a genuine temperature effect; however, they can also be due to experimental error variance.

#### Yamaguchi *et al.* (1970a,b)

The investigation by Yamaguchi *et al.* is one of the most extensive mixture studies published. The sweetness intensity of sucrose was matched to various reference concentrations of fructose, glucose, xylose, sorbitol, xylitol, mannitol and all binary mixtures of these substances. Sucrose was also matched to binary mixtures of sucrose and each of these six sweeteners. Yamaguchi *et al.* used the method of constant stimuli, and applied probit analysis for the determination of the PSEs (points of subjective equality).

Figure 6, panels A – U, shows the sweetness intensities of the single compounds and mixtures, expressed in equisweet sucrose concentrations. From this figure the same picture emerges as from the data of Cameron (1947), Stone and Oliver (1969), Stone *et al.* (1969), Frijters and Oude Ophuis (1983), and Frijters *et al.* (1984). The conclusions with respect to the first rule drawn in the previous sections, hold for all 21 binary sugar mixtures investigated by Yamaguchi *et al.*, even in cases where the psychophysical functions of the mixture's components are nearly identical. For example, the psychophysical functions of sorbitol and glucose have virtually the same shape (see

Figure 6, panel M); the psychophysical function of a GluSor 0.50/0.50 mixture appears to be indistinguishable from the psychophysical functions of glucose and sorbitol. The same is also true for the glucose and mannitol functions (panel O).

The data of Yamaguchi *et al.* also support the second rule. The sweetness intensities of the mixtures represented by the solid points are closer to the sweetness intensity of the sweetest component than the sweetness intensities of the mixtures represented by the open points. The solid point mixtures contain relatively more of the sweetest substance than the open point mixtures.

#### *Curtis et al. (1984)*

Curtis *et al.* determined the sweetness intensities of sucrose, fructose and their mixtures using the method of magnitude estimation. No standard stimulus was presented, and subjects were free to use any number to respond with.

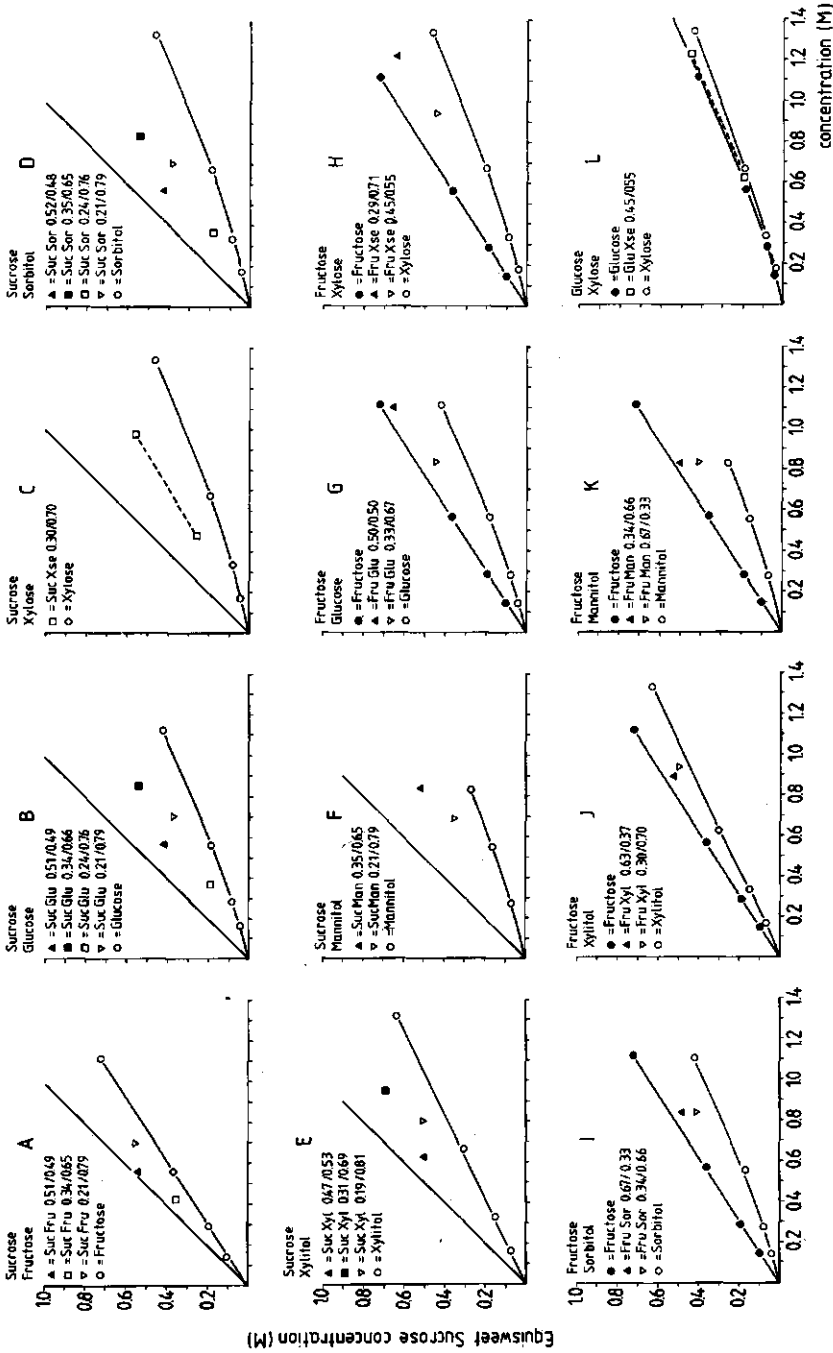
Figure 7 shows part of the results. These data do not give unequivocal support to the former conclusions. The sweetness intensities of some sucrose-fructose mixtures appear to slightly exceed the sweetness intensity of an equimolar concentration of sucrose or fructose. However, some of the results of Curtis *et al.* (1984) conflict with all other data reported on the sweetness of sucrose and fructose. Figure 7 shows that in their experiment the low concentrations of fructose are perceived as sweeter than low concentrations of sucrose. This finding is doubtful, since there is an abundance of data which shows that a particular concentration of sucrose is sweeter than an equimolar concentration of fructose (e.g. Stone and Oliver, 1969; Yamaguchi *et al.*, 1970a; McBride, 1983b). In addition, the crossing over of the psychophysical functions of sucrose and fructose has not been demonstrated by other investigators (Dahlberg and Penczek, 1941; Cameron, 1947; Schutz and Pilgrim, 1957; Yamaguchi *et al.*, 1970a; Moskowitz, 1970; McBride, 1983b).

#### *Munton and Birch (1985)*

Munton and Birch assessed the perceived sweetness intensity and the 'persistence', using an alternative method of magnitude estimation. They investigated a number of disaccharides, monosaccharides, sugar alcohols and eleven different combinations of these substances in binary mixtures. The sweetness intensities of mixtures and single compounds were assessed in different sessions.

With reference to Figure 8, panels, A-K, it is apparent that the sweetness intensities of the mixtures are intermediate to the sweetness intensities of equimolar concentrations of the constituents, in seven out of the eleven mixtures. The data in these seven panels also support the second rule. However, the data on sucrose-fructose, galactose-glucose, and lactose-glucose mixtures do not allow a definite conclusion to be drawn, and the data on lactose-galactose mixtures seriously violate the basic postulate of this paper, since lactose-galactose mixtures are less sweet than the equimolar concentrations of either galactose or lactose.

In order to check the validity of this contradictory result, the experiment on the sweetness intensity of lactose-galactose mixtures was repeated by the present authors. Using the same stimuli as Munton and Birch, 10 subjects judged the sweetness intensity, relative to the sweetness of a 0.146 M (5% w/v) sucrose solution, which had an assigned value of 10. Each subject judged each stimulus three times, and all stimuli





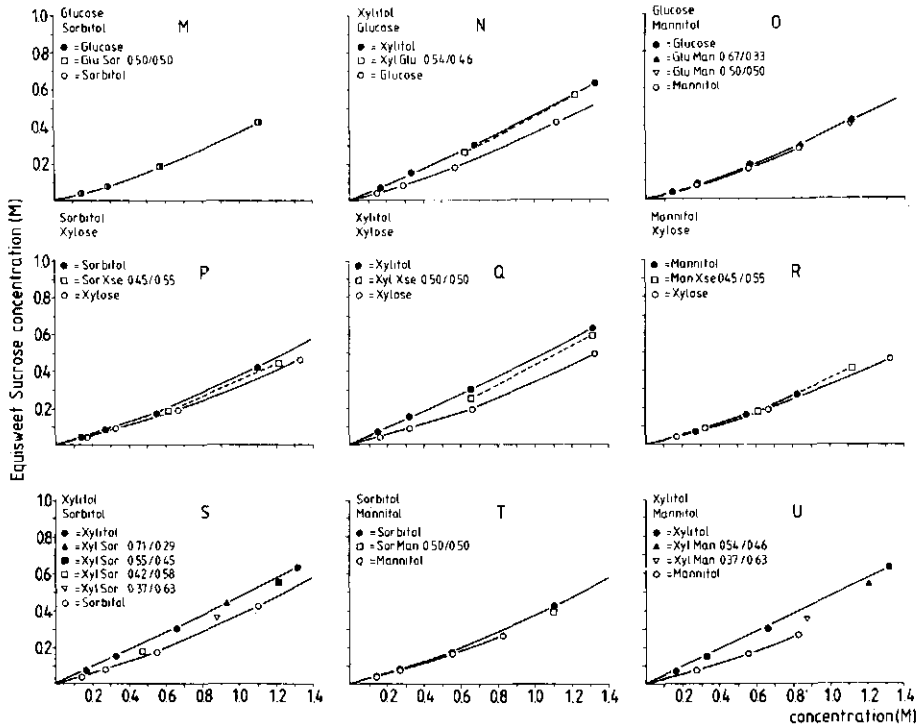


Fig. 6. Results of the studies of Yamaguchi *et al.* (1970a,b). The sweetness intensity of mixtures and single substances are expressed in units of equisweet sucrose concentrations. The data were obtained using the method of constant stimuli.

(mixtures and single compounds) were tasted in one session. Figure 8, panel L, shows the results of the repeat experiment. These results do not concur with the results of Munton and Birch. Firstly, the repeat experiment shows that lactose is sweeter than galactose (on M/l basis). This is in line with the results from Cameron (1947) and Schutz and Pilgrim (1957). Munton and Birch found that the psychophysical functions of lactose and galactose cross each other; this was not found in the repeat experiment. It is also evident from the repeat experiment, that the intensities of lactose-galactose mixtures lie in between the single compound intensities. It is proposed that the results of the repeat experiment are more reliable than those of Munton and Birch for two reasons. Firstly the data of the repeat experiment are in line with earlier published data on galactose and lactose (Cameron, 1947; Schutz and Pilgrim 1957). Secondly, in the repeat experiment, the mixtures and single compounds were presented in one single session, whereas in Munton and Birch's experiment, the two single compounds and mixtures were presented in different sessions with a different stimulus context.

In summary, seven out of the eleven data sets on mixtures unequivocally support the hypothesis of this paper, three data sets are borderline cases, and one data set seriously violates the postulate. However, since the latter data set was shown to be suspect, it cannot be considered as a serious challenge to the hypothesis.

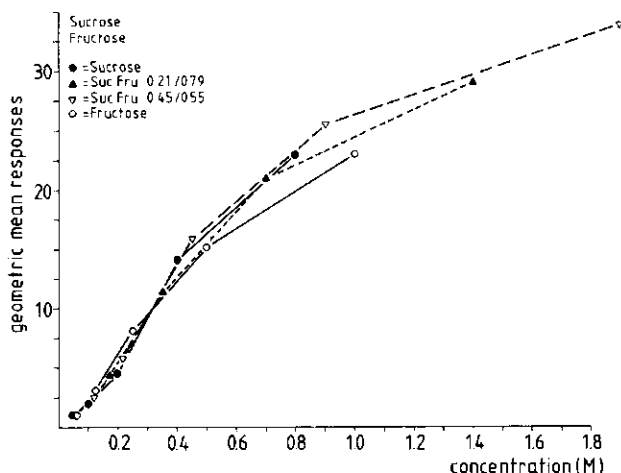


Fig. 7. Results of a study by Curtis *et al.* (1984) on sucrose-fructose mixtures. The data were obtained using the method of magnitude estimation without a standard or modulus. The data points represent the geometric means of the responses.

#### McBride (1982, 1983a,b, 1986)

McBride (1982) obtained data on the perceived sweetness intensities of glucose, fructose and sucrose using a 13-point category scale. He paid special attention to the internal consistency of the ratings, and he argues that the scale values obtained are linear with perceived sweetness intensity (McBride, 1983a). The sweetness intensities of binary mixtures of glucose, fructose and sucrose were determined in separate experiments, with the same scaling method, but with different subjects (McBride, 1986).

Figure 9, panels A-C, shows part of the results. The closed and open circles represent the sweetness intensities of single compounds, and the other symbols refer to the data on mixtures. The data on fructose-glucose mixtures, and sucrose-glucose mixtures confirm the hypothesis, whereas the results from sucrose-fructose do not. Despite this contradictory evidence, these results do not provide sufficient evidence to refute the hypothesis. The results of the data on mixtures and single compounds were obtained in different experiments with different subjects, and a different stimulus context in each experiment. Although McBride (1983a,b) claims that his method is free of biases, his data show some variability on the scale values of the same stimuli presented in different experiments. For example, 0.0625 M, 0.50 M sucrose and 0.085 M of the Suc-Fru 0.33/0.67 mixture (this mixture has a 0.50/0.50 ratio on weight/volume basis) were each presented in three different experiments. The scale values of these stimuli show a variability up to one scale unit. None of the scale values of sucrose-fructose mixtures exceed the scale value of sucrose by more than one scale unit. Thus, the fact that some mixture scale values are higher than the sucrose scale values could well be explained by experimental error variance. In an extensive study on sucrose-fructose mixtures conducted by De Graaf and Frijters (in preparation), it was shown that the scale values of sucrose-fructose mixtures are intermediate to the scale values of sucrose and fructose at five different concentration levels, varying from 0.125 to 2.0 M.

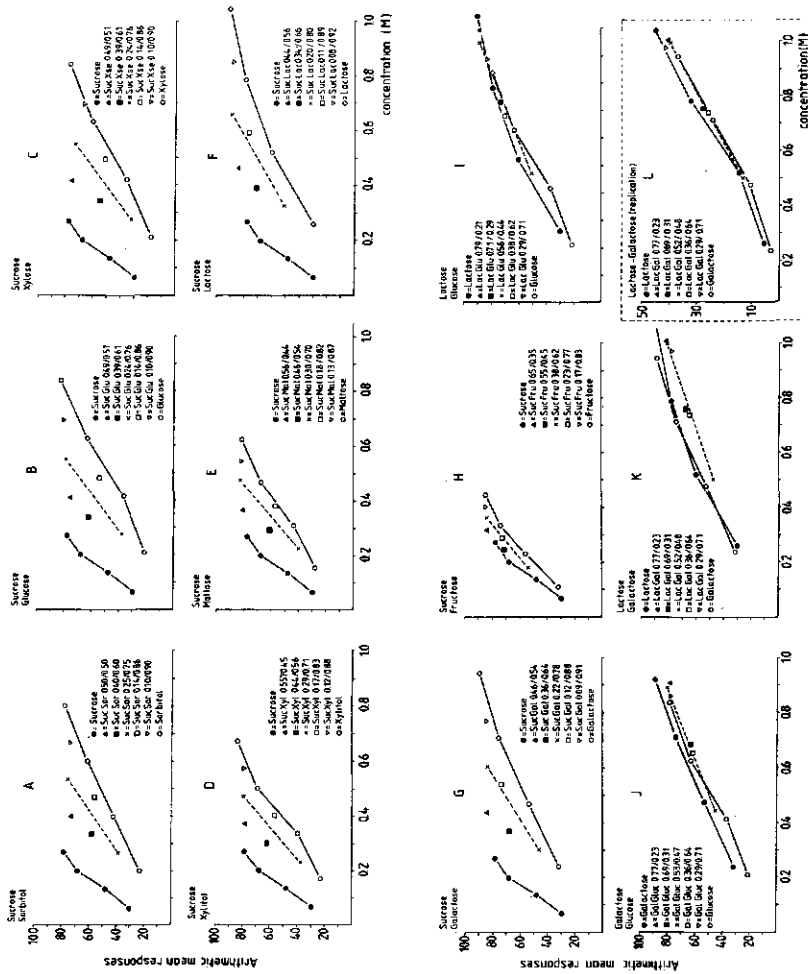
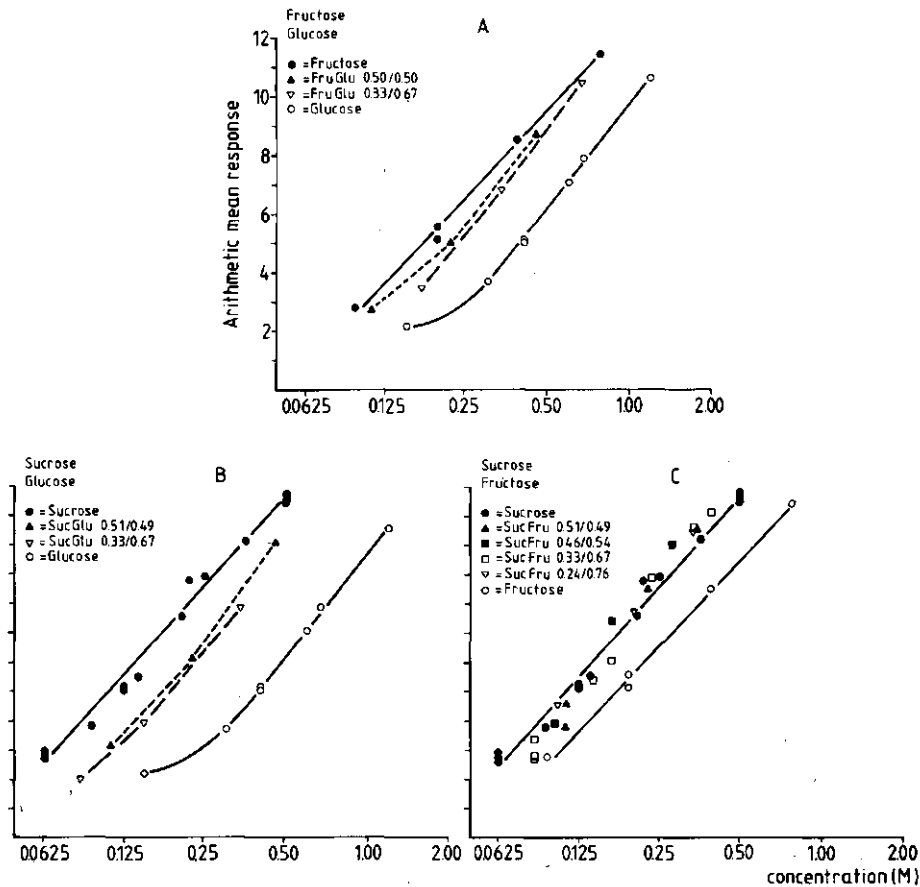


Fig. 8. Panels A - K show the results of the study of Munton and Birch (1985). The data were obtained with an alternative method of magnitude estimation. The judgements were made relative to the sweetness intensity of 0.146 M sucrose, which had an assigned value of 50. Panel L shows the results of the replication of the data on lactose - galactose mixtures. The same stimuli and standard were presented. The standard stimulus (0.146 M sucrose) had an assigned value of 10.



**Fig. 9.** Results of the studies of McBride (1982, 1983a,b, 1986), on sucrose-glucose (panel A), fructose-glucose (panel B), and sucrose-fructose (panel C) mixtures. The data were obtained using a 13-point category scale. The lines representing the psychophysical functions of sucrose, fructose and glucose were fitted by eye (cf. McBride, 1983b).

## Discussion

Reviewing the results, it can be concluded that, of the 52 data sets presented, 46 are unambiguously in favour of the main hypothesis of this paper. The remaining six contradictory data sets do not provide conclusive evidence against the hypothesis for reasons discussed.

Munton and Birch (1985) obtained three data sets, from which no definite conclusions could be drawn, and one data set on lactose-galactose mixtures, which clearly contradicts the postulate. However, when the latter experiment was repeated by the present authors, it was shown that the sweetness intensity of lactose-galactose mixtures is intermediate to the sweetness intensities of the single compounds. Since Munton and Birch's data have been shown to be suspect, the authors hold the view that three other inconclusive data sets may also be unreliable, and do not necessarily invalidate the hypothesis.

The two other data sets which contradict the hypothesis both refer to sucrose – fructose mixtures (Curtis *et al.*, 1984; McBride, 1986). However, since the results of Curtis *et al.* conflict with all other data on the sweetness of sucrose and fructose, they must also be considered as suspect. As was shown in the results section, violation of the hypothesis by McBride's data (1986) could be easily explained by experimental error variance. Moreover, the results of two other studies on sucrose – fructose mixtures (Stone and Oliver, 1969; Yamaguchi *et al.*, 1970a,b) confirm that the intensity of sucrose – fructose mixtures are intermediate to the single compound intensities.

It can be argued that, of all the results presented above, those of Yamaguchi *et al.* are the most precise and reliable. Yamaguchi *et al.* used the method of constant stimuli for the determination of the PSEs. This is a form of relative judgement which is considered to be more accurate than the absolute judgements (Shepard, 1981) that were made in the other experiments. Additional evidence for the precision of data resulting from use of the method of constant stimuli can be obtained from a study of De Graaf and Frijters (1986). In ten control experiments, these authors found that the PSEs showed a mean absolute error of 0.64%. The results of Yamaguchi *et al.* therefore provide the most conclusive evidence in favour of the hypothesis. Her results show that the psychophysical functions of glucose, sorbitol, xylose and mannitol do not diverge much from each other, yet even under these exacting circumstances, the mixture intensities were intermediate to the intensities of single compounds or equal molarity. These observations provide particularly substantial support for the hypothesis.

With respect to the second rule hypothesized, i.e. that the sweetness intensity of a particular mixture approaches the sweetness intensity of an equimolar concentration of the mixture's sweetest component, it can be noted that only the data of Stone and Oliver (1969), and Stone *et al.* (1969) do not give unequivocal support for this rule. However, these deviations were small and can be easily explained by experimental error variance. Considering the abundance of data in support of this rule, it is concluded that this rule applies for all binary sugar (alcohol) mixtures.

## Summary

The taste interaction between two arbitrary sugars in a mixture can be described by two simple but general rules.

The first rule is that the perceived sweetness intensity of a binary mixture lies in between the intensities of the components, when each is tasted alone and at the same total molarity as the mixture. The second rule is that, as the proportion of the sweetest sugar in the mixture increases, the sweetness intensity of that mixture approaches the sweetness intensity of the sweetest component tasted alone and at the same total molarity as the mixture. Similarly, as the proportion of the least sweet sugar in the mixture increases, the sweetness intensity of that mixture approaches that of the least sweet substance tasted alone at the same total molarity as the mixture. With respect to the psychophysical functions, this means that the parameters of the psychophysical functions of binary equiratio mixtures (irrespective of their forms) are intermediate to the parameters of the psychophysical functions of the unmixed components. As the proportion of A in an AB mixture increases, the form of the psychophysical function of such an equiratio mixture approaches the form of the psychophysical function of

substance A. Similarly, as the proportion of B increases, the mixture behaves more like substance B.

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**CHAPTER FIVE**

**TASTE INTERACTION BETWEEN GLUCOSE AND FRUCTOSE ASSESSED BY  
FUNCTIONAL MEASUREMENT**

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## Taste interaction between glucose and fructose assessed by functional measurement

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The description of the sensory interaction between two taste substances in terms of numerical responses obtained under a magnitude estimation instruction is biased, because the sensory processes are confounded with the judgmental process. Because the judgmental process is irrelevant to the sensory processes involved in the perception of taste substance mixtures, a correct description of mixture interaction can be obtained only with an experimental setup that separates the sensory processes from the judgmental process. Functional measurement in combination with a two-stimulus procedure can separate these two mechanisms. When this approach is used, parallelism in the factorial plot of the responses depends not on the underlying sensory processes, but on the comparative operation between two sensory impressions and on the form of the judgment function. In this experiment, solutions of glucose, three equiratio mixture types of glucose and fructose (i.e., mixtures in which the ratio of the components is constant), and fructose were compared with glucose solutions for sweetness intensity. Under the assumption that the comparative operation between two perceived sweetness intensities is subtractive, this scaling procedure yields interval scales of perceived sweetness intensity. The results showed that the data obtained are reliable, and that the psychophysical functions for equiratio mixtures of glucose and fructose lie in between the psychophysical functions for unmixed glucose and fructose.

Sensory interaction in mixtures of two qualitatively similar taste substances has frequently been studied using the method of magnitude estimation (e.g., Curtis, Stevens, & Lawless, 1984; Frijters, De Graaf, & Koolen, 1984; Frijters & Oude Ophuis, 1983; Moskowitz, 1971, 1973, 1974a, 1974b; Rifkin & Bartoshuk, 1980; Stone & Oliver, 1969; Stone, Oliver, & Kloeck, 1969). The use of this procedure, in conjunction with describing sensory interactions in terms of suppression, addition, and synergism, may lead to erroneous conclusions about the nature and magnitude of the taste interaction due to scaling artifacts. This is a major contention of this paper, and is substantiated below.

Magnitude estimation, as developed by Stevens (1956), originates from the stimulus-response (S-R) conception of psychophysics; it is assumed that the overt response is a perfect external representation of the internal sensation (McKenna, 1985; Shepard, 1981). In contrast, the stimulus-organism-response (S-O-R) paradigm of psychophysical judgment identifies a psychophysical stage relating stimulus to sensation and a judgmental stage relating sensation to overt response (Attneave, 1962; Torgerson, 1961; Treisman, 1964). Investigators who have adopted the S-O-R view have shown that the judgment function in magnitude estimation is a nonlinear and positively accelerating function of the internal sensation (e.g., Curtis, Attneave, & Harrington, 1968; Rule & Curtis, 1977; Rule, Curtis, & Markley, 1970; Veit, 1978; Weiss, 1972).

This implies that the description of the sensory interaction between two taste substances, in terms of numerical responses obtained by magnitude estimation, is biased by the nonlinear judgment function. This point can be elucidated by the following example. Suppose that concentration  $x$  M of substance A has a taste intensity of 5 units on a ratio scale, and that concentration  $y$  M of substance B has a taste intensity of 10 units, also on a ratio scale. If the two taste substances behave additively when mixed, then the taste intensity of a mixture containing  $x$  M of A plus  $y$  M of B should have a taste intensity of 15 units. If these three stimuli ( $x$  M of A,  $y$  M of B, and  $x$  M of A +  $y$  M of B) were presented in a magnitude estimation experiment in which the response function has the form (Perceived Intensity)<sup>1.47</sup> (1.47 being the mean value for the exponent of the response function found in magnitude estimation experiments; Birnbaum, 1980), then the reported magnitude of  $x$  M of A would be 11, that of  $y$  M of B would be 30, and the response to the mixture would be 54. From this result it would then erroneously be concluded that substances A and B behave synergistically when mixed, because the number 54 is larger than the sum of 30 and 11. This example demonstrates that in magnitude estimation, the sensory processes involved in the perception of the taste intensity of a mixture are confounded with the judgmental process. Since the judgment operation is irrelevant to the sensory interaction, a correct description of the sensory processes involved in the perception of taste substance mixtures can be achieved only by a measurement procedure that separates the sensory processes from the judgment function. We believe that a functional measurement approach in combination

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with a two-stimulus procedure (Anderson, 1981, 1982) is appropriate to achieve this goal.

The aim of the present experiment was to investigate the sensory interaction between two qualitatively similar taste substances, with a measurement procedure yielding overt responses that are a linear function of the perceived taste intensities. Since the psychophysics of taste mixtures has rarely been studied with a functional measurement procedure (Klitzner, 1975; McBride, 1986), some additional explanation is given first.

### FUNCTIONAL MEASUREMENT AND MIXTURES OF TASTE SUBSTANCES

One of the main features of functional measurement is the use of factorial designs as a tool for the evaluation of the form of the judgment function (Anderson, 1981). For the investigation of mixtures of taste substances, two different factorial designs can be constructed: one at a physical level and the other at a judgmental level. There is a fundamental difference between these two factorial designs.

A physical factorial design does not help to resolve the entanglement between sensory interaction and the judgment function. In this type of experimental design, parallelism in a factorial plot of responses is obtained if two conditions are satisfied. The first condition is that the two tastants in a mixture contribute in an additive way to the total taste intensity of the mixture. The second condition is that the judgment function is linear with perceived taste intensity. If, and only if, taste additivity holds, parallelism in a factorial plot signifies linearity of the judgment function. To put it differently, nonparallelism in a factorial plot can result from three different causes: (1) Tastants used for the mixture composition behave nonadditively; (2) responses are not linear with perceived taste intensity; or (3) a combination of 1 and 2. The contention that a factorial design at a physical level does not help to separate sensory interaction from the cognitive judgmental operation is based on the logical impossibility of distinguishing among these three causes.

The use of a factorial design at a judgmental level prevents the confounding between sensory interaction and the judgmental operation. Such a procedure allows for the determination of the shape of the judgment function independently from the nature of the sensory interaction that occurred. This argument is substantiated below.

McBride (1982, 1986) applied functional measurement to mixtures of taste substances. In a series of five experiments he investigated whether sucrose, fructose, and glucose in binary mixtures contribute in an additive way to the perceived sweetness intensity of those mixtures. Figure 1 diagrams McBride's experimental setup. The factorial design in these experiments was constructed at the physical level; each of a number of concentrations of sucrose, fructose, and glucose was mixed with each of a number of concentrations of one of the other sugars, yielding sucrose-fructose, sucrose-glucose, and fructose-glucose mixtures. We call this a *factorial mixing design*. The perceived sweetness intensities of single stimuli, each comprising two substances, were rated on a 13-point category scale. McBride found that the factorial plots of the obtained data in the five experiments did not exhibit sets of parallel lines: All plots showed a convergent and significant interaction between the two sugars constituting the mixtures. However, due to the nature of this type of experimental design, it is logically impossible to separate nonparallelism resulting from a nonlinear judgment function from nonparallelism resulting from a nonadditive sensory integration. As Figure 1 shows, in this type of experimental design the judgment function is still confounded with the sensory processes involved when two tastants are mixed.

Disentanglement of the sensory processes and the judgmental process can be achieved by a modified experimental setup that makes use of a two-operation model (see Anderson, 1974, Table II). This approach was first used in taste psychophysics by Klitzner (1975), who investigated whether the preference structure for mixtures of apple juice and a bitter substance could be described by an additive integration model. Klitzner found that the lines in the factorial plots of the responses converged, which

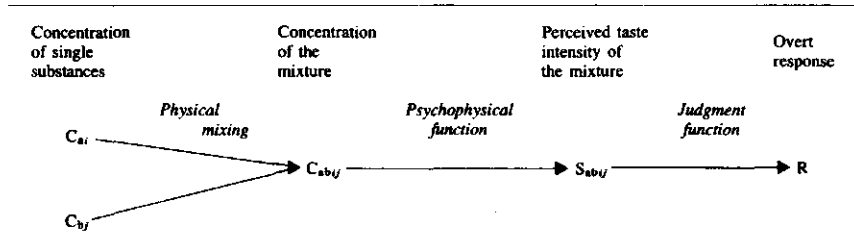


Figure 1. Outline of McBride's (1982, 1986) experimental setup from a stimulus-organism-response (S-O-R) point of view. Each concentration  $i$  of substance A is mixed with each concentration  $j$  of substance B (i.e., a factorial mixing design), resulting in concentration  $C_{Abij}$ . The mixture concentration  $C_{Abij}$  evokes perceived taste intensity  $S_{Abij}$ . The judgment function transforms  $S_{Abij}$  into the overt response  $R$ .

means that there was a significant interaction. However, as argued above, he was not in a position to decide whether this interaction resulted from the taste interaction or from a taste-hedonic interaction between the apple juice and the bitter substance. A third possibility would be a nonlinear relationship between preference and response. To determine the origin of the observed non-parallelism, he subsequently introduced a second judgmental step in the psychological model. In a second experiment, Klitzner asked subjects to judge the difference in preference between two bitter-substance/apple-juice mixtures. The parallelism of the lines in the factorial plot of the responses in this experiment demonstrated that the preference-response function was linear. On the basis of this result, Klitzner argued that the interaction in the factorial plot in the first experiment had most probably been due to a nonadditive taste interaction or to a taste-hedonic interaction between apple juice and the bitter substance.

Two-operation models in psychophysics have been extensively investigated by Birnbaum and colleagues (Birnbaum & Elmasian, 1977; Birnbaum & Mellers, 1978; Birnbaum & Veit, 1974; Hagerly & Birnbaum, 1978; Mellers, Davis, & Birnbaum, 1984; Veit, 1978). In these experiments, a factorial design was not used at a physical level, as it was in McBride's (1982, 1986) experiments, but it was used at a judgmental level (i.e., a *factorial judgment design*). The subjects compared the sensory impression of each level of the row stimulus with the sensory impression of each level of the column stimulus. Figure 2 illustrates this type of experimental setup. A major advantage of this setup is that parallelism or non-parallelism in the factorial plot of the data obtained does not depend on the underlying sensory processes (including the psychophysical functions). Parallelism or non-parallelism in this type of experiment depends on the na-

ture of the comparative operation between two sensory impressions and also on the form of the judgment function; it cannot depend on sensory interaction, because the stimuli used are not compound stimuli. From four studies carried out with such a two-stimulus procedure, it was concluded that the comparative operation between two sensory impressions can be best described by an algebraic subtractive rule, even when subjects are instructed to judge ratios (Birnbaum & Mellers, 1978; Hagerly & Birnbaum, 1978; Mellers et al., 1984; Veit, 1978).

Application of this approach to taste mixtures implies that the perceived taste intensity of each of a number of concentrations of the row stimulus should be compared with the perceived taste intensity of each of a number of concentrations of the column stimulus. Because we are dealing with taste mixtures, the row and column stimuli may consist of mixtures of taste substances, instead of unmixed tastants. The question then arises of how to deal with the physical composition of these mixtures. In most experiments, the physical intensity of a stimulus is varied in one dimension (e.g., weight in kg, sound pressure in  $N/m^2$ ), whereas in mixtures of taste substances there are two stimulus dimensions that are being manipulated (i.e., the concentrations of each of two substances in a binary mixture). This problem can be handled by conceiving of a binary mixture of taste stimuli as if it were one particular type of taste stimulus; this was done by Frijters and Oude Ophuis (1983), who introduced the concept of the *equiratio taste substance mixture*. An *equiratio mixture* type was defined as a series of taste substance mixtures in each of which the ratio of the components is constant. Frijters and Oude Ophuis showed that a psychophysical function of an *equiratio mixture* type can be experimentally determined in the same way as such a function for a single substance. The measure of physical intensity of

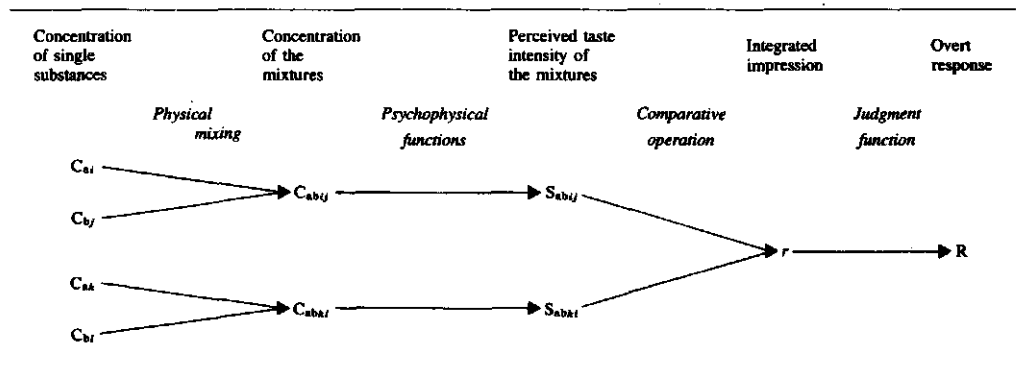


Figure 2. Outline of the present experimental setup from a stimulus-organism-response (S-O-R) point of view. Concentration  $i$  of substance A is mixed with concentration  $j$  of substance B, resulting in mixture concentration  $C_{abij}$ . Mixing of  $k$  of A and  $l$  of B results in mixture concentration  $C_{abkl}$ . Both *equiratio* mixtures (i.e.,  $ilj = \text{constant}$  and  $k/l = \text{constant}$ ) and single substances (i.e., either  $i$  or  $j = 0$  or  $k$  or  $l = 0$ ) were used. The concentrations  $C_{abij}$  and  $C_{abkl}$  evoke perceived taste intensities  $S_{abij}$  and  $S_{abkl}$ , respectively. If the comparative operation between two perceived taste intensities can be represented by an algebraic difference function, then the integrated impression  $r$  resembles the perceived difference between  $S_{abij}$  and  $S_{abkl}$ . Each  $S_{abij}$  is compared with each  $S_{abkl}$  (i.e., a factorial judgment design). The judgment function transforms  $r$  into the overt response  $R$ .

a mixture is the total concentration of the mixture (i.e., the sum of the concentrations of the mixture's components). Figure 2 diagrams the present approach to the psychophysics of taste mixtures. A complete factorial design in such an experiment consists of a comparison of the perceived taste intensity of each level of a mixture having concentration  $i$  of substance A and concentration  $j$  of substance B ( $C_{abij}$ ) with the perceived taste intensity of each level having concentration  $k$  of substance A and concentration  $l$  of substance B ( $C_{abkl}$ ).

To draw a logically sound conclusion about the sensory interaction between two taste substances, we must compare the perceived taste intensities of the mixture with the perceived taste intensities of the mixture's unmixed components. For that reason, concentrations of the single substances (i.e., either  $i$  or  $j = 0$ , or  $k$  or  $l = 0$ ) also have to be incorporated in the factorial judgment design. The experimental setup in the present study consisted of a series of factorial designs, in each of which the perceived taste intensity of each of a number of mixtures was compared with the perceived taste intensity of each of a number of concentrations of an unmixed substance.

If it is assumed that the comparative operation between two perceived taste intensities follows a subtractive rule, then parallelism in the factorial plot of the obtained responses implies that the judgment function is linear with sweetness differences. If this is the case, it is possible to obtain scale values for the perceived intensities of mixtures of taste substances (or single substances) on linear scales, and psychophysical functions can be constructed subsequently.

## METHOD

### Subjects

Twelve paid volunteers were used, 10 women and 2 men, ranging in age from 18 to 25 years. All subjects were graduate or undergraduate students from the Agricultural University. Most of the subjects had had previous experience with psychophysical tasks, but all were naive with respect to the substances used and the purpose of the study.

### Stimuli

The stimuli were solutions of glucose (Merck: 15639), fructose (Merck: 5321), and three equiratio mixture types in demineralized water. The equiratio mixture types comprised mixtures containing

three times as much glucose as fructose (GluFru 0.75/0.25), mixtures with an equal concentration of both substances (GluFru 0.50/0.50), and mixtures containing three times as much fructose as glucose (GluFru 0.25/0.75). Solutions were prepared at least 24 h before tasting and stored for no longer than 5 days at 4°C. The concentrations used were the same for each of the five stimulus types: 0.000 (water), 0.125, 0.25, 0.50, 1.00, and 2.00 M. Water and 2.50-M fructose served as the reference pair.

### Design

Glucose, GluFru 0.75/0.25, GluFru 0.50/0.50, GluFru 0.25/0.75, and fructose were all compared with glucose in nine separate 6 (concentrations of the first stimulus)  $\times$  6 (concentrations of the second stimulus) factorial designs. In four factorial designs glucose served as the first stimulus and either fructose or one of the three equiratio mixture types was the second stimulus, in four other designs the converse sequence was used, and in one design both the first and second stimulus contained glucose only.

### Procedure

The subjects were instructed to judge the magnitude of the difference in perceived sweetness intensity between the first and second stimulus within each pair. The instructions emphasized that only the sweetness intensity was to be judged, and that both the hedonic value and side tastes were to be disregarded. The judgments were to be expressed by a slash mark on a 250-mm symmetric scale (see Figure 3), of which the middle (having the assigned value of 125) was defined as "the first and second stimulus are equal in sweetness intensity" (no difference). When the second stimulus was perceived as sweeter than the first stimulus, the subjects were to mark a slash on the right-hand side of the scale. When the first stimulus was perceived as sweeter than the second, the subjects were to mark a slash on the left-hand side of the scale. In the instructions, the term *maximum difference* was defined as the difference between the perceived sweetness intensities of the stimuli within the reference pair (water as the first stimulus and a 2.5-M fructose solution as the second stimulus). The difference in this pair was expected to be larger than the difference in any other pair to be judged in the experiment.

The subjects were requested to rinse their mouths thoroughly with demineralized water both between the two stimuli within a pair and between pairs. The stimuli were presented at room temperature in polystyrene medicine cups, each cup containing about 10 ml of solution. Each factorial design was composed of 36 (6  $\times$  6) pairs, presented in a random sequence and in a different order for each subject. The reference pair was presented at the beginning of each session and again after the 12th and 24th pair of a series. In a pilot study, it had been determined that a time interval of 50 sec between the first and second stimulus of a pair was sufficient to prevent adaptation. The time interval between pairs was also 50 sec. Each of the nine series of 36 pairs was tasted three times by each subject.

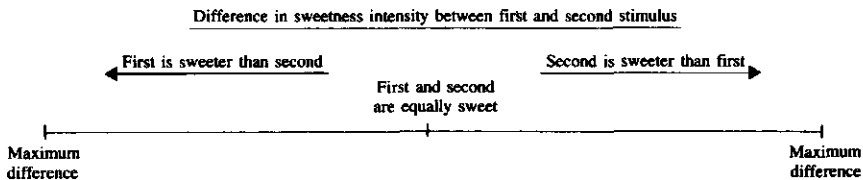


Figure 3. The 250-mm rating scale (shown at 50.8%) used by subjects to assess the difference in perceived sweetness intensity between the first and second stimulus within a pair. The responses were measured as the distance in millimeters from the left anchor of the scale. Thus, the left anchor of the scale is 0 (mm), the middle of the scale (implying no difference in sweetness intensity between the first and second stimulus) is 125 (mm), and the right anchor of the scale is 250 (mm).

The order of presentation of the various series was randomized. In each session, one series of 36 pairs was judged by each subject, so it took each subject 27 sessions to complete the experiment.

## RESULTS

To draw conclusions about the sensory interaction between glucose and fructose, it is necessary to derive one scale value for each stimulus tasted. This scale value should represent the perceived sweetness intensity on a linear scale. However, before these scale values can be calculated, it must be determined whether or not the judgment function is linear.

### The Judgment Function

The subjects were instructed to judge the difference between the perceived taste intensities within each pair of stimuli. If it is assumed that subjects have indeed judged a difference (i.e.,  $r = S_{abij} - S_{abik}$ ; see Figure 2), parallelism in a factorial plot implies that the response function is linear with the perceived difference (i.e.,  $R = a + br$ ). The term *factorial plot* refers to a plot of reported differences (not of the perceived taste intensities themselves) against the concentration of the second stimulus with a separate curve for each concentration of the first stimulus.

Because individuals may vary in their (linear or nonlinear) judgment functions, or in their comparative operations (which may or may not be subtractive), we first performed individual analyses. To test whether parallelism was actually obtained, an analysis of variance was carried out for each subject and each type of design (i.e.,  $12 \times 9 = 108$  analyses). The measure of the degree of nonparallelism, that is, the row  $\times$  column interaction, was tested for statistical significance, with the row  $\times$  column  $\times$  replicate interaction as error term. Two subjects showed significant row  $\times$  column interactions at the  $p < .01$  level [ $F(25,50) \geq 2.12$ ] in two or more of their nine response matrices. Apparently, either these subjects had nonlinear response functions or their comparative operations were not subtractive. The data derived from these subjects were excluded from further data analyses. In the analyses of the 10 remaining subjects, no significant interactions at the  $p < .01$  level were obtained.

After these individual analyses, the responses for each pair were averaged across the three replicates and the 10 subjects. Figure 4 shows the arithmetic mean of the responses to each pair for each of the nine factorial designs. Analyses of variance for each of the nine response matrices showed no significant row  $\times$  column interactions (see upper left part of each panel in Figure 4). The error term for this interaction in these group analyses was the row  $\times$  column  $\times$  subject interaction. The six curves within each of the nine panels show no systematic deviations from parallelism; therefore, it can be concluded that the responses are linear with sweetness differences.

It should be noted that, in principle, parallelism in a factorial plot can also be obtained by a nonsubtractive

comparative operation in combination with a nonlinear judgment function, for example, a ratio operation in combination with a logarithmic judgment function (Birnbbaum, 1982). It is logically impossible to decide from the data which combination of comparative operation and judgment function is used; this is the problem of "monotonic indeterminacy" (Anderson, 1974). However, considering that the subjects were explicitly instructed to make difference judgments, and in view of a substantial body of empirical evidence supporting a difference operation (Birnbbaum & Mellers, 1978; Hagerty & Birnbbaum, 1978; Mellers et al., 1984; Veit, 1978), it is likely that the observed parallelism in the present experiment resulted from the use of difference judgments in combination with linear judgment functions.

### Scale Values of Perceived Sweetness Intensity

The observed parallelism also implies that the marginal means of the row (first) and column (second) stimuli are valid estimates of the sweetness intensities of the corresponding row and column concentrations on linear scales (Anderson, 1981). As water was incorporated in each of the series of row and column stimuli, the scale value of water can be used as a conventional point of reference. The perceived sweetness intensity of each stimulus can then be defined as the distance between the scale value of that stimulus and the scale value of water. For practical purposes, the scale value of water was set equal to zero. If it is assumed that water lacks a sweet taste, then this point might be treated as an absolute zero point for the scale of perceived sweetness intensity, implying that the derived scale is a ratio scale. However, it appears that additional evidence is required before we can claim that the developed scale does indeed have ratio scale properties.

Table 1 shows, for illustrative purposes, the derivation of scale values for sweetness intensity for the fructose-glucose factorial judgment design. Each factorial design yielded two marginal means for water—one for water as the first stimulus in a pair, and one for water as the second stimulus. The scale values for each of the sugar-containing row stimuli were determined by calculating the difference between their respective marginal means and the marginal mean of water in that same design. The scale values of the column stimuli were determined in a similar way. These calculations yielded 10 sets of scale values for glucose—5 sets for glucose as the first stimulus (of each pair) and 5 sets for glucose as the second stimulus (of each pair). For fructose and each of the three equiratio mixture types, two sets of scale values were derived—one set for each stimulus when presented as the first stimulus, and one set for each stimulus when presented as the second stimulus. The scale values for each row (first) stimulus were virtually identical to the scale values for the same stimulus when it was used as column (second) stimulus. This result indicates an absence of order effects.

The conclusion that there were no order effects can also be reached through another line of reasoning. Each stimu-

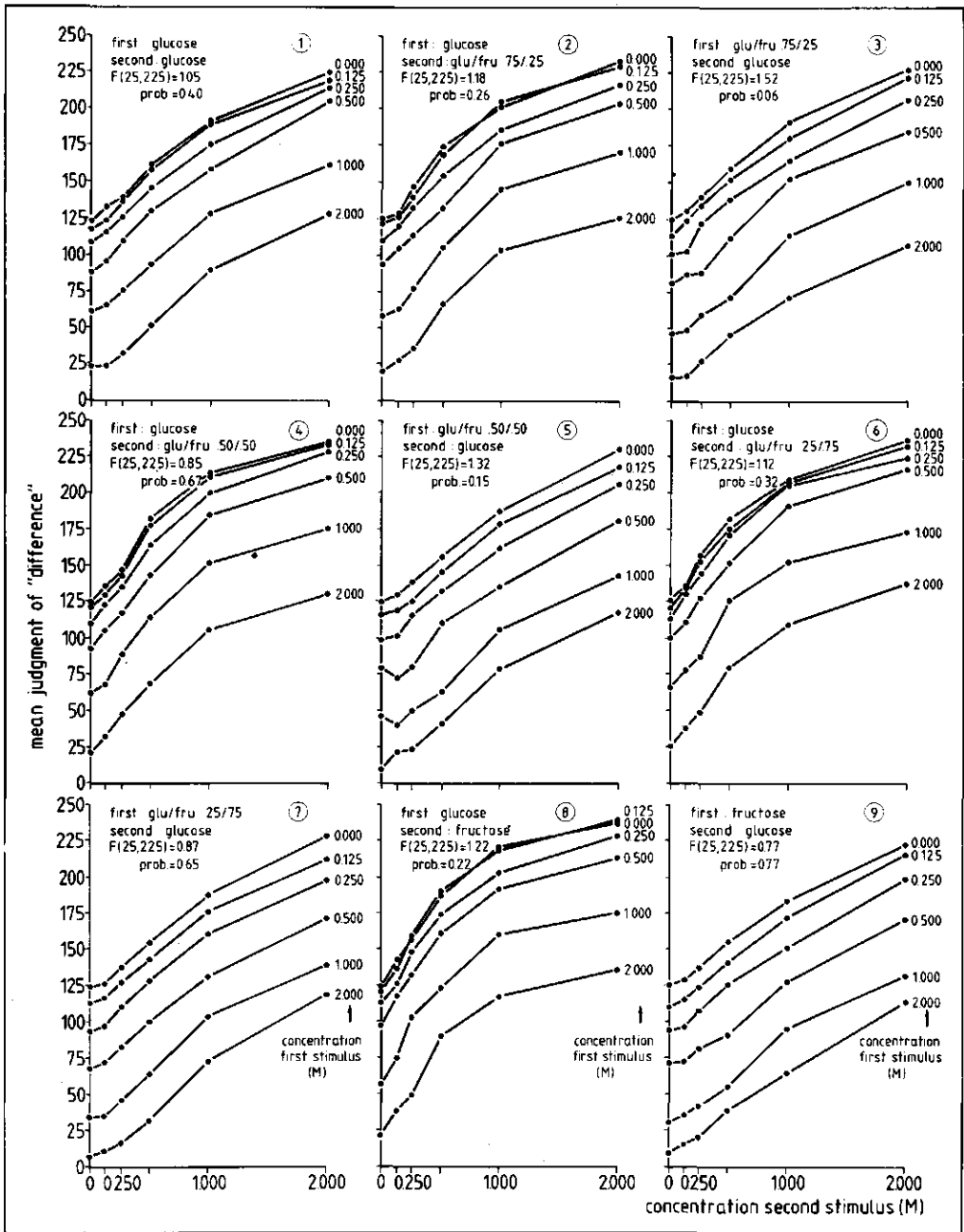


Figure 4. Mean reported judgment of difference in perceived sweetness intensity between the first and second stimulus within a pair. Each panel represents a different factorial judgment design. The substances used and the  $F$  ratio for the row (first)  $\times$  column (second) interaction are given in the upper left part of each panel.

Table 1  
Derivation of Ratio Scale Values of Perceived Sweetness Intensity

Concentration (M) of the First Stimulus (Fructose)	Concentration (M) of the Second Stimulus (Glucose)						Marginal Mean First Stimulus	Distance to Scale Value of Water
	0.000	0.125	0.250	0.500	1.000	2.000		
0.000	125.37	129.27	137.93	154.70	183.60	223.33	159.03	0.00
0.125	110.10	115.33	122.90	140.73	173.37	215.90	146.39	12.64
0.250	94.53	96.13	107.57	124.60	151.03	199.17	128.84	30.19
0.500	71.30	71.63	75.93	90.53	128.33	171.87	101.60	57.30
1.000	31.87	36.63	41.53	55.20	95.47	131.97	65.44	93.59
2.000	9.87	16.07	20.07	38.03	64.07	113.33	43.75	115.46
Marginal mean second stimulus	73.84	77.51	84.32	100.63	132.64	175.93		
Distance to scale value of water	0.00	3.67	10.49	26.79	58.80	102.09		

Note—The figures in the response matrix represent the mean reported difference between the first (row) stimulus and second (column) stimulus within each pair of the fructose(first)-glucose(second) factorial judgment design.

lus was presented the same number of times as the first and as the second stimulus. Without an order effect, the overall arithmetic mean of the responses should be 125 (i.e., the middle of the scale). If the first stimulus had a greater weight than the second stimulus in determining the response, the overall mean would be lower than 125. Similarly, if the second stimulus had a greater weight, the overall mean would be higher than 125. The means (averaged over  $9 \times 36 \times 3 = 972$  responses) for each of the 10 subjects were 126.0, 123.1, 124.0, 127.0, 125.4, 125.2, 126.8, 126.5, 126.7, and 125.6. The value of the standard errors of the means is about 2, so none of these values deviates significantly from 125. Therefore, it can be safely concluded that no order effects occurred.

The final scale value for each stimulus was obtained by calculating the arithmetic mean of the scale value(s) for that stimulus when tasted first and the scale value(s) of that stimulus when tasted second. The final scale values of each stimulus are shown in Figure 5.

Bogartz (1980) proposed an analysis of variance procedure to test whether the row psychophysical function is the same as the column psychophysical function. How-

ever, this test can be applied only to designs in which the series of row stimuli and the series of column stimuli are the same. In the present study, this was the case for the glucose-glucose design only. Using a second-order polynomial function as an approximation of the unknown psychophysical function (Bogartz, 1980), we performed an analysis of variance on the means of the overt responses for the glucose-glucose design. No difference was found between the psychophysical function for glucose tasted first (row) and the psychophysical function for glucose tasted second (column) [ $F(2,31) = 0.81, p > .5$ ]. This provides additional justification for averaging the scale values of the row and column stimuli.

#### Comparison With Matching Data

The reliability (not the validity) of the present data was verified through comparison of the present data with data on glucose-fructose mixtures obtained by matching in an earlier experiment (De Graaf & Frijters, 1986). In that experiment, fructose, GluFru 0.75/0.25, GluFru 0.50/0.50, and GluFru 0.25/0.75 were matched in perceived sweetness intensity to 0.125-, 0.25-, 0.50-, 1.00-, and 2.00-M glucose, using the method of constant stimuli. These data were shown to be accurate: the points of subjective equality (PSEs) in 10 control experiments had a mean absolute error of 0.64%.

The PSEs in the present experiment were calculated as follows. For fructose, GluFru 0.25/0.75, GluFru 0.50/0.50, and GluFru 0.75/0.25, second-order polynomial regression equations were fitted with  $\log(\text{concentration})$  and  $[\log(\text{concentration})]^2$  as independent variables and the log of the final scale values as a dependent variable. All fitted functions had an  $R^2$  of 0.9998 or higher, and were monotone with the relevant domain. The obtained equations were set equal to the log of the five scale values of glucose concentrations, and the resulting quadratic equations were resolved for the log of the required concentration.

Table 2 shows that the PSEs determined from the present data have an average absolute deviation of about

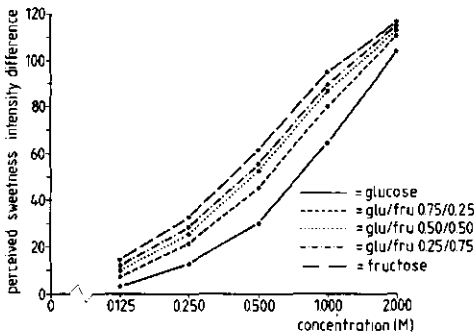


Figure 5. Scale values of the differences in perceived sweetness intensity between water and glucose, fructose, and the three equimolar mixture types.

Table 2  
Comparison of Points of Subjective Equality (PSEs) Determined Using the Method of Constant Stimuli\* and PSEs Calculated From the Data of the Present Study

Concentration of Glucose (M)	Type of Comparison Stimulus	PSE Determined From Matching (M)	PSE Determined From Present Data (M)	Difference in %
				$\frac{PSE_{\text{matching}} - PSE_{\text{present}}}{PSE_{\text{matching}}}$
0.125	Fructose	0.0485	0.0480	-1.0
0.125	GluFru 0.25/0.75	0.0540	0.0558	+3.3
0.125	GluFru 0.50/0.50	0.0650	0.0666	+2.5
0.125	GluFru 0.75/0.25	0.0873	0.0772	-11.6
0.250	Fructose	0.1027	0.1038	+1.0
0.250	GluFru 0.25/0.75	0.1206	0.1298	+7.6
0.250	GluFru 0.50/0.50	0.1439	0.1486	+3.2
0.250	GluFru 0.75/0.25	0.1817	0.1739	-4.3
0.500	Fructose	0.2374	0.2275	-4.0
0.500	GluFru 0.25/0.75	0.2682	0.2594	-3.3
0.500	GluFru 0.50/0.50	0.3118	0.2862	-10.8
0.500	GluFru 0.75/0.25	0.3639	0.3308	-9.1
1.000	Fructose	0.5790	0.5266	-9.1
1.000	GluFru 0.25/0.75	0.5928	0.6013	+1.4
1.000	GluFru 0.50/0.50	0.6550	0.6350	-3.1
1.000	GluFru 0.75/0.25	0.7729	0.7221	-6.5
2.000	Fructose	1.3828	1.3038	-5.7
2.000	GluFru 0.25/0.75	1.4007	1.4587	+4.1
2.000	GluFru 0.50/0.50	1.4552	1.4841	+1.9
2.000	GluFru 0.75/0.25	1.6310	1.6506	+1.2
Mean absolute deviation:				4.7

\*From De Graaf and Frijters (1986).

5% from the PSEs determined from the matching data. There appears to be no systematic deviation; nearly half of the PSEs estimated from the present study are higher than those obtained from matching, and half are lower. The greatest deviation is -11.6%, which is less than one JND.

It should be borne in mind that the present psychophysical functions were established on the basis of the assumption that the scale value of water can be used as a conventional point of reference that can be set equal to zero. If this assumption were incorrect (e.g., if water evoked a different sensory impression when compared to glucose than when compared to fructose), systematic deviations between the two sets of PSEs would have resulted. Because there are no such deviations, the data of Table 2 support the validity of the assumption that water represents a meaningful zeropoint.

#### Sensory Interaction Between Glucose and Fructose

As Figure 5 shows, the scale values of equiratio mixtures lie in between the scale values of equimolar concentrations of unmixed glucose and unmixed fructose. Thus, the sweetness intensity of a particular mixture of glucose and fructose does not exceed the sweetness intensity of an equimolar concentration of fructose, nor is it less than the sweetness intensity of an equimolar concentration of glucose. When the proportion of fructose in a mixture increases, the scale value of the mixture approaches the scale value of an equimolar concentration

of fructose. Similarly, when the proportion of glucose in a mixture increases, the scale value of the mixture approaches the scale value of an equimolar concentration of glucose.

#### DISCUSSION

The similarity of the present data, obtained by direct scaling, to the data obtained by matching (De Graaf & Frijters, 1986) shows that the scaling approach proposed in this study results in reliable estimates of perceived sweetness intensity. In addition, the present methodology provides a means of separating the sensory processes involved when mixing two tastants from the judgmental process. It makes possible an unbiased description of the sensory interaction between glucose and fructose.

#### The Sensory Interaction Between Glucose and Fructose

One conclusion to be drawn from the present results is that the psychophysical functions of equiratio mixtures of glucose and fructose lie in between the psychophysical functions of unmixed glucose and fructose. When the proportion of fructose in a fructose-glucose mixture increases, the behavior of the mixture approaches the behavior of fructose. Similarly, when the proportion of glucose in such a mixture increases, the behavior of the mixture becomes more like that of glucose. Thus, the values of the parameters of the psychophysical functions of equiratio mixtures of glucose and fructose (irrespec-



tive of their forms) lie in between the values of the parameters of the psychophysical functions of unmixed glucose and fructose. This conclusion confirms the results of Frijters and Oude Ophuis (1983), who used the same stimuli but used magnitude estimation as the scaling method.

The nature of the taste interaction between two taste substances is usually characterized in terms of suppression, addition, and synergism, meaning, respectively, that the perceived taste intensity of a mixture is less than, equal to, or greater than the sum of the intensities of the unmixed components (e.g., Stone & Oliver, 1969; van der Heyden, Brussel, Heidema, Kosmeyer, & Peer, 1983; Yamaguchi, Yoshikawa, Ikeda, & Ninomiya, 1970). As Frijters (in press) noted, a description of the taste interaction in these terms requires that the perceived taste intensities be assessed on a ratio scale. Some investigators hold the view that the type of sensory interaction is an attribute of the components used for mixture composition. We do not share this view. Following Bartoshuk (1975, 1977), we take the position that the type of sensory interaction that occurs is dependent on the shape of the psychophysical functions of the mixture's constituents. However, knowing the magnitude of the exponent of these functions, which is often thought to give an adequate description of the form of the psychophysical function, is insufficient for predicting the type of taste interaction that will occur. Assuming that the present scale values resemble perceived sweetness intensities on a ratio scale, it would be concluded that at the low sweetness levels used in this experiment, glucose and fructose show synergism when mixed. A 0.125-M glucose solution has a sweetness intensity of about 3 units (see Figure 5), a 0.125-M fructose solution has a perceived sweetness intensity of 14 units, and a mixture of both concentrations (i.e., 0.25 M of the GluFru 0.50/0.50 mixture) has a sweetness intensity of 25 units ( $25 > 3+14$ ). At intermediate levels, it would be concluded that addition takes place. A 0.50-M glucose solution is 30 units sweet, a 0.50-M fructose solution is 61 units sweet, and a mixture of these concentrations (i.e., 1.00 M of the GluFru 0.50/0.50 mixture) is 88 units sweet, which is almost equal to the sum of the intensities of the unmixed components ( $30+61 = 91$ ). At high intensities, it would be concluded that glucose and fructose suppress each other, because the sweetness intensity of a mixture of 1.00-M glucose and 1.00-M fructose (i.e., 2.00 M of the GluFru 0.50/0.50 mixture) is 114 units, which is less than the sum of the intensities of the unmixed components (1.00-M glucose is 64 units sweet, and 1.00-M fructose is 90 units sweet). The kind of taste interaction is evidently related to the forms and local steepnesses of the psychophysical functions of glucose and fructose. These are positively accelerating at low concentrations and negatively accelerating at high concentrations.

The conclusion that glucose and fructose show synergism at low sweetness levels is not in line with the results of McBride (1986), who concluded that glucose and fructose show additivity at low sweetness levels. However,

McBride did not present unmixed glucose and fructose; he presented only mixtures. Therefore, in his study, the perceived taste intensity of a mixture could not be compared with the sum of the perceived taste intensities of the mixture's components outside the mixture. McBride's results therefore suggest an additive increment in sweetness intensity when the concentration of one of the two substances in the mixture is increased, at low sweetness levels only.

### Sensory Interaction in General

The sweetness intensity of glucose-fructose mixtures always lies in between the sweetness intensities of equimolar concentrations of the unmixed components. This has also been observed for sucrose-sorbitol mixtures (Frijters et al., 1984) and mixtures of L-ascorbic acid and itaconic acid (Frijters & Stevens, 1986). The same rule appears to apply for a host of pairs of sugars (De Graaf & Frijters, 1987). Interpretation of these findings suggests a general rule applicable to binary mixtures of substances with similar tastes: The taste intensity of any mixture of A and B having a particular molarity lies in between the taste intensities of the components A and B, each having the same molarity as that of the mixture. This rule, suggested earlier by De Graaf and Frijters (1987), is in contrast to McBride's (1986) notion that the sweetness intensity of sucrose-fructose mixtures may exceed the highest intensity of the unmixed components. His claim is based on the use of weight/volume as the measure of concentration. When McBride's comparison of the psychophysical functions of sucrose, fructose, and the sucrose-fructose equiratio mixture are replotted with molarity as the measure of concentration, this appears not to be the case. We hold the view that comparisons should be made on the basis of molarity, not percentage of weight/volume, because molecules are the basic units for elicitation of a taste response.

### Conclusion

Functional measurement in combination with the use of equiratio mixtures and a two-stimulus procedure provides a means of separating the sensory processes involved when mixing two taste substances from the judgmental process. In the present experiment, this methodology was used to derive psychophysical functions for glucose, fructose, and three equiratio mixture types of the two. The results confirm earlier findings that the taste intensity of a mixture of similar-tasting substances lies in between the intensities of the components when the concentration of the mixture and the concentrations of the components (outside the mixture) are the same.

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## CHAPTER SIX

### ASSESSMENT OF THE TASTE INTERACTION BETWEEN TWO QUALITATIVELY SIMILAR TASTING SUBSTANCES: A COMPARISON BETWEEN COMPARISON RULES

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**ABSTRACT** The taste interaction between sucrose and fructose was assessed using three different comparison procedures; the summated response comparison, the factorial plot comparison, and the equimolar comparison rule. The perceived sweetness intensities were obtained on a ratio scale using a functional measurement approach in combination with a two stimulus procedure. The conclusions obtained from each of the three comparison rules were identical. The taste interaction between sucrose and fructose could be explained to a large extent, but not completely, by the apparent taste "interactions" within sucrose and fructose as single substances. It is argued that the apparent taste "interaction" within a large number of single sugars, and the taste interaction between two of these sugars in a mixture is a little synergistically at low sweetness levels, additive at intermediate sweetness levels, and suppressive at high sweetness levels.

## INTRODUCTION

There are two reasons why studies of taste mixture phenomena are carried out. The first is a practical one. Food scientists nowadays substitute traditional tastants by compounds which supposedly have more desirable characteristics from the point of view of food production or marketing. For example, sucrose is substituted by aspartame in soft drinks to obtain a beverage of low caloric content. In the terminology of food science two compounds behave synergistically, additively or suppressively, respectively, if a binary mixture of these tastants contains a smaller, an equal or a larger amount of substance than an unmixed compound of the same taste intensity (Homler, 1984). For example, suppose that  $x$  mol/L of sweetener A and  $y$  mol/L of substance B have the same sweetness intensities. Two substances show addition if a mixture containing  $p$  times A and  $(1 - p)$  times B ( $0 < p < 1$ ) has the same sweetness intensity as the unmixed compounds. If less substance is needed to elicit the same sweetness intensity, i.e., the mixture contains less than  $p$  times A and/or less than  $(1 - p)$  times B, the components in the mixture are supposed to behave synergistically. This definition of a taste interaction in mixtures evolves from stimulus substitution, and is currently used in the food industry. It can be found in a large number of studies on the industrial application of tastant mixtures. As these studies were not aimed at the study of perceptual phenomena in taste substance mixtures as such, we will not discuss in this article the rules used for assessment of taste interaction in the industry.

The second reason for studying taste mixture interactions is that understanding the behaviour of two compounds in a mixture can help to clarify perceptual and sensory physiological mechanisms of the modality of taste. Two taste substances can interact at various levels in the transduction process, for instance at a physical-chemical level in the solution, at the periphery of the taste sense where molecules of the components of

the mixture can compete for adsorption at the same receptor sites, at a peripheral neural level, or at a central level. However, before the relevance of taste interaction phenomena for these issues can be addressed properly, it must first be clear how the taste interaction in mixtures can be assessed. This is the background of the present paper.

One problem in the psychophysical taste mixture literature is the inconsistency of use of terminology for describing taste mixture interactions (Frijters, in press). It is often unclear as to what rule or reasoning is being used to conclude that a certain mixture interaction has occurred in a particular instance. Currently there are three comparison rules in use, illustrated in Figure 1, panels A and B.

#### The summated comparison rule

With the most frequently used procedure, called the summated response comparison (De Graaf & Frijters, 1987) (Figure 1, panel A), the taste interaction is inferred from the comparison of the perceived taste intensity of the mixture ( $R_{b_{xx}}$ ) with the sum of the perceived taste intensities of its components ( $R_{bx}$ ,  $R_{bx}$ ) when tasted independently (Curtis, Stevens & Lawless, 1984; Hyvönen, 1980; Moskowitz, 1973, 1974a, 1974b; Stone & Oliver, 1969; Stone, Oliver & Kloehn, 1969; Yamaguchi, Yoshikawa, Ikeda & Ninomiya, 1970b). In this case, the taste interaction is usually described in terms of either suppression, addition, or synergism, where ( $R_{b_{xx}} < R_{bx} + R_{bx}$ ), ( $R_{b_{xx}} = R_{bx} + R_{bx}$ ), and ( $R_{b_{xx}} > R_{bx} + R_{bx}$ ), respectively.

Bartooshuk (1975, 1977) and Bartooshuk & Cleveland (1977) demonstrated that the nature of the interaction that occurs according to the summated response comparison rule depends on the forms of the psychophysical functions of the mixture's components. If the functions are compressing suppression occurs and when both functions are expanding synergism will occur. However, explanation of the taste interaction between two

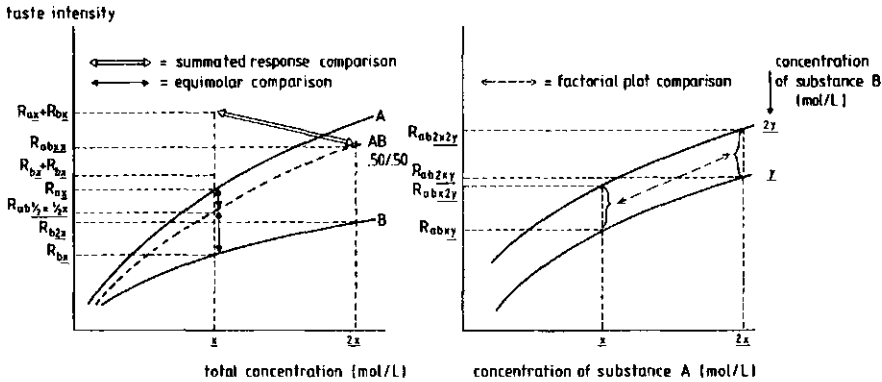


Figure 1. Illustration of three different procedures for the assessment of the taste interaction between two taste substances.

Panel A shows hypothetical psychophysical functions for substance A, substance B, and the AB 50/50 equiratio mixture type. Using the 'summated response comparison rule', the response to a mixture containing  $x$  mol of A, and  $x$  mol of B ( $= R_{abxx}$ ) is compared to the sum of the responses to the mixture's components when tasted alone ( $= R_{ax} + R_{bx}$ ). Using the 'equimolar comparison rule', the responses to the mixture and the single compounds are compared at those concentrations, where each of the single compounds and the mixture have equal total molarities. Thus, the responses  $R_{ax}$  and  $R_{bx}$  are not compared to  $R_{abxx}$ , but to  $R_{ab1/2x1/2x}$  i.e., the response to a mixture containing a  $1/2 x$  mol of A, and a  $1/2 x$  mol of B.

Panel B plots sensory response as a function of the concentration of substance A with a separate curve for each of two concentrations of substance B ( $y$  and  $2y$  in this example). It should be noted that in panel B, the x-axis represents the concentration of substance A, whereas in panel A, the x-axis represents the total concentration. The 'factorial plot comparison' investigates how the increment in taste intensity, due to the addition of a particular concentration of substance B (from  $y$  to  $2y$  in this example) to an AB mixture, varies over different levels of substance A ( $x$  and  $2x$  in this example). Thus,  $(R_{abx2y} - R_{abxy})$  is compared to  $(R_{ab2x2y} - R_{ab2xy})$ .

qualitatively similar taste substances on the basis of the slopes of the psychophysical functions does not separate the taste interaction between the two taste substances from the apparent taste "interaction" within the single components themselves. For

example, if a particular taste substance has a compressing psychophysical function, then the apparent taste "interaction" of that taste substance with itself is suppressive. This example is illustrated in Figure 1, panel A. If concentration  $x$  of substance B with an intensity of  $R_{bx}$  is added to itself, the intensity of the mixture containing  $2x$  Mol/L of B becomes  $R_{b2x}$ . This is less than  $(R_{bx} + R_{bx})$ . If two taste substances are mixed instead of adding more of one to itself and each has a compressive psychophysical function, suppression will also occur, according to Bartoshuk. However, from this finding it cannot be concluded that suppression is entirely the result of the properties of the substances that are mixed. It only indicates that the taste interaction between these two substances is the same as the apparent taste "interaction" that would have occurred within each of these substances. A description of the specific taste interaction between two substances can only be obtained by separating it from the apparent taste "interactions" within the substances. Disentanglement of the taste interaction between and apparent taste "interactions" within taste substances can be achieved. 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.

As already noted by Frijters (in press) and De Graaf, Frijters & Van Trijp (1987), application of the summated comparison rule requires that the perceived taste intensities are assessed on a ratio scale. Another requirement is that the concentrations of the components in the mixture are identical to the concentrations of the components tasted separately outside the mixture.

#### The factorial plot comparison rule

McBride (1986) introduced another method for the assessment of taste interactions. This method is based on the principle of factorial plot comparison (Figure 1, panel B), originating from

the theory of information integration (Anderson, 1981, 1982). The nature of the taste interaction is inferred from the pattern of lines in a factorial plot. This is a plot of taste intensity as a function of concentration level of one component with a separate curve for each concentration of the other component. If the lines in such a plot diverge, i.e.,  $(R_{ab2x2y} - R_{ab2xy}) > (R_{abx2y} - R_{abxy})$ , synergism occurs. If the lines run parallel, i.e.,  $(R_{ab2x2y} - R_{ab2xy}) = (R_{abx2y} - R_{abxy})$ , addition takes place, and if the lines show a convergent pattern, i.e.,  $(R_{ab2x2y} - R_{ab2xy}) < (R_{abx2y} - R_{abxy})$ , two taste substances suppress each other. With respect to the separation of taste interaction between and the apparent taste "interactions" within substances, the same applies as in the case of the summated response comparison. In order to draw a proper conclusion about the specific taste interaction between two substances, this interaction must be compared with the apparent taste "interaction" within each of the single substances. Assessing the apparent taste "interaction" within a single substance can be achieved by conceiving a single compound solution as a mixture of that substance with itself, and subsequently constructing a factorial plot for that substance. Such a plot is obtained by plotting the taste intensity of that substance as a function of its concentration with a separate curve for each of a number of concentrations of the same substance. This procedure is equivalent to replacing each concentration of substance B by another concentration of substance A, as illustrated in Figure 1, panel B.

An advantage of McBride's approach over the summated response comparison is that the taste intensities need not to be measured on a ratio scale. An interval scale suffices.

Using the factorial plot comparison for the assessment of the taste interaction implies that mixtures must be physically composed according to a factorial mixing design (De Graaf, et al., 1987, McBride, 1986), where each of a number of concentrations of one component is mixed with each of a number of concentrations of the other component. This method of preparing mixtures allows for post-experimental analysis of the pattern in a factorial plot of



taste intensities.

#### The equimolar comparison rule

The third procedure for comparing the intensities of mixtures and single components is called the equimolar comparison (De Graaf & Frijters, 1987). As the name implies, the taste intensity of the mixture is compared with the intensities of the single components, where the concentrations of the single components and the total concentration of the mixture have equal molarities. As can be seen in Figure 1, panel A, the responses to concentration  $x$  mol/L of A ( $= R_{Ax}$ ) and  $x$  mol/L of B ( $= R_{Bx}$ ) are compared with the response to a mixture comprising  $1/2 x$  mol/L of A and  $1/2 x$  mol/L of B ( $= R_{0.5x1/2x1/2x}$ ). This rule has been applied by Frijters and colleagues (De Graaf & Frijters, 1987; De Graaf, et al., 1987; Frijters, De Graaf & Koolen, 1984; Frijters & Oude Ophuis, 1983; Frijters & Stevens, 1986). These studies used the concept of equiratio mixture type. This was defined as a series of mixtures of different concentrations each of which having the same ratio between constituent components (Frijters & Oude Ophuis, 1983). The taste interaction is inferred from the relation of the psychophysical functions of equiratio mixtures to the psychophysical functions of single compounds when the equimolar comparison is used. The terms synergism, addition and suppression have not been defined in the context of the equimolar comparison rule. In the terminology of Berglund, Berglund & Lindvall (1976) partial addition, compromise, and subtraction occur when the mixture intensity is larger, intermediate or smaller, than the intensities of the unmixed equimolar concentrations of the compounds (Frijters, in press).

In contrast to the summated response comparison, based on the additivity of intensities, and the factorial plot comparison rules, based on the subtractivity of intensities, the equimolar comparison rule is independent of the properties of the scale used for assessment of the taste intensities (De Graaf & Frijters, 1987). The ordinal comparison between the mixture intensity and the single

component intensities takes place at concentrations where the total molarity of the mixture is equal to each of the molarities of the single components.

In order to be able to make such comparisons at different concentration levels, the total molarity of the mixture must be varied in the same way as the molarity of the single components. In addition, the series of mixtures must be composed in such a way that a psychophysical mixture function can be determined experimentally. This goal is achieved by using equiratio mixture types (Frijters & Oude Ophuis, 1983)

The purpose of the present study is to assess the taste interaction between two qualitatively similar tastants using the three mentioned comparison rules. The results obtained are then compared. The scaling method used to obtain values of perceived sweetness intensities on a linear response scale, was similar to that used by De Graaf et al. (1987). The reader is referred to that paper for a detailed discussion of this methodology. It is based on functional measurement in combination with a two stimulus procedure (Anderson, 1974; Birnbaum, 1982). In this type of experiment subjects compare the sensory impression of each of a number of 'row (=first) stimuli' with the sensory impression of each of a number of 'column (=second) stimuli' (i.e., a factorial judgment design). This procedure is attractive because it provides an internal check on the linearity of the response scale.

The substances in the mixtures were fructose and sucrose. Stone & Oliver (1969), and Yamaguchi et al. (1970b) found that sucrose and fructose show synergism when mixed. Curtis et al. (1984) concluded that they show synergism at low sweetness levels, addition at intermediate levels, and suppression at high sweetness levels. McBride (1986) concluded that sucrose and fructose show addition at low sweetness levels, but suppression at high sweetness levels. The latter author also suggested that the sweetness intensity of sucrose-fructose mixtures may exceed the sweetness intensity of equivalent concentrations of one of the components. De Graaf &

Frijters (1987) argued that this finding was largely due to the use of weight/volume rather than molarities as the unit of concentration.

## METHOD

This investigation involved two overlapping studies. One consisted of experiments to investigate taste interaction according to the summated comparison and the factorial plot comparison rules. The other consisted of experiments to study taste interaction according to the equimolar comparison rule.

### Subjects

The subjects were twelve paid volunteers, two men and ten women, ranging in age from eighteen to twenty-five years. All were students at the Agricultural University. Most of the subjects had previous experience with psychophysical tasks but were naive with respect to the purpose and substances used in this study.

### Stimuli

The stimuli were solutions of sucrose (Merck: 7853) and fructose (Merck: 5321) and mixtures of these substances in demineralized water. Figure 2, panel A, shows all experimental stimuli.

As noted above, the application of the equimolar comparison rule requires that the total molarity of an equiratio mixture type varies in the same way as the concentrations of each of the single components. The stimuli used in this part of the investigation were 0.00 (water), 0.125, 0.250, 0.500, 1.00, and 2.00 molar solutions of fructose and sucrose. The same concentrations were used for the FruSuc .50/.50 equiratio mixture type, a mixture containing equal molarities of both fructose and sucrose. These stimuli are shown in Figure 2, panel B.

For a post-experimental comparison of responses according to the factorial plot comparison, it is necessary to use a factorial mixing design in the experiment. Such a factorial mixing design can also be used for the assessment of the taste interaction according to the summated response comparison. Each of the concentrations 0.00 (water), 0.125, 0.250, 0.500, and 1.00 mol fructose was mixed with each of the concentrations 0.00 (water), 0.125, 0.25, 0.50, and 1.00 mol sucrose. Except for the 0.50/0.50 mixture type already shown in panel B, the composition and concentration of these stimuli which are the result of a factorial mixing design are shown in Figure 2, panel C.

Solutions were prepared at least 24 hours before tasting. They were stored for a period not longer than five days, at 4 degrees C.

### Design

The study involved 19 experiments each of which consisted of a factorial judgment design. Table 1, columns 1-5, gives the purpose and number of each experiment. It also shows the type of factorial judgment design, i.e., the number of various stimuli used as the first stimulus of a pair, and the number of the various stimuli tasted second, and the substances that were used as first and second stimulus of each pair.

For the purpose of the present study, it was necessary that the stimuli resulting from the factorial mixing design, are incorporated into the factorial judgment designs. The explanation below provides the rationale for doing this.

As noted above, the use of a factorial judgment design implies that subjects are presented with pairs of stimuli, where each stimulus of a pair is one stimulus of a series of row (= second) or column (= first) stimuli. In a situation where two single substances are used, a simple  $m \times n$  design can be employed, where  $m$  and  $n$  denote the number of concentrations of the first and second stimulus. When mixtures rather than single compounds have to be incorporated in a factorial judgment design, the situation becomes

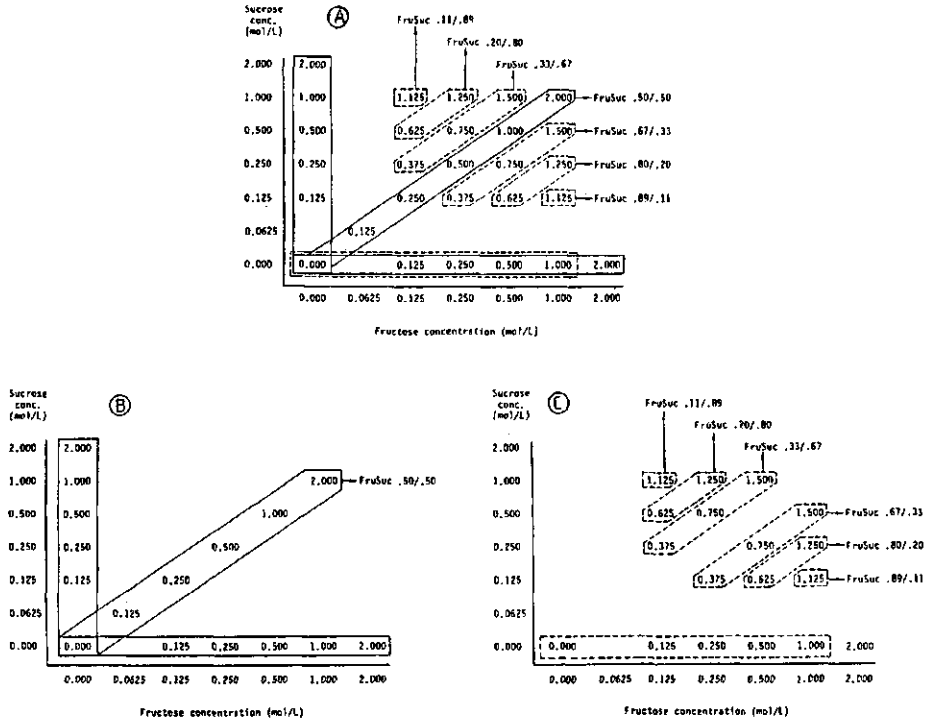


Figure 2. Total concentration and composition of the experimental stimuli. Panel B shows the series of concentrations, (surrounded by the undashed lines) and equiratio mixture type, that were used for the assessment of taste intensity using the equimolar comparison rule. Panel C shows the series of concentrations (surrounded by the dashed lines), and equiratio mixture types, which were used for assessing taste interaction using the factorial plot and the summated response comparison. Panel A was obtained by combining panels B and C, and shows all the experimental stimuli.

more complicated. In a design involving single substances, the series of row and column stimuli vary over one dimension (i.e., the concentration level of each of the substances). When binary mixtures are used, the series of row or column stimuli vary over two dimensions (i.e., the concentration levels of each of the two components). This problem can be overcome by conceiving a mixture as if it were a single substance. This was achieved by using the concept of an equiratio mixture type, where the mixtures have different total concentrations but a constant ratio of constituent components. A psychophysical function for an equiratio mixture type can then be constructed in the same way as a function for a single substance (Frijters & Duda Ophuis, 1983). This enables the incorporation of mixtures resulting from a factorial mixing design into a factorial judgment design. In total, seven series of equiratio mixture types (including the 0.50/0.50 mixture type) were constructed so as to include the 16 mixtures from the factorial mixing design into the factorial judgment designs.

Of the 19 experiments, No. 1 in Table 1, served as a control for order effects. Six experiments (No. 2 - 7) were carried out to assess taste interaction using the equimolar comparison rule, and twelve (No. 8 - 19) were carried out to assess taste interaction using the factorial plot and the summated comparison rule.

The control experiment consisted of a 6 (concentrations of the first stimulus)  $\times$  6 (concentrations of the second stimulus) factorial judgment design, in which 0.00 (water), 0.125, 0.25, 0.50, 1.00, and 2.00 mol fructose solutions served both as first and as second stimulus.

Each of the six experiments for the equimolar comparison (No. 2 - 7 in Table 1) also employed a 6  $\times$  6 factorial judgment design. The first and second stimulus of a pair of each design, the first stimulus mentioned first, were fructose-sucrose, sucrose-fructose, fructose- FruSuc .50/.50, FruSuc .50/.50- fructose, sucrose- FruSuc .50/.50, and FruSuc .50/.50- sucrose. The concentrations of the series of first and second stimuli were 0.00 (water), 0.125, 0.25, 0.50, 1.00, and 2.00 mol/L. The responses to

the sweetness intensities of 0.25, 0.50, 1.00 and 2.00 mol/L of the FruSuc .50/.50 mixture were also used for the factorial plot and the summated response comparison. Figure 2, panel B, shows the stimuli used in these experiments.

Each of the series of 12 experiments (No. 8 - 19) conducted for the factorial plot and the summated response comparisons also consisted a factorial judgment design. Six equiratio mixture types were prepared, so as to include all of the mixtures necessary for the summated response and factorial plot comparisons. This was with exception of the .50/.50 mixtures, the diagonal in Figure 2, panel B, which were already incorporated in the other part of the study. Water, being the 0.00 mol/L solution of each mixture type, was included in each of these series. The six series' of equiratio mixture types were compared to a series of 5 fructose solutions, i.e., 0.00, 0.125, 0.25, 0.50, and 1.00 mol/L fructose. The stimuli and equiratio mixture types used in these experiments are shown in Figure 2, panel C. Fructose was presented as the first stimulus of the pair in six of the experiments, and as the second stimulus in the remaining six.

### Procedure

The subjects were instructed to judge the magnitude of the difference in perceived sweetness intensity between the first and second stimulus of each pair. The instructions emphasized that only the sweetness intensity was to be judged, and that the hedonic value and side tastes were to be disregarded. The judgments were expressed by a slash mark on a 250 mm visual analogue scale. The middle of the scale was defined as 'the first and second stimulus are equal with respect to perceived sweetness intensity' (De Graaf et al., 1987; Figure 3). If a subject perceived the first stimulus as sweeter than the second, he placed on the left side of the scale according to the magnitude of the difference. Similarly, the subject marked the right side of the scale when the second stimulus was perceived as sweeter. The left and right poles of the scale were labelled 'maximum

difference'. In the instructions 'maximum difference' was defined as the difference in sweetness intensity between the stimuli of the reference pair, i.e. water as first stimulus and a 2.5 mol/L sucrose solution as second stimulus. The difference in the reference pair was expected to be larger than the difference in any other pair. The responses were measured as the distance in mm from the left pole of the scale. A response value of 125 meant no difference, a value above 125 meant that the second stimulus was perceived as being sweeter than the first one, and a value below 125 indicated that the first stimulus was perceived as being the sweetest stimulus of the pair.

The subjects were requested to rinse their mouths thoroughly with demineralized water, both within and between pairs. The stimuli were presented at room temperature (20 degrees C), in polystyrene medicine cups. Each cup contained about 10 ml solution. The pairs of each factorial design were presented in a random sequence, and in a different order for each subject. The reference pair was presented at the beginning of each session, and again after the 12th and the 24th pair of each session. The time interval between the first and second stimulus of a pair was 50 seconds, and the interval between pairs was also 50 seconds. Each of the 19 factorial designs was presented twice to each subject. The order of presentation of the various designs was randomized. It took each subject 24 one-hour sessions to complete the experiment.

## RESULTS

In order to be able to draw conclusions about taste interactions, it is necessary to derive one scale value for each stimulus tasted. For the factorial plot comparison rule and the summated comparison rule, these scale values must represent sweetness intensities on an interval and ratio scale.

Whether or not the scale to be derived has interval properties, depends on the validity of the assumption that the overt responses vary linearly with differences in perceived sweetness intensity.



The first step in data analysis was to test this assumption. The data were then analyzed to see if the first and second stimulus had an equal weight in determining the response, i.e., whether or not order effects occurred. After having satisfied these criteria, it was possible to derive a scale value for each of the experimental stimuli. Taste interaction was finally assessed using the three comparison rules.

#### The judgment function

If subjects judged differences between perceived sweetness intensities, parallelism in a factorial plot of the responses implies that the overt responses are linear with sweetness intensity differences.

Individual analyses were carried out in the first place because individuals may differ in the way they compare the two sensory impressions within each pair or in the form of their judgment function. Analyses of variance were carried out for each subject and each factorial judgment design ( $12 \times 19 = 228$  analyses). An indicator for the degree of non-parallelism is the Row  $\times$  Column interaction. This term was tested for statistical significance with the Row  $\times$  Column  $\times$  Replicate interaction as error term. Two subjects showed significant Row  $\times$  Column interactions at ( $p < .01$ ) in one or more of their 19 response matrices. The data of these subjects were excluded from further data analysis. The analyses of the ten remaining subjects showed no significant interactions ( $p < .01$ ).

The responses for each pair were then averaged across the two replicates and the ten subjects. Figure 3, panels 1- 19, shows the arithmetic mean of the responses to each pair of each of the 19 factorial judgment designs. Visual inspection of these factorial plots shows no apparent deviations from parallelism. However, a statistical test showed that the Row  $\times$  Column interaction tested against the Row  $\times$  Column  $\times$  Subject interaction was significant in three out of the 19 cases ( $p < .05$ ). These three cases were the sucrose-fructose, the fructose- FruSuc .50/.50, and the fructose-

FruSuc .33/.67 design. In the 16 remaining responses matrices no significant interactions at the  $p < .05$  level were found.

The question now arises as to whether the three statistically significant deviations from parallelism invalidate the assumed psychological model, i.e. a comparative operation that can be described by a algebraic subtractive rule plus a linear judgment function. We agree with Anderson (1982; p. 167) with regard to the statistical power of a test in relation to criteria for accepting and rejecting models. He writes: "Power is adequate when the discrepancies are significant statistically but unimportant substantively". As the central issue in this study is the taste interaction between sucrose and fructose, the question is, whether the deviations have a substantive effect on the scale values of perceived sweetness intensity. The estimation of the relative magnitude of experimental effects was obtained by calculating the value of omega-squared for a non-additive model in a fixed factor repeated measurement design (Dodd & Schultz, 1973). Table 1 shows the relative contributions of the concentration level of the first stimulus, the concentration level of the second stimulus, the sum of these two, and the first order interaction between the first (column) and second (row) stimulus, for each of the 19 designs. This table shows that the sum of the contributions of the first and second stimuli is in between 85% and 93%, implying that 85% to 93% of the variance in each of the designs is due to the concentration levels of the first and second stimuli. The omega-squared value of the Row x Column interaction varies between -0.3 % and +0.6 %, a negative value results from a F-ratio  $< 1$ , implying that this interaction term is unimportant as a source of variance. As this source of variance does not have a substantive influence on the scale values to be obtained, conclusions to be drawn about the taste interaction between sucrose and fructose are not likely to be affected by these deviations from parallelism. It is concluded that the assumptions concerning the subtractive comparative operation and the linear judgment function were met in this experiment.

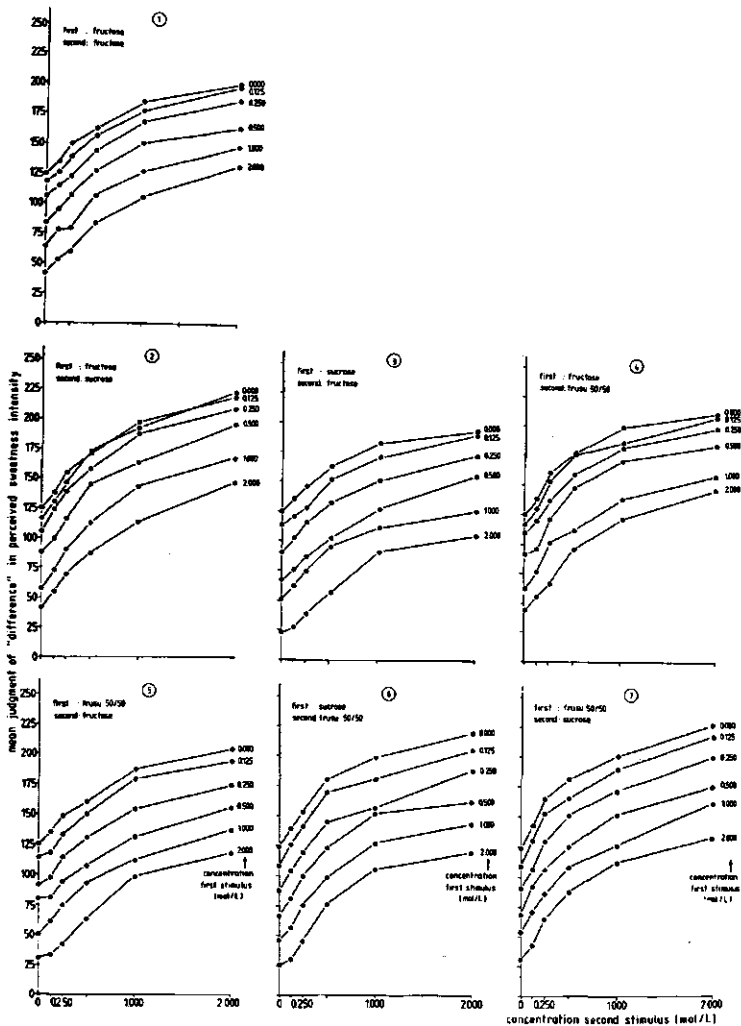


Figure 3. For each factorial judgment design, the mean response to the difference in perceived sweetness intensity between the first and second stimulus of each pair. The responses are plotted as a function of the concentration of the second stimulus with a separate curve for each concentration of the first stimulus. The type of stimulus tasted first and second are given in the upper left corner of each panel. A value of 125 implies no difference, a value below 125 implies that the first stimulus is perceived as being sweeter, and a value above 125 implies that the second stimulus has a greater perceived sweetness intensity. The number of each panel corresponds to the number of each experiment in Table 1.

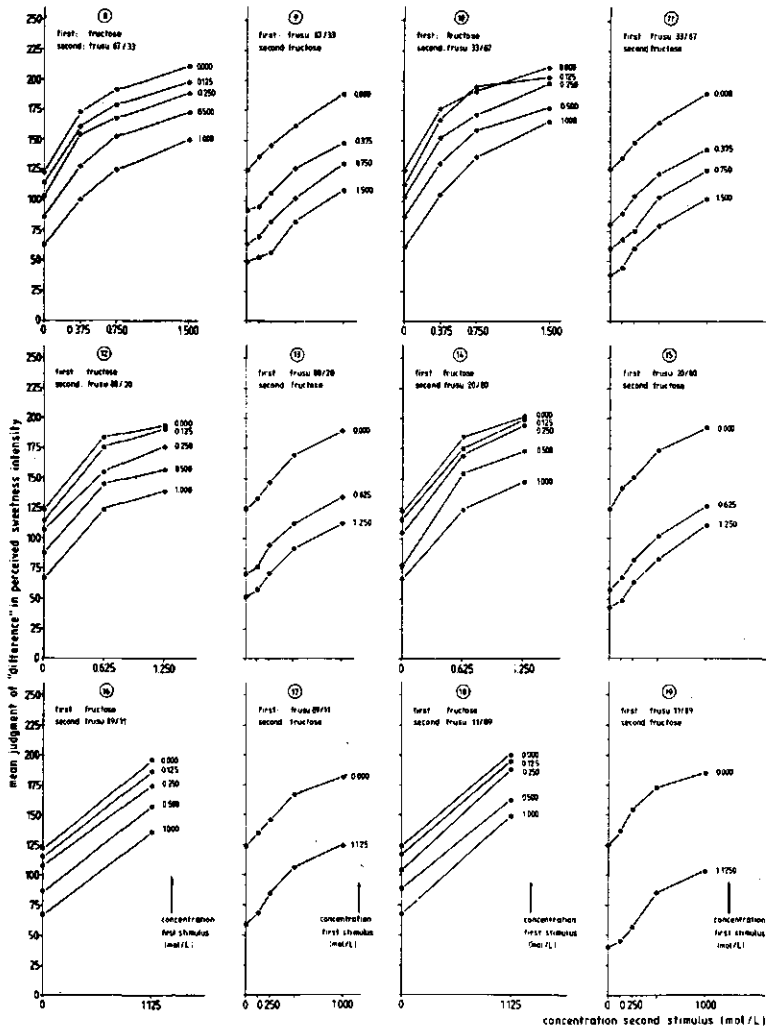


Figure 3 continued

Table 1. For each experiment the relative magnitude  
(=Omega-squared) of effects

Experiment				Omega-squared in % (a)				
Purpose	Type of	stimulus		stimulus		sum of first	first x sec.	
Number	design	first	second	first	second	and second	interaction	
control	[1	6 x 6	fructose	fructose	45.39	46.25	91.64	-0.01
	2	6 x 6	fructose	sucrose	37.04	53.52	90.56	0.00
	3	6 x 6	sucrose	fructose	54.72	36.83	91.55	0.26
equi-	4	6 x 6	fructose	FruSuc .50/.50	38.94	52.20	90.69	0.31
molar	5	6 x 6	FruSuc .50/.50	fructose	50.03	39.89	89.92	0.04
compe-	6	6 x 6	sucrose	FruSuc .50/.50	46.75	43.65	90.40	0.10
rison	7	6 x 6	FruSuc .50/.50	sucrose	42.60	48.99	91.59	-0.04
	8	5 x 4	fructose	FruSuc .67/.33	29.99	59.20	89.28	-0.01
sum-	9	4 x 5	FruSuc .67/.33	fructose	55.16	30.39	85.55	0.04
mated	10	5 x 4	fructose	FruSuc .33/.67	24.37	63.18	87.55	0.57
res-	11	4 x 5	FruSuc .33/.67	fructose	57.57	28.54	86.11	-0.05
ponse	12	5 x 3	fructose	FruSuc .80/.20	27.38	59.28	86.66	0.01
compe-	13	3 x 5	FruSuc .80/.20	fructose	56.42	29.57	85.99	-0.24
rison	14	5 x 3	fructose	FruSuc .20/.80	22.29	67.09	89.38	0.26
	15	3 x 5	FruSuc .20/.80	fructose	61.06	25.34	86.40	-0.06
	16	5 x 2	fructose	FruSuc .89/.11	23.98	66.64	90.62	-0.15
	17	2 x 5	FruSuc .89/.11	fructose	58.05	31.27	89.32	0.03
	18	5 x 2	fructose	FruSuc .11/.89	18.03	71.24	88.27	0.04
	19	2 x 5	FruSuc .11/.89	fructose	73.25	19.66	92.91	0.13

a) The replication factor was excluded from these calculations.

### Order effects

No evidence of order effects was seen applying the method of Bogartz (1980) to compare psychophysical functions of row vs. column stimuli of the fructose-fructose factorial judgment design. Furthermore, overall means of the difference judgments for no subject deviated significantly from 125. Deviations would have occurred if there were a systematic order effect (De Graaf et al., 1987).

### Derivation of scale values of perceived sweetness intensity

The observed parallelism, and the absence of order effects, implies that the marginal means of the row (first) and column (second) stimuli are valid estimates of the sweetness intensities of the corresponding row and column stimuli on a linear scale (Anderson, 1981). As water was included in each of the series of row and column stimuli, the scale value of water can be used as a conventional zero point. The perceived sweetness intensity of each stimulus can thus be defined as the distance between the scale value of that stimulus and the scale value of water. Each of the 19 factorial designs yielded two marginal means for water, one for water as the first stimulus and one for water as the second stimulus. The scale values of the sugar containing row stimuli were determined by calculating the difference between their marginal means and the marginal row mean of water in that same design. The scale values of the column stimuli were determined in a similar way.

These calculations yielded 18 sets of scale values for fructose, 9 sets for fructose presented as first stimulus, and 9 sets for fructose serving as second stimulus. The 6 x 6 factorial designs, containing unimixed fructose stimuli (Table 1, no. 1 - 5), yielded six sets of five scale values, two sets from the fructose-fructose design, and one from each of the other designs. The remaining twelve other designs (Table 1, no. 6 - 19) each yielded one set of scale values for the four unimixed fructose stimuli.

Four sets of scale values were derived for sucrose and the FruSuc .50/.50 equiratio mixture type; two sets of five scale values, for those stimuli tasted first, and two sets of five scale values for those stimuli tasted second. For each of the other stimuli, all mixtures except the .50/.50 mixtures, two sets of scale values were derived.

Since there were no order effects, the final scale value for each of the experimental stimuli could be determined by calculating the arithmetic mean of the scale value(s) of the stimuli tasted first, and the scale values for the stimuli tasted second. These scale values are shown in Figures 5 and 6.

#### Ratio scale properties

Assuming that water does not taste sweet (Kroeze, 1982, p. 132; De Graaf et al., 1987) its scale value can be treated as the absolute zero-point for the scale of perceived sweetness intensity. For the summated response comparison, it is necessary that the sweetness intensities are assessed on a ratio scale. The description of the taste interaction between sucrose as fructose as well as the description of the "apparent" taste interactions within fructose and sucrose, depend on the assumption of water being the absolute zero point. The shape of the psychophysical function, whether it is expanding or compressing also depends on this assumption. The descriptions of the taste interaction according the factorial plot comparison and the equimolar comparison are independent of this assumption.

#### Taste interaction between sucrose and fructose

##### The summated response comparison

In Figure 4, panel A, the sum of the intensities of each of the concentrations 0.125, 0.25, 0.50, and 1.00 mol/L fructose, and each of the concentrations 0.125, 0.25, 0.50, and 1.00 mol/L sucrose are

compared with the intensities of the mixtures. This results in 16 comparisons. It is apparent that at low levels the mixture intensity is higher than the sum of the component intensities, at intermediate levels it is approximately equal to the sum of the component intensities, and at high intensities the mixture intensity is less than the sum of the component intensities. From this result it is concluded that sucrose and fructose show little synergism at low sweetness levels, addition at intermediate levels and suppression at high sweetness levels.

However, as argued above, to arrive at a proper description of the specific taste interaction between sucrose and fructose, this taste interaction should be compared with the apparent taste "interactions" within sucrose and fructose as single substances. In order to get similar diagrams for these apparent within substance "interactions" (Figure 4, panel B and C), several values shown in these panels had to be estimated. This was because they had not been experimentally determined. For instance, the taste interaction between 0.25 mol sucrose and 0.125 mol fructose, had to be compared to the apparent taste "interaction" between 0.25 mol fructose and 0.125 mol fructose, as well as to the apparent "interaction" between 0.25 mol and 0.125 mol sucrose. For such a comparison, the intensities of 0.375 (= 0.125 + 0.25) mol/L fructose, and 0.375 mol/L sucrose must be known. The same applies for the intensities of 0.625, 0.75, 1.125, 1.25, and 1.50 mol/L fructose and sucrose. These intensities were estimated using second order polynomials, where the natural logarithm of the concentration and its squared value were the independent variables, and the natural logarithm of the obtained scale values was the dependent variable. The fructose function had an R-squared of .9997, and sucrose had an R-squared of .9965. Both functions were monotonic within the relevant domain. In view of the goodness of fit, these polynomials were considered to be appropriate for the estimation of the intensities required.

Figure 4, panels B and C, shows the apparent taste "interactions" within fructose and within sucrose. The solid points represent experimentally determined scale values, and the open



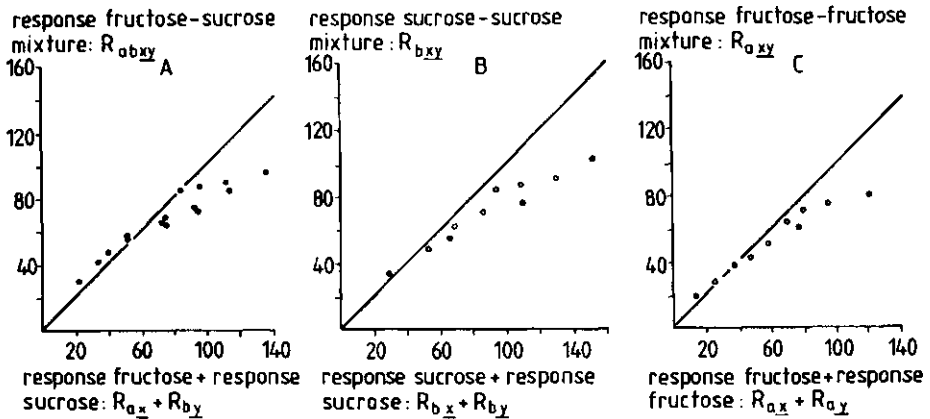


Figure 4. Panel A shows the relationship of the sum of the sweetness intensities of each of the concentrations 0.125, 0.25, 0.50, and 1.00 mol/L fructose, and each of the concentrations 0.125, 0.25, 0.50, and 1.00 mol/L sucrose, to the sweetness intensity of the mixtures. If additivity was the rule, all points should lie on the straight line drawn from the origin. If the mixture intensity is higher than the sum of the intensities of its components, the points will lie above this line, and if the mixture intensity is lower than the sum of the components intensities, the points will fall below this line.

Panel B shows the corresponding summated response comparisons for the apparent taste "interaction" within sucrose, and panel C shows these comparisons for the apparent taste "interaction" within fructose. The solid points represent scale values experimentally obtained, and the open points represent estimated scale values.

points are estimates. Panel B shows that the apparent taste "interaction" within sucrose changes from being slightly synergistic at low levels to suppressive at high levels. However, compared to panel A, there are less points above and more points below the additivity line. The summated response comparisons for the apparent fructose-fructose "interaction" in Panel C show a similar pattern to panel B.

This analysis shows that the taste interaction between sucrose and fructose is similar to the apparent taste "interactions" within fructose and within sucrose. However, the between substance taste

interaction shows a greater magnitude and frequency of synergism, and a smaller magnitude and frequency of suppression than the apparent within substance "interactions".

#### The factorial plot comparison

Figure 5, panel A, shows perceived sweetness intensity as a function of fructose concentration, with a separate curve for each sucrose concentration. It is important to bear in mind, that this factorial plot represents a different integration process than the factorial plots in Figure 3. The factorial plot in Figure 5, panel A, represents the taste interaction between sucrose and fructose. The factorial plots in Figure 3, represent the comparative operation between two sensory impressions and the form of the judgment function. It could be said, that Figure 5 represents the psychophysical interaction, and that Figure 3 shows the psychological integration.

The overall pattern in this panel is convergent, since the vertical distance between the curves diminishes as the fructose concentration increases. The degree of non-parallelism i.e. convergence or divergence, is reflected in the magnitude of the Row (= fructose)  $\times$  Column (= sucrose) interaction. Analysis of variance showed that the Sucrose  $\times$  Fructose interaction, with the Sucrose  $\times$  Fructose  $\times$  Subjects interaction as the error term, is statistically significant [  $F(16,144) = 12.97, p < .0001$  ].

There seems to be a differential effect on the taste interaction of concentration level. The 0.00 mol/L sucrose line and the 0.125 mol/L sucrose line diverge up to the level of 0.125 mol/L fructose. This indicates that synergism occurred. Analysis of variance showed that this divergence is statistically significant [  $F(1,9) = 24.4, p < .001$  ].

In some other parts of panel A, the taste interaction between sucrose and fructose appears to be additive. For example, the curves of 0.00 mol/L sucrose and 0.125 mol/L sucrose from 0.125 mol/L to 0.25 mol/L fructose are parallel [  $F(1,9) = 0.05$  ]. This implies that

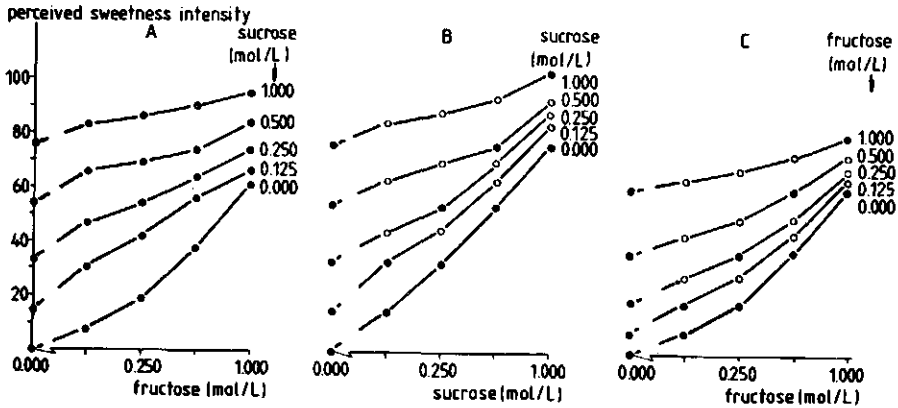


Figure 5. In panel A the perceived sweetness intensity of fructose-sucrose mixtures is plotted as a function of the fructose concentration, with a separate curve for each of the sucrose concentrations. Panels B and C represent similar factorial plots as in panel A, but the single substances are conceived as a mixture of the substances with themselves. In panel B, the perceived sweetness intensity of sucrose-sucrose "mixtures" is plotted as a function of the sucrose concentration, with a separate curve for each sucrose concentration. In panel C, the sweetness intensities of fructose-fructose "mixtures" are plotted as a function of the fructose concentration, with a separate curve for each fructose concentration. The closed circles represent scale values obtained experimentally, and the open circles represent estimated scale values using polynomial regression equations.

the addition of 0.125 mol/L sucrose to 0.125 mol/L fructose yields the same increment in perceived taste intensity as the addition of 0.125 mol/L sucrose to a 0.25 mol/L fructose solution. The same applies for the lines of 0.125 and 0.25 mol/L sucrose up to 0.125 mol/L fructose [ $F(1,9) = 0.73$ ]. The taste interaction between 0.25 mol/L fructose and 0.25 mol/L sucrose is also additive [ $F(1,9) = 0.17$ ].

At the higher sweetness levels for sucrose and fructose, suppression takes place. The F-ratio representing the taste interaction between 0.50 mol fructose and 0.50 mol sucrose is 12.01, and the  $F(1,9)$ -ratio representing the taste interaction between 1.00 mol fructose and 1.00 mol sucrose is 50.82. These F-ratios also show that the degree of suppression increases at higher

concentration levels.

In order to get similar factorial plots for the apparent taste "interactions" within fructose and sucrose, Figure 5, panel B and C, several values shown in these panels (the sweetness intensities of 0.375, 0.625, 0.75, 1.125, 1.25, and 1.5 mol/L) were estimated using the same functions as in the summated comparison rule. ANOVA's of the data similar to those carried out on the data of panel A are not feasible because several values within the plots B and C are experimentally dependant.

Visual inspection of panels B and C shows that the overall patterns are similar to that of panel A. However, it appears that the convergences in panels B and C are more pronounced than in panel A.

To summarize: Taste interaction between sucrose and fructose can be largely explained by the apparent taste "interaction" within the single substances themselves. However, there appears to be a tendency towards less suppression, implying more synergism and addition, than could be expected on the basis of the apparent within taste substance "interactions".

#### The equimolar comparison

Figure 6 shows that the FruSuc .50/.50 function lies in between the functions of unmixed sucrose and fructose. In the terminology of Berglund et al. (1976) this means that fructose and sucrose compromise when mixed. This finding reinforces the general rule postulated by De Graaf & Frijters (1987), who argued that the sweetness intensities of binary sugar mixtures always lie in between the intensities of their components, when each is tasted alone and at the same total molarity as the mixture.

It is evident, however, that the FruSuc .50/.50 function does not lie halfway in between the sucrose and fructose functions. Up to 0.125 M, the slope of the .50/.50 function lies in between the slopes of the sucrose and fructose functions. Between 0.125 and 0.25 M, the .50/.50 function approaches the sucrose function, and stays

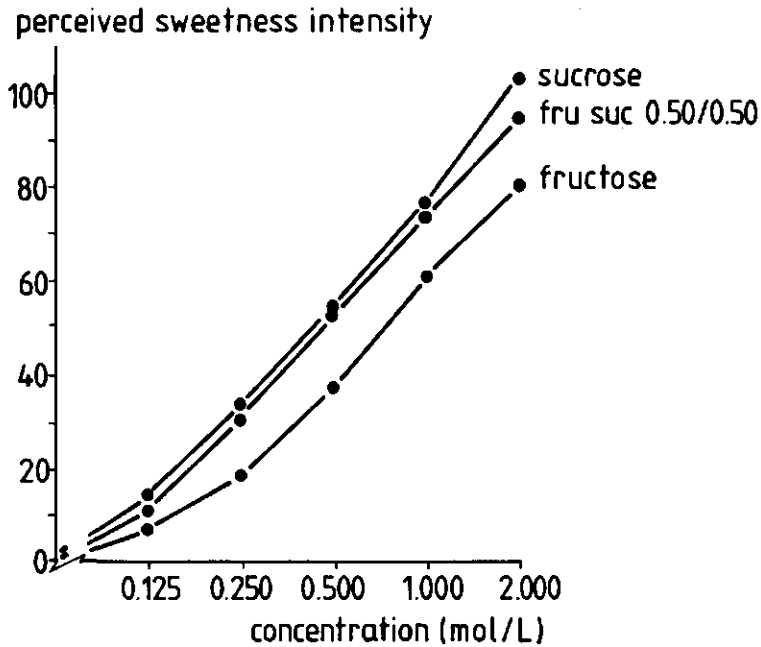


Figure 6. Psychophysical functions for fructose, sucrose, and the FruSuc .50/.50 equiratio mixture type.

near that function up to the level of 1.00 M. Above 1.00 M, the slope of the .50/.50 function gets shallower than the sucrose function. The sweetness of 2.00 mol/L of the FruSuc .50/.50 mixture is about 10 units less than that of 2.00 mol/L sucrose.

## DISCUSSION

### A comparison between comparison rules

As the three methods of assessing taste interaction describe the same phenomena, there should be a straightforward relationship between the results obtained.

The conclusions from the summated response comparison and the factorial plot comparison are almost identical. Fructose and sucrose

show synergism at low levels, additivity at intermediate levels, and suppression at high levels. In both analyses, the taste interaction between sucrose and fructose could be explained to a large extent by the apparent taste "interactions" within sucrose and within fructose. However, it is concluded from both comparisons that taste interaction between sucrose and fructose is more synergistically, more additively and less suppressively than each of the apparent within taste substance "interactions".

Similar conclusions can be obtained from the equimolar comparison rule. At the low concentrations of sucrose and fructose, doubling the concentration yields a more than twofold sweetness intensity (see Figure 6). At high concentrations doubling the concentration yields a less than double sweetness intensity. Thus, if the apparent taste "interactions" within sucrose and fructose was to be described in terms of suppression, addition or synergism, it would be concluded that they show synergism at low sweetness levels, addition at intermediate sweetness levels, and suppression at high sweetness levels. The finding that the psychophysical function of the FruSuc .50/.50 mixture type lies in between the psychophysical functions of sucrose and fructose as single substances shows that the taste interaction between sucrose and fructose is approximately equal to the apparent taste "interactions" within sucrose and fructose. The tendency towards more synergism, more addition and less suppression of the taste interaction between sucrose and fructose compared to the apparent taste "interaction" within these substances, is reflected in the relative position of the FruSuc .50/.50 function. It does not lie halfway between the fructose and sucrose functions but it is located close to the function of the sweetest sugar, i.e., sucrose.

The main difference between the three comparison procedures lies in the way the conclusions are obtained. The conclusions derived from the equimolar comparison were more easily obtained than those from the factorial plot and summated response comparisons. It is required that the scale values represent taste intensities on a ratio scale, for a sound conclusion based on the summated response

comparison rule. An interval scale is required for the factorial plot comparison. These requirements place constraints on the type of scaling method that can be employed. For the assessment of taste interaction according to the equimolar comparison rule, an ordinal level of assessment is sufficient (De Graaf & Frijters, 1987).

Another essential difference between the equimolar comparison and the summated response, and the factorial plot comparisons is that the equimolar comparison rule compares psychophysical functions whereas the other procedures do not. In order to draw conclusions about the taste interaction between two taste substances according to the summated response and the factorial plot comparison rules, the between substance interaction must be compared to the apparent taste "interactions" within these substances. Since the apparent taste "interaction" within a substance is reflected in the shape of its psychophysical function, the comparison of between and within substance interactions is implicit in the equimolar comparison rule. This means that a comparison of the psychophysical functions of single substances with the psychophysical function of an equiratio mixture type already involves a comparison of the taste interaction between substances with the apparent taste "interaction" within substances.

Another advantage of the equimolar comparison over the summated response and factorial plot comparisons is that the equimolar comparison shows directly that the sweetness intensity of sucrose-fructose mixtures lie in between equimolar concentrations of sucrose and fructose. This appears to be a general rule applicable to a large number of binary sugar(alcohol) mixtures (De Graaf & Frijters, 1987). This phenomenon is not apparent in the other comparisons.

#### Taste interaction in sugar(alcohol) mixtures: some general rules

The present data on sucrose and fructose and the data from De Graaf et al. (1987) on glucose and fructose, suggests that the psychophysical functions of these substances are positively accelerating at low concentrations and negatively accelerating at

high concentrations. As the shapes of the psychophysical functions of a large number of sugars and sugar alcohols are similar (see Schutz & Pilgrim, 1957; Yamaguchi, Yoshikawa, Ikeda & Ninomiya, 1970a), it can be inferred that the psychophysical functions of these sugars and sugar alcohols expand at low concentrations and compress at high concentrations. This means that the apparent taste "interaction" within these sugars can be expected to be synergistically at low sweetness levels, additively at intermediate concentrations, and suppressively at high concentrations. With respect to the psychophysical functions of equiratio mixture types of sugars, it is noted that these functions always lie in between the psychophysical functions of the single compounds constituting the mixture (De Graaf, & Frijters, 1987). This means that the psychophysical functions of equiratio sugar mixtures exhibit a similar shape as the psychophysical functions for single sugars. Thus, in conclusion, the taste interaction between any two sugars or sugar alcohols can also be expected to be synergistically at low levels, additive at intermediate levels, and suppressive at high levels.

It follows from the foregoing paragraphs that the same rule applies for the apparent taste "interaction" within single sugars, and for the taste interaction between two sugars in a mixture. Thus, for binary sugar mixtures the question arises as to whether any of the taste interaction is specific for the substances mixed. In other words, can the taste interaction between two sugars be totally explained by the apparent taste "interaction" within these substances ?

From the data obtained in this experiment and from other data in the literature, it appears that for certain sugars and sugar alcohols this question can be answered affirmatively. Some sweet substances, like glucose, sorbitol, galactose, mannitol, and xylose have virtually identical psychophysical functions, when determined under identical conditions (Cameron, 1947, De Graaf & Frijters, 1987; Frijters & De Graaf, submitted; Munton & Birch, 1985; Yamaguchi et al., 1970a). They also have similar threshold



concentrations in mol/L (Haefeli, 1983). The data from several mixture studies show that the psychophysical functions of various equiratio mixture types of these substances are similar to the single compound psychophysical functions (De Graaf & Frijters, 1987; Frijters & De Graaf, submitted; Yamaguchi, 1970b). This means that the taste interaction among these substances must be virtually identical to the apparent taste "interactions" within these substances. Thus, glucose seems to interact with sorbitol in the same way as it interacts with itself and also in the same way as sorbitol interacts with itself. The same applies for other possible mixtures of the substances mentioned above.

In addition, the data of Yamaguchi et al. (1970b) show that the taste interaction patterns between glucose, sorbitol and mannitol on the one hand and each of a number of sweeteners like sucrose, fructose, xylitol, saccharin and cyclamate on the other hand, are similar. Thus, glucose interacts with sucrose, fructose, xylitol, saccharin and cyclamate in a similar way as do sorbitol and mannitol.

The data discussed in the two preceding paragraphs suggest that the sugars(alcohols) glucose, galactose, mannitol, sorbitol, and xylose operate in a similar way to elicit sweetness.

This seems not to be the case for substances which have readily distinguishable psychophysical functions, like glucose, fructose, and sucrose. As the present study shows, the taste interaction between fructose and sucrose cannot be completely explained by the apparent taste "interactions" within the single substances. The same applies for mixtures of glucose and fructose. The sweetness intensities of glucose-fructose mixtures approach the sweetness intensity of equimolar concentrations of fructose at high concentration levels (De Graaf et al., 1987; Frijters & Oude Ophuis, 1983). In a previous paper (De Graaf & Frijters, 1986) it was shown that Beidler's mixture model, which assumes competition for the same receptor sites, could adequately describe the glucose-fructose interaction at low sweetness levels only. At high sweetness levels, the taste system operated more efficiently than could be expected on

the basis of this competition model. It was concluded that glucose and fructose share common receptor sites but either one or both must have additional secondary binding mechanisms. The same explanation may also apply to fructose and sucrose.

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## CHAPTER SEVEN

### "RATIOS" AND "DIFFERENCES" IN PERCEIVED SWEETNESS INTENSITY

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**ABSTRACT** For a number of perceptual continua, it has been shown in previous studies that subjects use only one quantitative comparison between two sensory impressions of a pair of stimuli, irrespective of whether they are instructed to judge "ratios" or to judge "differences". This comparison can be described by algebraic subtraction. The present study was designed to investigate whether this one-operation theory for psychophysical judgment also applies to the sensory continuum of sweetness. Subjects were presented with pairs of fructose solutions, and judged "ratios" of, or "differences" in, perceived sweetness intensities. The pairs were constructed on the basis of a factorial judgment design. The results showed that the reported "differences" could be adequately described by a difference response model, and that the reported "ratios" could be adequately described by a ratio response model. However, the reported "ratios" and reported "differences" were monotonically related, and the marginal means of the log-transformed response matrix of "ratios" were a linear function of the marginal means of the response matrix of "differences". These results are incompatible with the notion that subjects judged differences, when instructed to judge "differences", and ratios when instructed to judge "ratios". The consistency of the ratio response model with "ratio" judgments is probably caused by a comparative operation based on "differences" in combination with an exponential response output function. It is concluded, that subjects judge only "differences" between perceived sweetness intensities, and not "ratios".

## INTRODUCTION

For several perceptual continua, such as, heaviness (Birnbbaum & Veit, 1974; Mellers, Davis & Birnbbaum, 1984), loudness (Schneider, Parker, Kanow & Farrell, 1976; Birnbbaum & Elmasian, 1977), pitch (Schneider, Parker & Upenieks, 1982), darkness of dot patterns (Birnbbaum, 1978; Mellers & Birnbbaum, 1982) and of gray papers (Veit, 1978), it has been shown, that the way in which subjects compare the absolute magnitudes of two sensations elicited by a pair of stimuli is independent of the instructions. The type of comparison is the same when instructed to judge "differences" or to judge "ratios". This cognitive operation can be described by algebraic subtraction. Birnbbaum and colleagues (e.g., Birnbbaum, 1982; Mellers et al., 1984) argued that under proper experimental conditions, "difference" instructions (e.g., category scales) induce a linear response output function, (i.e., the function relating subjective intensity "differences" to observable "difference" responses is linear). On the contrary, "ratio" instructions (e.g., magnitude estimation), in which the numerical examples are geometrically spaced (e.g., the standard is 10; if a stimulus is 10 times stronger as the standard, assign the number 100; if a stimulus is 1/10 as strong as the standard, assign the number 1) are supposed to induce an approximately exponential response function (Birnbbaum, 1978; Birnbbaum, 1980; Mellers et al., 1984). An exponential response output function transforms perceived "differences" into numerical ratings that are consistent with a "ratio" response model.

The empirical evidence in favour of Birnbbaum's one-operation theory evolves from experiments in which the functional measurement approach, in combination with a two-stimulus procedure was applied (e.g. Anderson, 1974, 1981; Birnbbaum, 1982). In these experiments, pairs of stimuli were presented under the instruction to judge either the "ratio" or the "difference" between the subjective intensities of each of a

number of row stimuli, and each of a number of column stimuli. The results of these experiments showed that reported "ratios" were monotonic with, and an approximately exponential function of reported "differences". Such monotonicity is incompatible with the notion that subjects report differences when instructed to judge "differences", and that they report ratios when instructed to judge "ratios". The rank order in magnitude of reported ratios must be different from the rank order in magnitude of reported differences, if each kind of instruction generates the comparative operation as intended (e.g., Veit, 1978; Birnbaum, 1982).

Monotonicity between difference and ratio judgments is an indication that subjects use one comparative operation only under the condition that the psychological range of the sensory impressions of the experimental stimuli is sufficiently large. When the psychological range is small, "difference" and "ratio" judgments will have the same rank order, even if subjects distinguish between a psychological difference and a psychological ratio (Rule & Curtis, 1980; Schneider, *et al.*, 1982). Therefore, rank order between "ratio" and "difference" judgments must be evaluated in combination with the psychological range of sensory impressions.

This study was designed to investigate whether or not the one-operation theory of comparative judgment holds for judgments of perceived sweetness intensity. The design of the study was similar to that of the studies previously cited, where there were two experimental conditions, one for each type of instruction. In the "difference" condition, subjects were instructed to judge the "difference" in perceived sweetness intensity of two fructose solutions, whilst in the "ratio" condition, subjects were instructed to judge the "ratio" of the perceived sweetness intensities of two fructose solutions.



## METHODS AND MATERIALS

### Subjects

Forty paid volunteers were used as subjects. All were undergraduate students from the Agricultural University, whose ages ranged from 18 to 29 years. None of the subjects had prior experience in psychophysical scaling tasks. They were given no information about the aim of the experiment or the nature of the substances used.

### Stimuli

The stimuli were solutions of fructose (Merck, 5321) dissolved in demineralized water. The concentrations of the six fructose solutions were 0.125, 0.218, 0.379, 0.660, 1.149, and 2.00 M. A pair comprising of 0.125 M fructose as the first stimulus, and 2.50 M fructose as the second stimulus, served as the reference pair. The solutions were prepared at least 24 hours prior to tasting, and were stored at 4 degrees C for no longer than seven days.

### Design

The subjects were randomly assigned to each of two groups of 20 subjects. One group was instructed to judge the "difference" in perceived sweetness intensity between two stimuli of each pair, and the other group was instructed to judge the "ratio" of the intensities.

Both conditions involved a 6 (number of different stimuli tasted first) times 6 (number of different stimuli tasted second) symmetrical factorial judgment design (De Graaf, Frijters & Van Trijp, 1987). Thus, each of the six fructose stimuli served as both first and second stimulus in all possible pairs of stimuli (i.e., 36 in total).

### Procedure

In both the "difference" and the "ratio" condition, the instructions emphasized that only the sweetness intensity was to be judged, and that the hedonic value and potential side tastes were to be disregarded. The subjects were requested to rinse their mouths thoroughly with demineralized water, both within and between pairs. The stimuli were presented at room temperature, in polystyrene medicine cups, each containing about 10 ml of solution. The 36 pairs in the factorial judgment design were presented in a random sequence, and in a different order for each subject. The reference pair (0.125 M fructose as first and 2.5 M fructose as second stimulus) was presented at the beginning of each session, and again after the 12th and 24th pair in each series of 36. The "difference" between, or "ratio" of, perceived sweetness intensities in this pair was expected to be larger than the "difference" in, or "ratio" of, any other pair to be judged.

The time interval between the two stimuli within a pair, as well as the time interval between pairs, was 50 seconds. Each subject tasted a series of 36 pairs three times, one in each of three sessions.

#### "Difference" task

The subjects were instructed to judge the magnitude of the "difference" in perceived sweetness intensity between the first and second stimulus of each pair. The ratings had to be expressed by a slash mark on a 250 mm visual analogue scale (see De Graaf *et al.*, 1987), of which the middle was defined as "the first and second stimulus are equal in sweetness intensity". If the first stimulus was perceived as sweeter than the second, the subject put a mark on the left side of the scale. Similarly, the subject put a mark on the

right side of the scale when the second stimulus was perceived as being sweeter. The larger the "difference" between stimuli, the larger the distance of the mark from the middle of the scale. The left and the right anchors of the scale were labelled with "maximum difference". In the instructions "maximum difference" was defined as the "difference" in sweetness intensity between the stimuli of the reference pair.

For data analysis, the ratings were measured as the distance in mm from the left anchor of the scale. Thus, the numerical value 125 means no "difference", values below 125 indicate that the first stimulus was perceived as sweeter than the second, and values above 125 indicate that the second stimulus was perceived as sweeter.

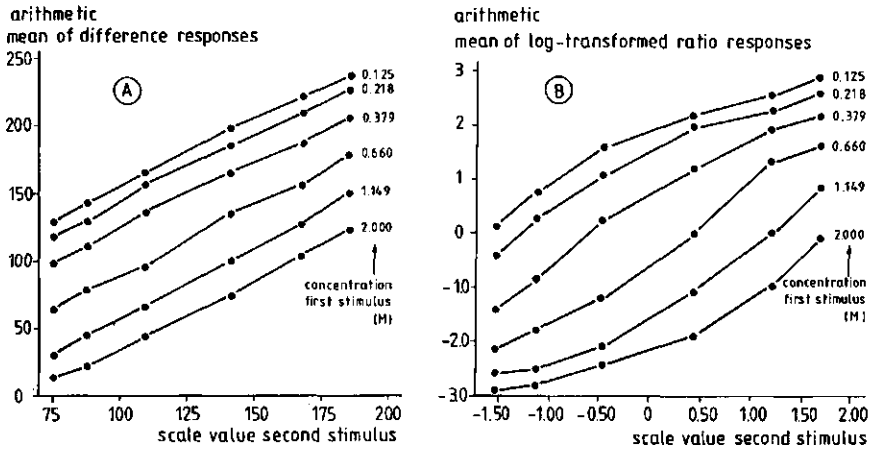
#### "Ratio" task

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Subjects were instructed to judge the magnitude of the "ratio" of the perceived sweetness intensity of the first and the perceived sweetness intensity of the second stimulus of each pair. They had to identify first, which stimulus of each pair was the sweetest, and subsequently to assign a number reflecting the "ratio" of the perceived sweetness intensity of the sweetest stimulus and the least sweetest stimulus. If the first and second stimulus were equal in perceived sweetness intensity, subjects had to assign the number one. The maximum "ratio", being the "ratio" of the perceived sweetness intensities of the stimuli of reference pair, was declared in the instructions to be 25.

## **RESULTS**

In Figure 1, panel A, the arithmetic means of "difference" judgments are plotted as a function of the marginal mean of the



**Figure 1. Panel A: Arithmetic means of reported "differences", averaged over subjects and replicates, plotted as a function of the scale values of the responses to the second stimulus with a separate curve for each concentration of the first stimulus. A scale value of 125 implies no difference, scale values above 125 imply that the second stimulus of the pair was perceived as being sweeter, and scale values below 125 indicate that the first stimulus of the pair was perceived sweeter than the second. Panel B: The arithmetic means of the log-transformed reported "ratios" averaged over subjects and replicates, plotted as a function of the scale values of the log-transformed responses to the second stimulus with a separate curve for each concentration of the first stimulus.**

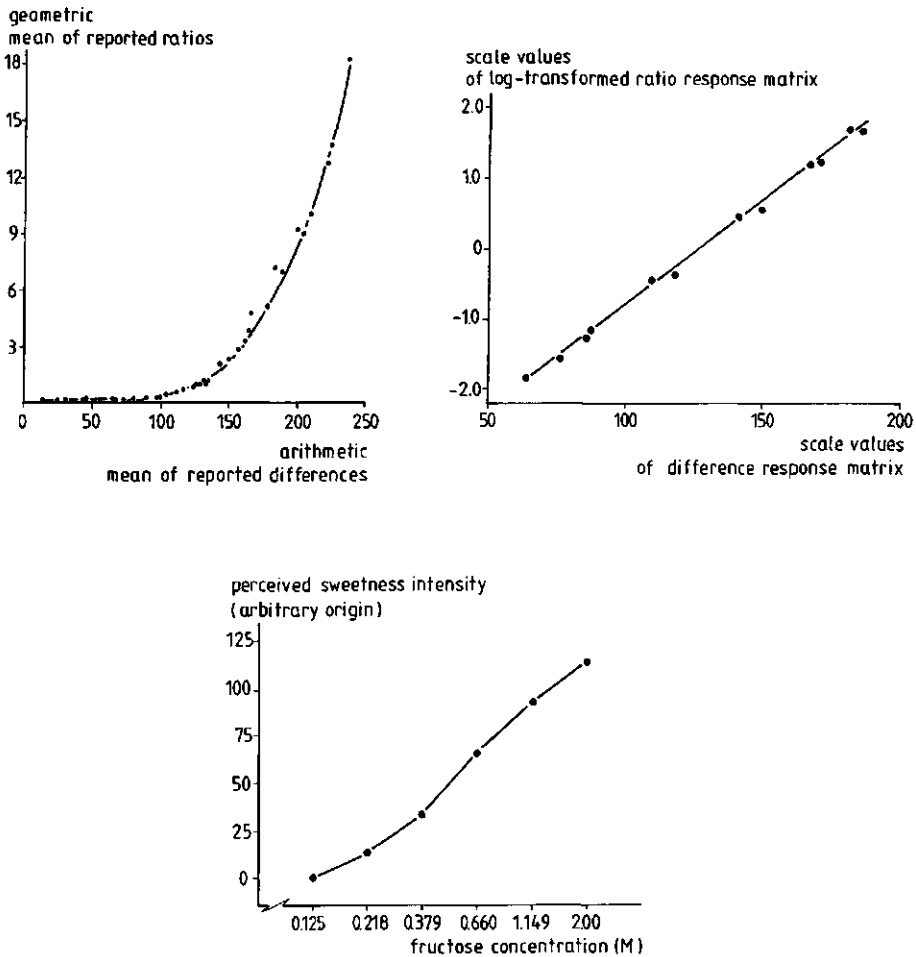
"difference" responses to the second (column) stimulus, with a separate curve for each level of the first stimulus. A subtractive comparative operation in combination with a linear judgment function, implies that this factorial plot must exhibit six straight lines, which run parallel to each other. This is confirmed by ANOVA, showing that row (second) \* column (first) interaction is statistically not significant [ $F(25,475) = 0.93$ ,  $p > 0.5$ ]. The row \* column interaction accounts for 0.16 % of the systematic variance (throughout this paper, systematic variance is the variance due to the first stimulus, the second stimulus, and the interaction between the first and second stimulus).

The "ratio" responses consisted of numbers between 1 and 25, where about half of the responses referred to pairs in which the

first stimulus was perceived as the sweetest, and the other half referred to pairs in which the second stimulus was perceived as the sweetest. The "ratio" response matrix consisted of the numerical values, reflecting how many times the second stimulus was rated as sweeter than the first stimulus (sweetness second/sweetness first). So, if it was reported that the second stimulus was five times sweeter than the first stimulus, the numerical value in the response matrix is five. Similarly, if it was reported that the first stimulus tasted five times sweeter than the second stimulus, the value in the response matrix is 0.2 (1/5).

If ratio response model applies, then the matrix of the natural logarithms of reported "ratios" can be described by a subtractive model. In Figure 1, panel B, the arithmetic means of the log-transformed "ratio" responses are plotted as a function of the marginal means of the log-transformed "ratio" responses of the second (column) stimulus, with a separate curve for each level of the first (row) stimulus. If the ratio response model is valid, then the lines within this panel must run parallel. However, parallelism is not a sufficient condition for the conclusion that reported "ratios" are a linear representation of judged ratios, as will be shown below. Visual inspection shows deviations from parallelism. This is confirmed by ANOVA, showing that the deviations from parallelism are statistically significant [ $F(25, 475) = 13.10, p < 0.0001$ ]. This row \* column interaction accounts only for 2.4 % of the total systematic variance. Thus, although the deviations from the ratio model are statistically significant, these deviations are not substantive.

In summary, the difference response model is confirmed by the results, and the ratio response model provides a good description of the data, although minor (but statistically significant) deviations occur. Thus, the results of the experimental condition in which subjects were instructed to judge "differences", suggest that subjects have judged differences indeed. Similarly, the results of the "ratio" condition suggests



**Figure 2. Geometric means of reported "ratios" plotted a function of arithmetic means of reported "differences".**

**Figure 3. Relationship between the scale values of the "difference" response matrix, and the scale values of the log-transformed "ratio" response matrix.**

**Figure 4. Scale values of the perceived sweetness intensity plotted as a function of the concentration of the fructose stimuli, averaged over the row and column scale values. The scale value of 0.125 M fructose was set equal to zero, and the scale values for the other stimuli were calculated as the absolute difference from this scale value. Thus, the origin of this scale is arbitrary.**

that subjects have judged ratios. On the basis of these results, one might be inclined to conclude, that subjects judge differences, when instructed to judge "differences", and judge ratios when instructed to judge "ratios".

However, if both models are valid at the same time, then consequently, the rank orders of reported "differences" and of reported "ratios" must be different (Birnbau, 1978, 1980). Additional analysis (Figure 2) shows that reported "ratios" are a monotonic function of reported "differences". The Spearman rank correlation coefficient between the geometric means of reported "ratios" and of the arithmetic means of reported "differences" is 0.996. This observation indicates that subjects must have used the same comparative operation in both judgmental tasks (Birnbau, 1982). According to the one-operation theory, subjects judge only differences and not ratios. If the "ratio" instructions induce an exponential response output function, the scale values (i.e., the marginal means) of the log-transformed responses of the "ratio" response matrix must be a linear function of the scale values of the "difference" response matrix (Birnbau, 1980). Figure 3 shows that this is confirmed by the data. The R-squared value of the function fitted by orthogonal linear regression (Hampton, 1983) is 0.998. This result also indicates that the deviations from parallelism in the log-transformed "ratio" response matrix (earlier found to be 2.4 % of the systematic variance; see Figure 1, panel B) are not due to deviations from judged "ratios", but result from deviations from an exponential response output function of judged "differences". Apparently, "ratio" instructions induce a response output function, that transforms judged "differences" into responses, that are spuriously consistent with a ratio model.

Figure 4 shows the relationship between the fructose concentration, and the mean scale value for each stimulus - averaged over the row marginal mean and the column marginal mean, for the "difference" response matrix. This function is an empirical estimation of the psychophysical function of fructose.

The magnitude of the psychological range of the sensory impressions in the present study can be estimated by using the data from other studies on the sweetness intensity of fructose. In the study of De Graaf *et al* (1987) 0.125 M fructose had a sweetness intensity of 14 units, and 2.00 M fructose had a sweetness intensity of 115 units on a ratio scale of perceived sweetness intensity. The calculated ratio between these two sensory impressions is about 8. De Graaf & Frijters (1988) obtained scale values for 0.125 M and 2.00 M fructose also on a ratio scale. In this study 0.125 M fructose had a scale value of about 8, and 2.00 M fructose had a scale value of about 80, a calculated ratio of about 10. Thus the actual ratio between 2.00 M fructose and 0.125 M fructose is about 8-10. Parker *et al* (1982) have shown that this range is sufficiently large to produce non-monotonicity between judged ratios and judged differences, if subjects distinguished between psychological differences and psychological ratios. In addition, when subjects distinguished between differences and ratios, the relationship shown in Figure 3 should be clearly non-linear (see Parker *et al*, 1982; Figure 9), which is not the case.

## DISCUSSION

The results of this study concur with those of similarly designed experiments investigating other perceptual continua. If the results of both experimental conditions were analyzed separately, it could have been concluded, that both the ratio and the difference response model were valid. The psychological range of the sensory impressions in this study was large enough to produce a non-monotonic relationship between "difference" and "ratio" judgments, if subjects had distinguished in actual fact between differences and ratios of perceived sweetness intensity. However, the monotone relationship between the arithmetic means of judged "differences" and the geometric means of judged "ratios", shows that either one of the two response models must



be invalid. Apparently, subjects compared the perceived sweetness intensities of each pair in the same way, irrespective of whether to judge "differences" or to judge "ratios". It can therefore be concluded that Birnbaum's one-operation theory applies also to judgments of perceived sweetness intensity. The comparison between two subjective impressions is amenable to description by algebraic subtraction.

The results from this study could also be explained by assuming that, subjects judged ratios of perceived sweetness intensities (Birnbaum & Veit, 1974), instead of differences, in both the "ratio" and the "difference" judgment condition. However, there is sufficient experimental evidence from studies on other perceptual continua to conclude that the comparative judgmental operation relating two subjective impressions is a subtractive and not a ratio operation (Birnbaum & Mellers, 1978; Hagerly & Birnbaum, 1978; Mellers & Birnbaum, 1982; Mellers et al., 1984; Schneider et al., 1976; Scheider et al., 1982; Veit, 1978).

Rule, Curtis and colleagues (e.g., Rule & Curtis, 1980, 1982; Rule, Curtis & Mullin, 1982) argued that subjects are able to judge differences when instructed to judge "differences", and are also able to judge ratios when instructed to judge "ratios". According to these authors, category ratings are linear with subjective intensity, and magnitude estimation instructions induce a response output function which has the form of a power function. This two-operation theory predicts that the geometric means of reported "ratios" are a non-monotonic function of the arithmetic means of reported "differences" (Rule & Curtis, 1980). It also predicts, that the scale values of the log-transformed "ratio" response matrix are a logarithmic function of the marginal means of the "difference" response matrix (Birnbaum, 1980). Figures 2 and 3 show that these data are not in line with either of both predictions, and hence do not support the two-operation theory.

The one-operation theory assumes that psychophysical judgment encompasses two stages, a psychophysical stage, relating

physical intensity to perceived intensity, and a judgmental stage, relating perceived intensity to observable response (e.g., Attneave, 1962; Torgerson, 1961; Treisman, 1964). Anderson's functional measurement approach, in combination with a two stimulus procedure provides, a means of separating these processes. The parallelism in Figure 1, panel A indicates, that the judgmental stage can be described by a linear (difference) function. This implies that the function plotted in Figure 4 is an empirically estimated psychophysical function of fructose, of which the scale values represent perceived sweetness intensities on an interval scale.

This function has a sigmoid form when plotted on a log-linear plot. This finding is in line with the results of De Graaf *et al.* (1987) and De Graaf and Frijters (1988), who used a similar methodology. The sigmoid shape of the psychophysical function of fructose on a log-linear plot also implies that the psychophysical function of fructose as assessed by the present procedure is not a power function.

The two stage interpretation of psychophysical judgment (the S-O-R paradigm) conflicts with the S-R approach of Stevens (1975) and Moskowitz (e.g., 1970, 1971), who believed that sensory responses obtained using magnitude estimation instructions have a one to one relationship with perceived taste intensities. Following the two-stage interpretation, we hold the view, that the observable response is a behavioural parameter, which is not necessarily a linear representation of subjective intensity (Frijters & De Graaf, 1987; Frijters & Oude Ophuis, 1983). Investigators who have adopted the two stage interpretation of psychophysical judgment, have shown that the responses obtained using magnitude estimation are a non-linear and positively accelerating function of subjective intensity (e.g., Rule and Curtis, 1982; Veit, 1978; Weise, 1972). This implies that the power functions, which Stevens (1969) and Moskowitz (1970, 1971) obtained by magnitude estimation, do not reflect the psychophysical functions as they intended. These (S-R) functions

comprise two functions; the psychophysical function (S-O), and the response output function (O-R). As the response output function depends on several experimental factors (e.g., Baird & Noma, 1978), it is not surprising that for example the exponents of fitted power functions for substances such as sucrose and NaCl (Meiselman, 1972), show a large variability.

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## CHAPTER EIGHT

### CONCENTRATION OF SUCROSE AND NaCl: EQUALITY IN PERCEIVED TASTE INTENSITY

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**ABSTRACT** Results from some previous studies suggest that sucrose and NaCl solutions have an equal perceived taste intensity, when the molar concentration of sucrose is 1.5 - 1.75 times the molar concentration of NaCl. However, according to other studies, sucrose and NaCl solutions taste equally strong, when their molar concentrations are about equal. This issue was further pursued using the method of constant stimuli, where subjects matched the perceived taste intensity of NaCl solutions to five sucrose references, and vice versa. The results concur with previous findings that sucrose and NaCl solutions have equal perceived taste intensities, when the molar concentration of sucrose is 1.5 - 1.75 times the molar concentration of NaCl.

## INTRODUCTION

For taste research on mixtures and cross-adaptation, and for MDS applications to taste, it may be necessary to know, which concentrations of NaCl and sucrose evoke equal perceived taste intensities.

The data of some previous studies suggest that the perceived taste intensity of sucrose and NaCl solutions is about equal, when the sucrose concentration is 1.5 - 1.75 times the concentration of NaCl (concentration in mol substance per litre solution = M) (Beebe-Center and Wadell, 1948; Beebe-Center, Rogers and Atkinson, 1955; Gillan, 1982; Frank and Archambo, 1986).

According to other authors (Bartoshuk, 1968, 1975; Kuznicki, Hayward and Schultz, 1983), sucrose and NaCl have about equal taste intensities when solutions of both substances are of equal molarity. In their cross-adaptation studies, Kroeze (1978, 1979), and Lawless (1982) used 0.32 M NaCl and 0.32 M sucrose as equi-intense concentrations. These concentrations were based on Bartoshuk's inferences (Bartoshuk, 1975), that they elicit approximately equal perceived taste intensities. However, the data of Schiffman, McElroy and Erickson (1980) suggest that 0.15 M NaCl has the same perceived taste intensity as 0.65 M sucrose, which is a concentration ratio of about four.

In view of the apparent discrepancies, this study was undertaken to further investigate the concentrations of sucrose and NaCl, which are perceived as being of equal intensity. A particular variation of the method of constant stimuli (Guilford, 1954) was used, as it had previously yielded reliable results in a within-sweetness modality matching experiment (De Graaf and Frijters, 1986).

Beebe-Center and Wadell (1948) reported that the concentrations at which sucrose and NaCl were of equal intensity, seemed to depend on which of the two substances was used as the reference stimulus. For this reason, it was necessary to carry out two experiments. The first experiment was designed to determine

the PSE's (Points of Subjective Equality) of NaCl solutions to five sucrose references. In the second experiment, which was carried out to verify the first, the concentrations of sucrose which matched the perceived taste intensities of the previously obtained PSE's of NaCl were determined.

## METHODS AND MATERIALS

### Subjects

The subjects were nine female and one male volunteers, ranging in age from 18 to 25 years. All of the subjects, who were undergraduate students at the Agricultural University, had previous experience in psychophysical tasks. They were given no information about the aim of the experiment or the nature of the substances used.

### Stimuli

The stimuli were solutions of sucrose (Merck, 7653) and NaCl (Merck, 7651) dissolved in demineralized water. All solutions were prepared at least 24 hours before tasting, and kept at 4 degrees C for no longer than one week.

#### Experiment 1

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The concentrations of the five reference sucrose solutions, were 0.125, 0.25, 0.50, 1.00, and 1.25 M. Each sucrose reference was compared to a different series of seven geometrically spaced NaCl solutions. The concentrations of the middle stimulus of each of the five different series of NaCl solutions, were 0.075, 0.175, 0.35, 0.75, and 0.90 M NaCl, respectively. In all of the NaCl series, the difference in concentration between two adjacent stimuli was 10%. For example, the concentrations of the stimuli compared to 0.50 M sucrose (one of the reference stimuli) were



0.262, 0.289, 0.318, 0.350 (the middle stimulus), 0.385, 0.424, and 0.466 M NaCl.

## Experiment 2

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The reference stimuli were the PSE concentrations of NaCl, determined in experiment 1, i.e., 0.065, 0.136, 0.327, 0.558, and 0.702 M NaCl (Table 1, column 2). Each of these NaCl reference stimuli was compared to a different series of seven geometrically spaced sucrose solutions. The concentrations of the middle stimuli of the five series were, 0.125, 0.25, 0.50, 1.00, and 1.25 M sucrose respectively (i.e., the original reference sucrose solutions, used in experiment 1). Within each series of sucrose solutions, the difference between the concentrations of two adjacent stimuli was 10%. For example, 0.065 M NaCl was compared to 0.094, 0.103, 0.114, 0.125, 0.136, 0.151, and 0.167 M sucrose.

## Procedure

The method of constant stimuli was used (Guilford, 1954). In both experiments, the subjects were instructed to identify the strongest stimulus within each pair, irrespective of taste quality. They were instructed to guess when in doubt. Subjects thoroughly rinsed their mouths with demineralized water between, but not within, pairs.

The stimuli were presented at room temperature, in pairs of polystyrene medicine cups, each containing about 10 ml solution. At each of the five levels of the reference substance and corresponding series of comparison stimuli, 14 pairs were presented, i.e., seven times the reference tasted firstly and the comparison stimulus tasted secondly, plus seven times the reversed order of tasting. The 14 pairs were presented in a different randomized order for each subject. Thus, in each series of pairs, both sucrose and NaCl served as first stimulus seven times. The interval between pairs was 70 seconds.

The subjects tasted each series of 14 pairs three times. In each of the 10 one-hour sessions, subjects tasted three series of 14 pairs.

## **RESULTS**

The NaCl concentrations which are equal in perceived taste intensity to the various sucrose references, and the corresponding 95% confidence intervals are shown in Table I, columns 2 and 3, respectively. PSE concentrations were calculated using Urban's solution for the method of constant stimuli (Bock and Jones, 1968). For a detailed description of the calculation procedure used, the reader is referred to De Graaf and Frijters (1986).

The function relating the concentrations of sucrose and NaCl which are perceived as being of equal intensity, was obtained by linear regression through the origin, with NaCl concentration as the dependent, and sucrose concentration as the independent variable. The equation obtained is  $(\text{Sucrose}) = 1.67 (\text{NaCl})$ , having an R-squared value of 0.998.

Table II, column 2 shows the concentrations of sucrose equal in perceived taste intensity to the PSE concentrations of NaCl, as determined in the first experiment. The 95% confidence intervals are shown in column 3. The linear function through the origin relating the NaCl concentration to equi-intense sucrose concentrations is  $(\text{NaCl}) = 0.57 (\text{Sucrose})$ . This function also has a R-squared value of 0.998.

If the relationship between the concentrations at which sucrose and NaCl are of equal intensity, is independent of the type of reference stimulus (sucrose or NaCl), then the PSE's of sucrose obtained in experiment 2, should be identical to the original reference sucrose levels in experiment 1. Table II, column 4, shows that of the various sucrose concentrations equal in perceived taste intensity to the PSE's of NaCl, four out of the five are about 5% lower than the original reference sucrose solutions. However, for these four concentrations, the

**Table I. Concentrations, and 95% confidence intervals, of NaCl solutions equal in perceived taste intensity to five sucrose references.**

Concentration of sucrose reference (M)	PSE of NaCl (M)	95% confidence interval of PSE.
0.125	0.065	0.060 - 0.070
0.250	0.136	0.123 - 0.152
0.500	0.327	0.293 - 0.365
1.000	0.558	0.466 - 0.669
1.250	0.702	0.624 - 0.789

**Table II. Concentrations of sucrose and 95% confidence intervals, equal in perceived taste intensity to five NaCl references, and deviations (in %) from the original reference sucrose concentrations (see Table I).**

Concentration of NaCl ref. (M)	PSE of sucrose (M)	95% confidence interval of PSE (M)	$(PSE_{sucr} - REF_{sucr}) / (REF_{sucr})$ (%)
0.065	0.117	0.109 - 0.125	- 6.8
0.136	0.210	0.197 - 0.224	- 16.0
0.327	0.481	0.445 - 0.520	- 3.8
0.558	0.957	0.860 - 1.064	- 4.3
0.702	1.182	1.108 - 1.310	- 5.4

corresponding original sucrose concentrations (Table I) all fall within the 95% confidence intervals. This is not the case for the sucrose concentration equal in perceived taste intensity to 0.136 M NaCl, where the PSE of sucrose obtained in the second experiment is 16% lower than the original reference sucrose solution (0.25 M).

## DISCUSSION

The results of this study concur with the data of Beebe-Center and colleagues (Beebe-Center and Wadell, 1948; Beebe-Center

et al., 1955), Gillan (1982), and Frank and Archambo (1986). Beebe-Center et al. (1955) stated that sucrose and NaCl taste equally strong when the sucrose concentration is about 10 times the salt concentration, when the concentrations of both substances are expressed in grams solute per 100 grams solvent. If the concentrations are re-expressed in M (Handbook of Chemistry and Physics, 1979-1980; Myers, 1982), the sucrose concentration is 1.51 (salt as reference) - 1.54 (sugar as reference) times the salt concentration. The data of Frank and Archambo (1986) suggest that the sucrose concentration must be 1.76 times the salt concentration. This figure was obtained by equating the fitted logarithmic functions, which relate sugar and salt concentration to total perceived taste intensity (both functions have an R-squared value of 0.999).

These findings do not concur with the sucrose and NaCl concentrations mentioned by Bartoshuk (1975), and Kuznicki et al. (1983). These authors suggested that sucrose and NaCl have equal perceived taste intensities at about equal molar concentrations. The present results also not in line with the figures given by Schiffman et al. (1980), which suggest, that 0.65 M sucrose matches the intensity of 0.15 M NaCl.

The experiment reported herein, and that of experiment of Beebe-Center and Wadell (1948), both employed the method of constant stimuli, which is ".. generally regarded as the most accurate and most widely applicable of all psychophysical methods .." (Guilford, 1954, p. 118). The data of Frank and Archambo (1986) were obtained by ratings on a 21- point category scale. Since the same response scale was used for both sucrose and NaCl solutions, the intensities of sucrose and NaCl solutions are expressed in the same units, enabling comparison of the perceived taste intensities of sucrose and NaCl.

In choosing equi-intense concentrations of sucrose and NaCl, Kroeze (1978, 1979) relied on the data given by Bartoshuk (1975). Lawless (1982) also used Bartoshuk's concentrations, when replicating part of Kroeze's work (Kroeze, 1978, 1979). Bartoshuk (1975) apparently derived her figures for equistrong sucrose and NaCl solutions, by interpretation of previously reported data (Bartoshuk, 1968). However, the details given in the earlier paper, do not make it clear, how she deduced that 0.32 M sucrose is equal in perceived taste intensity to 0.32 M NaCl. Since Kuznicki et al. (1983) do not describe how they arrived at the equistrong concentrations of sucrose and NaCl solutions, it is impossible to evaluate their findings.

In conclusion, there is a lack of convincing experimental evidence to support previous suggestions, that sucrose and NaCl are equally strong at equal molar concentrations. However, three sets of experimental data confirm that sucrose and NaCl are perceived as equally intense, when the molar concentration of sucrose is 1.5- 1.75 times the molar concentration of NaCl.

The results of this study do not allow a definite conclusion to be drawn, regarding previous observations that the relationship between concentrations of sucrose and NaCl having the same perceived taste intensity, depends on which substance is used as the reference. In one out of the five cases, the PSE of sucrose obtained in the second experiment differed significantly from the sucrose reference used in the first experiment. The fact, that the shift in the relationship between PSE's of sucrose and NaCl in this study, is opposite to the shift found by Beebe-Center and Wadell (1948), further confounds this issue.

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## CHAPTER NINE

### INTERRELATIONSHIPS AMONG SWEETNESS, SALTINESS AND TOTAL TASTE INTENSITY OF SUCROSE, NaCl AND SUCROSE/NaCl MIXTURES

Caes De Graaf & Jan E.R. Frijters

**ABSTRACT** The sweetness, saltiness and total taste intensity of sucrose, NaCl and sucrose/NaCl mixtures was assessed using a combination of a functional measurement approach and a two stimulus procedure. The scale values obtained were linear with perceived sweetness, saltiness and total taste intensity. The results showed that the psychophysical functions of sucrose and NaCl were positively accelerating at low concentrations and negatively accelerating at high concentrations. The total taste intensity of sucrose was equal to the sweetness intensity of sucrose, and the total taste intensity of NaCl was equal to its saltiness. NaCl had a sweet side taste of which the magnitude was independent of its concentration. Sucrose/NaCl mixtures were sweeter than the corresponding sucrose solutions when tasted alone when both the NaCl and the sucrose concentration were low. Sucrose/NaCl mixtures were perceived as being less sweet than sucrose when either the sucrose or the NaCl concentration was high. The saltiness of sucrose/NaCl mixtures was lower than the saltiness of unmixed NaCl. The saltiness of sucrose/NaCl mixtures depended only on the NaCl concentration and was independent of the sucrose concentration. The total taste intensity of sucrose/NaCl mixtures could be well predicted by the square-root of the sum of the squared intensities of its components when tasted alone. The total taste intensity of sucrose/NaCl mixtures was approximately equal to the sum of the sweetness and saltiness of the mixtures. Sweetness and saltiness had about equal weights in determining the total taste intensity of sucrose/NaCl mixtures.

## INTRODUCTION

Several perspectives and various psychophysical methods have been used in the past to study the taste interaction between sucrose and NaCl (Frank and Archambo, 1988). Most of the research focused on the relationships between the sweetness and saltiness of sucrose/NaCl mixtures on the one hand, and the sweetness and saltiness of unmixed sucrose and NaCl on the other hand (e.g. Beebe-Center, et al., 1959; Indow, 1969; Kamen, et al., 1961; Pangborn, 1962). The conclusions of these studies differ, but some generalizations can be made. In a number of studies it was observed that the sweetness intensity of a sucrose/NaCl mixture containing a high concentration of NaCl was lower than the perceived sweetness of equally concentrated unmixed sucrose solution (e.g., Beebe-Center, et al., 1959; Kamen et al., 1961; Pangborn, 1962). Some studies additionally showed that a mixture of a particular concentration sucrose and a low concentration of NaCl, was perceived as being sweeter than the same sucrose concentration tasted alone outside the mixture (e.g., Beebe-Center et al., 1959; Kamen, et al., 1961; Pangborn, 1962). Obviously, low concentrations of NaCl added to sucrose solutions enhance the sweetness intensity. The reverse seems not to be the case. The saltiness of sucrose/NaCl mixtures is lower than the saltiness of unmixed NaCl solutions irrespective of the sucrose concentration (e.g., Beebe-Center et al., 1959; Pangborn, 1962).

Another issue addressed in previous mixture studies is the relationship of the total taste intensity of a mixture to the perceived taste intensities of the mixture's constituents when tasted separately (e.g., Bartoshuk, 1975; Moskowitz, 1972). Frank and Archambo (1988) concluded that the total taste intensity of sucrose/NaCl mixtures is always less than the sum of the total taste intensities of the unmixed components. They also concluded that the degree of "subadditivity" increases with increasing concentrations of both solutes.

The present study was designed to investigate a number of



## INTRODUCTION

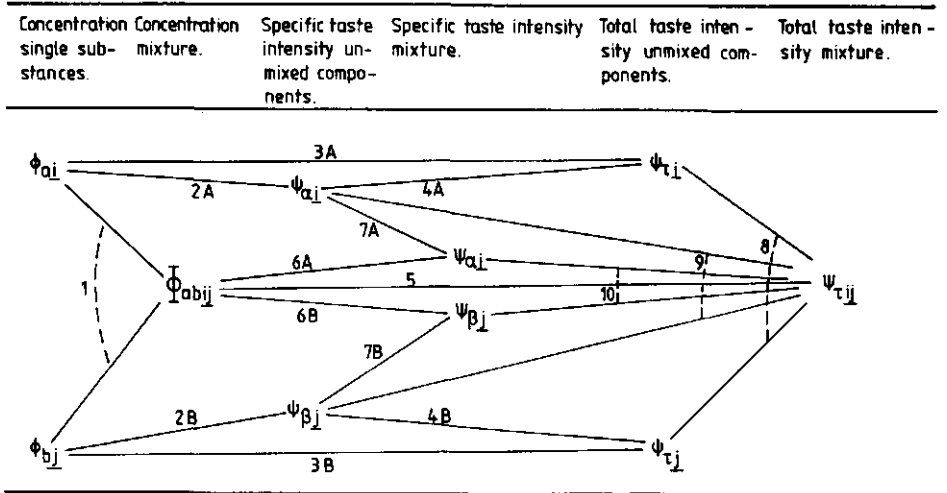
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The present study was designed to investigate a number of specific relationships between the sweetness, the saltiness, and the total taste intensity of sucrose, NaCl, and sucrose/NaCl mixtures. The conceptual framework specifying these relationships is illustrated in Figure 1 and explained in the Theory section. As argued elsewhere (De Graaf & Frijters, 1987b; De Graaf *et al.*, 1987), a proper description of the taste interaction phenomena requires that the perceived taste intensities are assessed on a linear response scale. The methodology used in the present investigation to obtain scale values of perceived taste intensities on a linear response scale was similar to that of De Graaf & Frijters (1987b), and De Graaf *et al.* (1987). The reader is referred to these papers for a detailed description. It was based on a functional measurement paradigm in combination with a two stimulus task (Anderson, 1974; Birnbaum, 1982). In the experimental procedure subjects compare the sensory impression of each of a number of 'row' (first) stimuli with the sensory impression of each of a number of 'column' (second) stimuli. This type of design is called a factorial judgment design.

## THEORY

In the scheme outlined in Figure 1, each relationship has a number. This is elaborated in a separate paragraph. The notation used is in line to that proposed by Frijters (1987). Throughout this paper the physical concentration of an unmixed solution is denoted by " $\phi$ "; the symbol " $\Phi$ " is used to denote the physical concentration of a mixture of substances. The taste intensity of single substances (i.e., outside the mixture) is denoted by " $\psi$ ". The taste intensities of mixtures and of the compounds within mixtures are denoted by " $\Psi$ ". The roman subscripts "a" and "b" refer to the chemicals sucrose and NaCl, respectively. The subscripts  $i$  and  $j$  represent particular concentrations of sucrose and NaCl in mol/L. The greek subscripts " $\alpha$ " and " $\beta$ " refer to the taste qualities "sweet" and "salt", respectively. The subscript



**Fig. 1. Outline of specific relationships between the sweetness, saltiness, and total taste intensity of sucrose, NaCl and sucrose/NaCl mixtures.**

" $\tau$ " refers to the "total" taste intensity which is defined as the subjective magnitude of a particular taste percept irrespective of its quality.

#### Explanation of Figure 1

1) When  $i$  mol of substance A ( $= \phi_{ai}$ ) and  $j$  mol of substance B ( $= \phi_{bj}$ ) are added together and subsequently dissolved in one litre of water, a mixture concentration  $\phi_{abij}$  is obtained. The total concentration of the mixture is  $(i + j)$  mol/L provided that no chemical reaction has taken place. This operation represents physical mixing.

2) The lines connecting  $\phi_{ai}$  and  $\psi_{ai}$  (2A), and  $\phi_{bj}$  and  $\psi_{bj}$  (2B), represent the psychophysical functions for the sweetness of sucrose and the saltiness of NaCl, respectively.

3) The concentrations  $\phi_{a1}$  and  $\phi_{b1}$  give rise to the perceived total taste intensities  $\psi_{t1}$  and  $\psi_{r1}$ , respectively. These relationships are described by the psychophysical functions for the total taste intensity of sucrose and NaCl, respectively.

4A) The line connecting  $\psi_{a1}$  and  $\psi_{r1}$  describes the relationship between the sweetness intensity and the total taste intensity of sucrose. If sucrose elicits only a sweet taste, this relationship can be described by an identity function ( $\psi_{a1} = \psi_{r1}$ ).

4B) The connection between  $\psi_{a1}$  and  $\psi_{r1}$  describes the relationship between the saltiness and the total taste intensity of NaCl. If NaCl would elicit only saltiness, the relationship could be described by an identity function. The results of various studies, however, suggest that some concentrations of NaCl have an additional sweet taste (e.g., Bartoshuk *et al.*, 1978; Kroeze, 1982a).

5) Each mixture of concentration  $\phi_{ab1}$  evokes a particular total taste intensity  $\psi_{t1}$ . The relationship between  $\phi_{ab1}$  and  $\psi_{t1}$  is determined by the psychophysical function of the mixture.

The experimental determination of a psychophysical function of a mixture of tastants is more complicated than establishing such a function for a single substance. In most experiments the physical intensity of a stimulus varies over one dimension, whereas in binary mixtures of taste substances two stimulus dimensions are being manipulated (i.e., the concentrations of each of the two substances in the binary mixtures). This problem can be handled by conceiving a binary mixture as if it were one particular type of taste stimulus. This was done by Frijters & Duda Ophuis (1983), who introduced the concept of "equiratio mixture type". The latter authors defined an equiratio mixture type as a series of mixtures with different concentrations, but

an equal ratio of its constituent components ( $i/j = \text{constant}$ ). A psychophysical function for a particular equiratio mixture type can be determined in the same way as such a function for a single substance. The measure of physical intensity of a mixture is the sum of the concentrations of its components.

6) The individual taste qualities of sucrose and NaCl can be reliably identified in mixtures of these substances (Kuznicki & Ashbaugh, 1982). The mixture  $\Phi_{sbj}$  gives rise to a particular sweetness intensity  $\Psi_{sj}$  and a particular saltiness intensity  $\Psi_{bj}$ . The sweetness and the saltiness intensities of a sucrose/NaCl mixture percept depend on the psychophysical functions of both substances and on the central interaction between sweetness and saltiness (Kroeze, 1978, 1979).

7) The function between  $\Psi_{sj}$  and  $\Psi_{bj}$  describes the relationship between the perceived sweetness intensity of a particular sucrose concentration tasted as a single substance and the sweetness intensity of a sucrose/NaCl mixture of the same sucrose concentration as the unmixed substance. As noted above, this relationship has been investigated extensively (e.g., Beebe-Center *et al.*, 1959; Kamen *et al.*, 1961; Pangborn, 1962). The same holds for the function between  $\Psi_{sj}$  and  $\Psi_{bj}$ , describing the relationship between saltiness of unmixed NaCl solutions and that of mixtures of NaCl and sucrose.

8) The relationship between the total taste intensity of a sucrose/NaCl mixture ( $\Psi_{tj}$ ), and both the total taste intensity of the constituent sucrose concentration tasted independently ( $\Psi_{sj}$ ) and the total taste intensity of the constituent NaCl concentration tasted independently ( $\Psi_{bj}$ ) can be assessed in various ways.

One way is to compare the total taste intensity of the mixture with the sum of the total taste intensity of sucrose when tasted separate from the mixture plus the total taste intensity of NaCl when tasted by itself ( $\Psi_{tj} \longleftrightarrow \Psi_{sj} + \Psi_{bj}$ ). This was

called "the summated comparison rule" (De Graaf & Frijters; 1987a, 1987b). Two other ways for comparing the single substance intensities with the mixture intensity are the "factorial plot comparison rule" and the "equimolar comparison rule" (De Graaf & Frijters, 1987b).

The factorial plot comparison originates from Anderson's theory of information integration (Anderson, 1981). It was recently applied in taste psychophysics by McBride (1986) and Frank & Archambo (1986). When this rule is applied, the nature of the taste interaction is inferred from the pattern of lines in a factorial plot. In the case of sucrose/NaCl mixtures this could be a plot of the total taste intensity as a function of the total taste intensity level of sucrose with a separate curve for each of the total taste intensity levels of NaCl. If the lines in such a plot diverge, synergism has taken place according to McBride (1986). If the lines run parallel, addition occurs, and when the lines converge, the two tastants suppress each other.

When the equimolar comparison rule is used the taste intensities of the mixtures and single compounds are compared at equimolar concentrations ( $\Phi_{abij} = \Phi_{ai} = \Phi_{bj}$ ). For example, the total taste intensity of 1.0 M of the sucrose/NaCl .50/.50 equiratio mixture type is compared with the total taste intensity of 1.0 M NaCl and with the total taste intensity of 1.0 M sucrose.

9) The relationship between the total taste intensity of the mixture ( $\Psi_{tj}$ ) and both the perceived sweetness intensity of sucrose ( $\Psi_{sj}$ ) and the saltiness of NaCl when tasted outside the mixture ( $\Psi_{bj}$ ), can be studied in a way similar to the relationship discussed in the previous paragraph. It can be investigated using the summated response comparison rule, the factorial plot comparison rule, or the equimolar comparison rule. These rules have been explained above.

A prerequisite for the application of these rules is that the sweetness intensity of sucrose, the saltiness intensity of

NaCl, and the total taste intensity of the mixtures are expressed in the same unit. Thus, a saltiness intensity of five units on the saltiness scale must be subjectively equal to a sweetness of five units on the sweetness scale, and also to a total intensity of five units on the total taste intensity scale.

10) The lines connecting  $\Psi_{s1}$  and  $\Psi_{s2}$  with  $\Psi_{t1}$ , describes the relationships between the sweetness and the saltiness of the mixture and the total taste intensity of the mixture. These relationships are the result of cognitive and/or perceptual integration processes.

Frank and Archambo (1986) suggested that the total taste intensity of a sucrose/NaCl mixture percept is less than the sum of the sweetness and saltiness of the mixture. Other investigators have tacitly assumed that the total taste intensity of a particular complex taste percept is the sum of the specific taste intensities, i.e., sweetness, saltiness, sourness and bitterness (Bartoshuk, 1975; McBurney & Bartoshuk, 1973; Moskowitz, 1972). In the latter studies, the over-all or total taste intensity was determined by calculating the sum of the specific taste intensities.

## METHODS AND MATERIALS

The entire study consisted of three investigations of similar design. One for assessing the sweetness, one for assessing the saltiness, and one for assessing the total taste intensity of sucrose, NaCl, and sucrose/NaCl mixtures. Each of the three investigations consisted of 18 experiments and each of these experiments employed a factorial judgment design (De Graaf and Frijters, 1987b; De Graaf *et al.*, 1987).

### Subjects

The subjects were fourteen paid volunteers, twelve women and

two men, ranging in age from 18 to 26 years. All were students of the Agricultural University. All subjects had had previous experience with psychophysical tasks.

### Stimuli

The stimuli were solutions of reagent grade sucrose (Merck: 7853), reagent grade NaCl (Merck: 7851) and mixtures of these substances in demineralized water.

Figure 2, panel A, shows the concentrations and composition of the experimental stimuli. The concentrations of both the unmixed sucrose solutions as well as the unmixed NaCl solutions were 0.00 (water), 0.125, 0.250, 0.500, and 1.00 M sucrose and NaCl, respectively. The mixtures were constructed on the basis of a "factorial mixing design" (De Graaf & Frijters, 1987b; McBride, 1986). Each of the afore mentioned NaCl concentrations was mixed with each of the afore mentioned sucrose concentrations, resulting in 16 binary mixtures. In addition, 0.0625 M NaCl was mixed with 0.0625 M sucrose, resulting in a 0.125 molar solution of the sucrose/NaCl .50/.50 equiratio mixture type.

In each of the three investigations subjects were presented with a reference pair. The first stimulus of the reference pair was always water. The second stimulus of the reference pairs were 1.25 M sucrose, 1.25 M NaCl, and 4.50 M of the sucrose/NaCl .50/.50 equiratio mixture type (a mixture containing 2.25 M sucrose and 2.25 M NaCl), in the "sweetness", "saltiness", and "total intensity" investigation, respectively.

Solutions were prepared at least 24 hours before tasting and were not stored for longer than one week, the storage temperature being 4 degrees C.

### Design

The designs for the investigations "sweetness", "saltiness", and "total intensity" were similar to each other, and therefore,



only the design for the "sweetness" investigation will be discussed in detail. Where specific differences did occur they will be mentioned.

As noted above the "sweetness" investigation consisted of 18 experiments, each of which employed a factorial judgment design. A factorial judgment design (used to check the linearity of the response scale) implies that subjects are presented with pairs of stimuli. Each stimulus of a pair is one stimulus of a series of "row" (first) stimuli, or "column" (second) stimuli. When two single substances are used, a simple  $m \times n$  design can be employed, where  $m$  and  $n$  denote the number of concentrations of the first and second stimulus. When mixtures instead of single compounds have to be incorporated in a factorial judgment design, the situation becomes more complicated. In a design involving single substances, the series of row and column stimuli vary over one dimension (i.e., the concentration level of each of the substances). When binary mixtures are used, the series of row or column stimuli vary over two dimensions (i.e., the concentration levels of each of the two components). This problem can be overcome by conceiving a mixture as if it were a single substance. This was achieved by using the concept of an equiratio mixture type, where the mixtures have different total concentrations but a constant ratio of constituent components. A psychophysical function for an equiratio mixture type can then be constructed in the same way as such a function for a single substance (Frijters & Oude Ophuis, 1983).

In order to incorporate all the experimental stimuli in factorial judgment designs, nine series of stimuli were constructed: two series of single substances (sucrose or NaCl), and seven series of different sucrose/NaCl equiratio mixture types. These series are surrounded by the undashed lines in Figure 2, panel A. Water being the 0.00 M solution of each stimulus type was included in each of these series.

Each of the nine series of experimental stimuli were compared with regard to perceived sweetness intensity with three

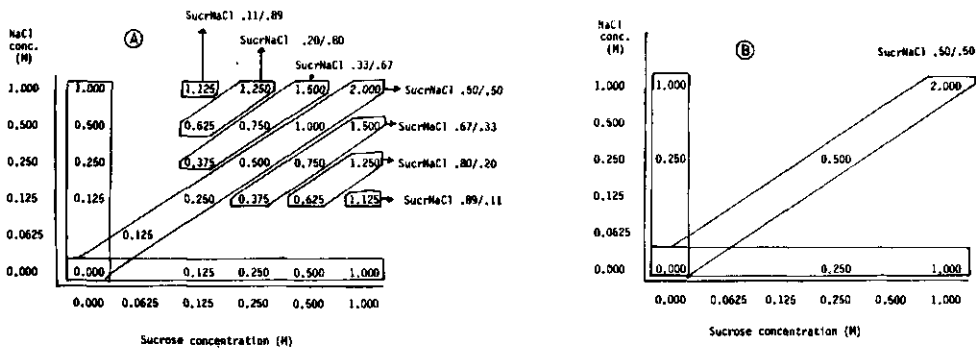


Fig. 2. Panel A shows the total concentration and composition of the nine series of experimental stimuli. The series of unmixed sucrose, unmixed NaCl and the seven different equiratio mixture types are surrounded by the undashed lines. Water was included in each of the nine series. This is shown only for the series of unmixed sucrose, unmixed NaCl and the sucrose/NaCl 0.50/0.50 equiratio mixture type. Panel B shows the concentration and composition of the three series of stimuli to which each of the series of stimuli shown in panel A were compared. In the sweetness investigation each of the series in panel A were compared to the series of sucrose stimuli in panel B. In the saltiness investigation the series in panel A were compared to the series of NaCl stimuli shown in panel B, and for the total taste intensity investigation the series of panel A were compared to the series of sucrose/NaCl 0.50/0.50 mixtures of panel B.

sucrose solutions, 0.00 (water), 0.250, and 1.00 M sucrose. These latter stimuli are shown in Figure 2, panel B. Each of the solutions in the series of three sucrose stimuli was presented as first stimulus in nine experiments, and as second stimulus in the other nine experiments.

In the "saltiness" investigation, each of the nine series of experimental stimuli was compared with respect to saltiness to each stimulus in a series of three NaCl solutions, 0.00 (water), 0.125, and 1.00 M NaCl. In the "total intensity" investigation, each of the nine series of stimuli was compared with regard to "total taste intensity" to each stimulus of a series of three mixtures, 0.00 (water), 0.50 , and 2.00 M of the sucrose/NaCl .50/.50 equiratio mixture type.

To summarize, the total study consisted of 54 experiments

(three investigations of 18 experiments). In every experiment each stimulus of one of the series of stimuli from Figure 2A was compared to each stimulus of one of the series of stimuli from Figure 2B.

### Procedure

Except for the instructions and response scale the experimental procedures for each of the three investigations were identical. Only the experimental procedures for the "sweetness" investigation will be described and where differences occur in experimental procedures these will be pointed out.

The subjects were instructed to judge the magnitude of the difference in perceived sweetness intensities (saltiness, total taste intensity) between the first and second stimulus of each pair. The instructions emphasized that only the sweetness (saltiness) intensity was to be judged, and that the hedonic value and side tastes of stimuli were to be disregarded. In the "total intensity" investigation, subjects were instructed to judge the taste intensity, irrespective of quality, and they were asked to include every quality they perceived. The judgments were expressed by a slash mark on a 250 mm visual analogue scale. The middle of the scale was defined as 'the first and second stimulus are equal with respect to perceived sweetness intensity' (saltiness, total taste intensity) (De Graaf *et al.*, 1987; Figure 3). If a subject perceived the first stimulus as sweeter (saltier, having a higher total taste intensity) than the second, he placed a mark on the left side of the scale according to the magnitude of the difference. Similarly, the subject marked the right side of the scale when the second stimulus was perceived as sweeter (saltier, having a higher total taste intensity). The left and right poles of the scale were labelled 'maximum difference'. In the instructions 'maximum difference' was defined as the difference in sweetness (saltiness, total taste) intensity between the stimuli of the reference pair, i.e. water as first

stimulus and a 1.25 M sucrose (1.25 M NaCl, 4.50 M sucrose/NaCl .50/.50) solution as second stimulus. The difference between the stimuli of the reference pair was expected to be larger than the difference in any other pair. A response was measured as the distance in mm from the left pole of the scale. A response value of 125 meant no difference, a value above 125 meant that the second stimulus was perceived as being sweeter (saltier, having the highest total taste intensity) than the first one, and a value below 125 indicated that the first stimulus was perceived as being the sweeter (saltier, having the highest total taste intensity) of the pair.

The subjects were requested to rinse their mouths thoroughly with demineralized water, both within and between pairs. The stimuli were presented at room temperature (20 degrees C), in polystyrene medicine cups. Each cup contained about 10 ml of solution. The pairs of each factorial design were presented in a random sequence and in a different order for each subject. The reference pair was presented at the beginning of each session, and again after the 12th and the 24th pair of each session. The time interval between the first and second stimulus of a pair was 40 seconds; the interval between pairs was also 40 seconds. Each of the 18 factorial designs of each investigation was presented twice to each subject. The order of presentation of the 18 experiments of each investigation was randomized. It took each subject 10 one-hour sessions to complete each investigation so that 30 sessions were needed to complete the entire study. The order of the three investigations involved that "sweetness" investigation was being carried out first, the "saltiness" investigation second, and the "total taste intensity" investigation was being carried out last.

## RESULTS

In order to be able to quantify the relationships outlined in Figure 1, it is necessary to obtain three separate scale

values for the sweetness, the saltiness, and the total taste intensity, for each of the experimental stimuli. A procedure to obtain such values has recently been developed by De Graaf & Frijters (1987b) and De Graaf *et al.* (1987). It was applied again to the present data. The reasoning behind these calculation procedures will not be repeated here. However, a brief outline of the psychometric properties of the response scale and an explanation of the derivation of the scale values will be given in the next section. For a more detailed discussion the reader is referred to the papers mentioned in this paragraph.

#### Psychometric properties of response scale and derivation of scale values

In order to check the linearity of the response scale, analyses of variance were carried out for each individual subject and for each factorial design in each of the three investigations. The indicator for nonlinearity, the Row x Column interaction was tested for statistical significance against the Row x Column x Replication as error term. Out of 758 analyses, seven showed a significant interaction at the  $p < 0.01$  level. None of the subjects had more than one significant interaction. Analyses of variance were also carried out on group level. For each of the 54 factorial judgment designs, the Row x Column interaction was tested for significance against the Row x Column x Subject interaction. In three cases, the interaction appeared to be significant at the  $p < 0.01$  level. None of these interactions however, accounted for a substantial proportion of the total variance (maximally 0.38 %). In all experiments the responses obtained are obviously a linear function of perceived taste intensity differences. Consequently the marginal means of the row and column stimuli are validated estimates of the perceived taste intensity on a linear scale (Anderson, 1981).

Each factorial design yielded two marginal means for water; one for water as row stimulus and one for water as column

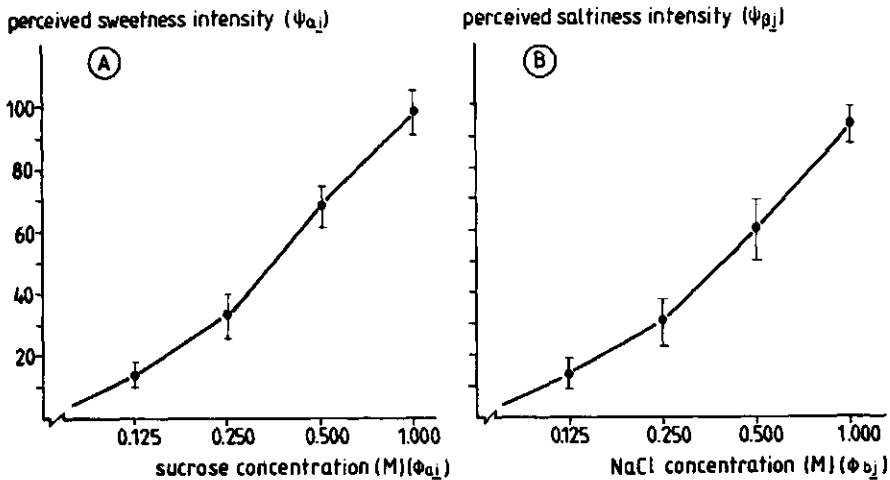
stimulus. The marginal means for water were set equal to zero so that the scale values of the other stimuli could be estimated by calculating the difference between their marginal means and the marginal mean of water in that same experiment. The final scale value for each stimulus was calculated by averaging the scale value(s) for that stimulus tasted as first stimulus of each pair, and the scale value(s) for that stimulus tasted as second stimulus of each pair. All data were averaged over subjects and replicates.

If it is assumed that water has no sweet, no salty, and no total taste intensity then the derived scale values represent taste intensities on a ratio scale.

The sweetness of sucrose and the saltiness of NaCl (Fig. 1: 2A, 2B)

Figure 3, panels A and B, shows the psychophysical functions for the sweetness of sucrose and the psychophysical function of the saltiness of NaCl on a log-linear plot. At low concentrations doubling the concentration (for example from 0.125 M to 0.25 M) yields a more than double sweetness or saltiness intensity. At high concentrations (for example from 0.50 M to 1.0 M), doubling the concentration yields a less than double sweetness or saltiness intensity. It can thus be concluded that the psychophysical functions for the sweetness of sucrose and the saltiness of NaCl are positively accelerating at low concentrations and negatively accelerating at high concentrations.

It is noted that the units of the sweetness scale are not necessarily equal to the units on the saltiness scale. The units on each scale are relative to the difference in taste intensity elicited by the reference pair in each investigation. As mentioned under the section Methods and Materials, the reference pair in the "sweetness" investigation consisted of water and 1.25 M sucrose. The reference pair in the "saltiness" investigation consisted of water and 1.25 M NaCl. It has been shown, that the



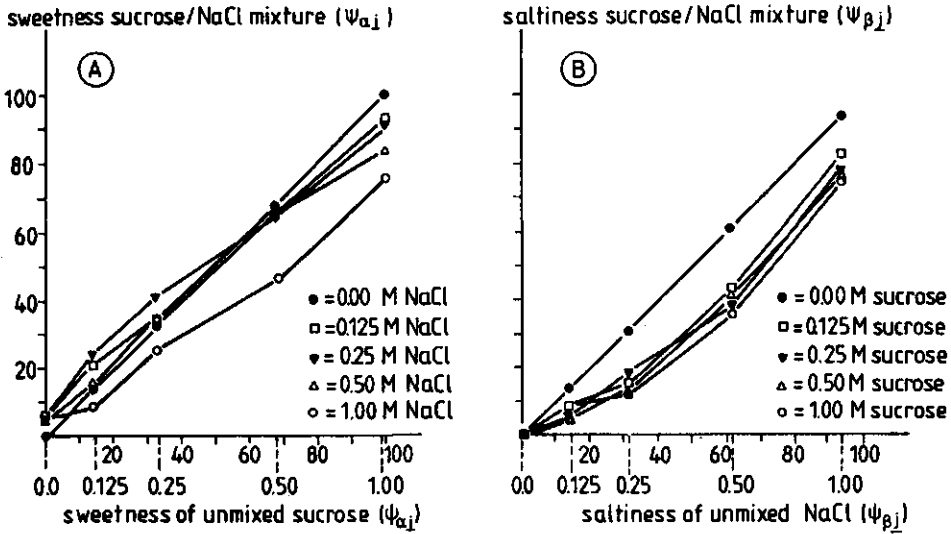
**Fig. 3. Panel A shows the psychophysical function of the sweetness of sucrose, Panel B shows the psychophysical function of the saltiness of NaCl. The error bars around each point represent the 95 % confidence interval for each scale value. The units of the sweetness scale and the saltiness scale are not equal.**

taste intensity of 1.25 M NaCl is higher than the taste intensity of 1.25 M sucrose (Beebe-Center & Waddell, 1948; Beebe-Center *et al.*, 1955; De Graaf & Frijters, 1987c), so that the same number of units (mm) on the saltiness scale represents a larger difference in taste intensity than on the sweetness scale.

Sweetness and saltiness of sucrose and NaCl compared to the sweetness and saltiness of sucrose/NaCl mixtures (Fig 1: 7A and 7B)

Figure 4, panel A, shows the sweetness of sucrose, NaCl, and the mixtures, as a function of the sweetness of sucrose, with a separate function for each NaCl concentration.

Analysis of variance of these data showed significant effects for sucrose [  $F(4,52) = 213.02$ ,  $p < 0.001$ ], NaCl [  $F(4,52) = 8.01$ ,  $p < 0.001$ ], and the sucrose by NaCl interaction [  $F(16,208) = 4.26$ ,  $p < 0.001$ ].



**Fig. 4.** Panel A shows the sweetness intensity of sucrose, NaCl and the sucrose/NaCl mixtures as a function of the sweetness of sucrose with a separate curve for each NaCl concentration, Panel B shows the saltiness of NaCl, sucrose and the sucrose/NaCl mixtures as a function of the saltiness of NaCl with a separate curve for each sucrose concentration. The units in panel A and panel B are not equivalent.

Visual inspection of Fig. 4, panel A, shows that the sweetness intensity of sucrose/NaCl mixtures is higher than the sweetness intensity of the corresponding unmixed sucrose solutions when both the sucrose concentration and the NaCl concentration are low. Sucrose/NaCl mixtures are less sweet than unmixed sucrose, when either the sucrose or the NaCl concentration is high. This pattern of taste interaction is similar to that observed by Frank & Archambo (1986; Fig. 7).

The four almost coinciding points on the y-axis of panel A represent the sweetness the unmixed NaCl solutions. These points show that each unmixed NaCl stimulus elicits a sweet taste of about the same magnitude. An analysis of variance of these data

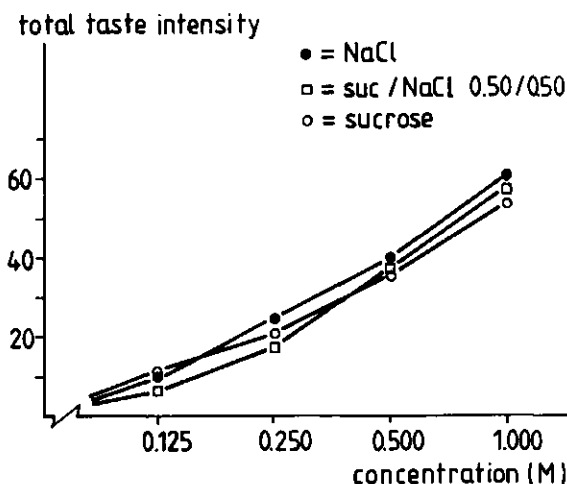


shows that the average sweetness of unmixed NaCl differs significantly from that of water [ $F(1, 13) = 7.19$ ,  $p = 0.02$ ], and that the sweetness intensity appears to be independent of the concentration level [ $F(3, 39) = 1.15$ ,  $p = 0.30$ ]. Kroeze (1982a) concluded that NaCl has a sweet side taste, both at weak concentrations and higher concentrations. The present findings suggest that the sweetness intensity of NaCl is independent of the NaCl concentration.

Figure 4 panel B shows the saltiness of sucrose, NaCl, and sucrose/NaCl mixtures as a function of the saltiness of NaCl. An ANOVA shows statistically significant effects of NaCl [ $F(4, 52) = 194.90$ ,  $p < 0.001$ ], sucrose [ $F(4, 52) = 18.77$ ,  $p = 0.001$ ], and the sucrose by NaCl interaction [ $F(16, 208) = 4.18$ ,  $p < 0.001$ ]. However, if the responses to the unmixed NaCl stimuli are omitted (i.e., the straight top line in Fig. 4B), the statistical significance of the effects of sucrose [ $F(3, 39) = 1.80$ ,  $p = 0.16$ ], and that of the sucrose by NaCl interaction [ $F(12, 156) = 1.33$ ,  $p = 0.21$ ] disappears.

Visual inspection of panel B shows that the saltiness of all sucrose/NaCl mixtures is lower than the saltiness of the corresponding unmixed NaCl concentrations in all cases. The results of the statistical analysis suggest that the four lower functions in this panel do not differ from each other. This implies that the saltiness of sucrose/NaCl mixtures containing both sucrose and NaCl depends only on the NaCl concentration and not on the sucrose concentration.

The points on the y-axis of panel B show the saltiness of the unmixed sucrose solutions. ANOVA of these data shows that the saltiness of sucrose does not deviate significantly from that of water [ $F(1, 13) = 0.12$ ,  $p > 0.5$ ], and is independent of the concentration level [ $F(3, 39) = 0.29$ ,  $p > 0.5$ ]. Sucrose does not elicit a salty taste.



**Fig. 5.** The psychophysical functions for the total taste intensity of sucrose, NaCl and the sucrose/NaCl 0.50/0.50 equiratio mixture type.

Total taste intensity of sucrose, NaCl, and sucrose/NaCl mixtures  
(Fig. 1: 3A, 3B, 5, 8)

As noted in the Theory section, the relationship between the total taste intensities of sucrose, NaCl and sucrose/NaCl mixtures can potentially be described according to three different comparison rules. In the subsequent paragraphs such relationships are established according to the equimolar comparison, the factorial plot comparison, and the summated response comparison rule (De Graaf & Frijters, 1987b).

Figure 5 is a log-linear plot of the psychophysical functions for the total taste intensity of sucrose, NaCl and the sucrose/NaCl .50/.50 equiratio mixture type. For each of these psychophysical functions it can be concluded that at low concentrations doubling the concentration yields a more than double total taste intensity, whereas at high concentrations, doubling the concentration yields a less than double total taste intensity. Each of these psychophysical functions is positively accelerating at low concentrations and negatively accelerating at

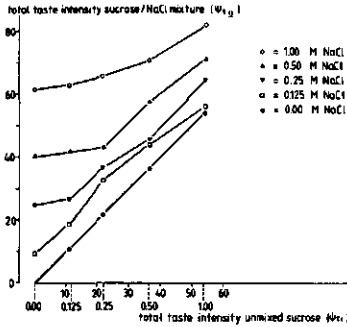


Fig. 6. The total taste intensity of sucrose, NaCl and the sucrose/NaCl mixtures as a function of the total taste intensity of sucrose, with a separate curve for each NaCl concentration.

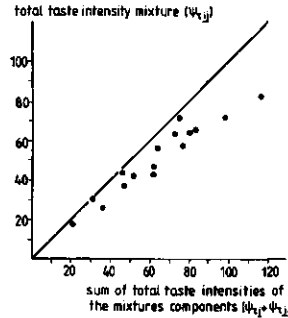


Fig. 7. The relationship between the total taste intensity of sucrose/NaCl mixtures and the sum of the total intensities of its components when tasted alone.

high concentrations, when plotted on linear-linear coordinates. This conclusion might not become evident from visual inspection of Fig. 5. It should be kept in mind however that the units on the x-axis are plotted logarithmically.

An ANOVA of these data shows that the psychophysical functions for the total taste intensity of sucrose, NaCl and the sucrose/NaCl .50/.50 mixture type do not differ. This conclusion can safely be drawn, because the main effect stimulus type and the interaction effect stimulus type  $\times$  concentration are statistically insignificant [  $F(2,13) = 1.82$ ,  $p = 0.18$ , and  $F(6, 78) = 1.56$ ,  $p = 0.16$ , respectively].

Figure 6 shows the total taste intensity of the experimental stimuli as a function of the total taste intensity of unimixed sucrose with a separate curve for each concentration of NaCl. The curves show a convergent pattern. The distance between the curves decreases as the total taste intensity of sucrose increases. Analysis of variance shows that the effects of sucrose [ $F(4,52) = 87.23$ ,  $p < 0.001$ ], NaCl [ $F(4,52) = 195.72$ ,  $p < 0.001$ ], and the sucrose by NaCl interaction [ $F(16,208) = 6.72$ ,  $p < 0.001$ ] are statistically significant. When the factorial plot comparison rule is applied, a statistically significant convergent pattern of lines implies suppression (McBride, 1986). In this case it means that sucrose and NaCl in a mixture suppress each other with respect to total taste intensity.

Figure 7 shows the relationship between the total taste intensities of the mixtures and the sum of the total taste intensities of its components according to the summated comparison rule. From this Figure it is evident that the total taste intensity of a mixture is always less than the sum of the total taste intensities of the unmixed components. This finding is in line with the observation of Frank & Archambo (1986).

Frank & Archambo (1986) investigated whether the vector-summation model (Berglund *et al.*, 1973) could be applied in describing the relationship between the total taste intensity of the mixture and the total taste intensities of the unmixed components. They used the formula:

$$\Psi_{Tij} = (\Psi_{Ti}^{**2} + \Psi_{Tj}^{**2} + 2\Psi_{Ti}\Psi_{Tj}\cos \alpha)^{**0.5},$$

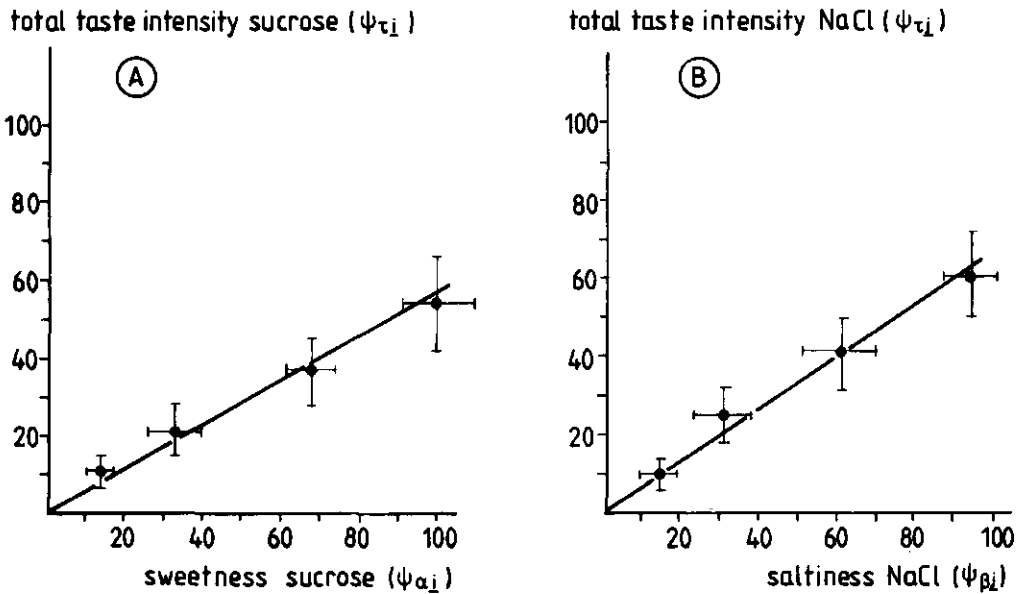
where  $\alpha$  represents the angle between the sucrose intensity (represented as a vector in a subjective space) and the NaCl intensity (also represented as a vector). This angle is supposed to reflect the degree of qualitative dissimilarity between the taste qualities of sucrose and NaCl. Frank & Archambo (1986) varied the value of  $\alpha$  to minimize the average absolute deviation of the mixture intensities predicted by the model from the mixture intensities experimentally obtained. They obtained a value for  $\alpha$  of 110 degrees. With this value for  $\alpha$ , the vector addition model provided a reasonable prediction for the observed mixture intensities. A similar analysis of the present data yielded a value for  $\alpha$  of 87 degrees i.e. the sucrose and NaCl axis are nearly orthogonal. Using this value for  $\alpha$  the mean absolute deviation of the predicted values from the observed values was 2.40; the mean relative deviation  $[(\text{value predicted} - \text{value observed})/(\text{value observed})] * 100 \%$  was -2.62 %. It appears that the total taste intensities of sucrose/NaCl mixtures can be accurately predicted by a pythagorean summation model of the intensities of the unmixed components [ $\Psi_{Tij} = (\Psi_{Ti}^{**2} + \Psi_{Tj}^{**2})^{**0.5}$ ].

Sweetness and total taste intensity of sucrose, and saltiness and total taste intensity of NaCl (Fig. 1: 4A, 4B).

Before discussing the results regarding the relationships between the sweetness of sucrose and the saltiness of NaCl and the total taste intensities of these tastants several points should be considered. As argued above the units of the "sweetness" scale, the "saltiness" scale, and the "total" taste intensity scale are not subjectively equal. All judgments in each investigation were made relative to the difference in taste intensity of the reference pair. The perceived taste intensity of 4.50 M of the Sucrose/NaCl .50/.50 equiratio mixture type is larger than the perceived taste intensity of either 1.25 M NaCl or 1.25 M sucrose. Therefore, a particular number of units on the total intensity scale represent a larger subjective taste intensity than the same number of units on the sweetness scale and the saltiness scale. This implies that if the total taste intensity of sucrose is perceived as identical to the sweetness intensity of sucrose then the scale values of the total taste intensity of sucrose must be lower than the scale values of the sweetness intensity of sucrose. The same holds for the scale values of NaCl.

Figure 8, panel A, shows the relationship between the scale values of sucrose on the sweetness scale and the scale values of sucrose on the total taste intensity scale. If the sweetness intensity of sucrose were identical to the total taste intensity of sucrose, then these scale values would differ with a multiplicative constant only. This would necessarily imply that the psychophysical functions for the sweetness of sucrose must be identical to the psychophysical function for the total taste intensity of sucrose, except for the multiplicative constant.

This constant was estimated by orthogonal linear regression through the origin (Hampton, 1983; Kendall & Stuart, 1961; Snedecor & Cochran, 1976). Its numerical value is 0.56, and the R squared value of the fitted line is 0.995 (see Figure 8A). After



**Fig. 8.** Panel A shows the relationship between the sweetness and total taste intensity of sucrose. Panel B shows the relation between the saltiness and total taste intensity of NaCl. The straight lines were obtained by linear orthogonal regression through the origin. The error bars parallel with the y-axis represent the 95 % confidence intervals for the scale values of total taste intensity. The error bars in panel A and B parallel to the x-axis represent the 95 % confidence intervals for the scale values of sweetness and saltiness respectively.

multiplying the scale values of the sweetness of sucrose with 0.56, ANOVA showed that the psychophysical functions for the sweetness and total taste intensity of sucrose are similar [ $F(3,39) = 1.19$ ,  $p = 0.33$ ]. To summarize, it can be concluded that the sweetness intensity of sucrose does not differ from the total taste intensity of sucrose.

The above reasoning would be incorrect in one special case only, that is if sucrose elicits side tastes of magnitudes which are a constant fraction of the sweetness intensity and add to sweetness to form the total taste intensity of sucrose. We assume that this is not the case.

Figure 8, panel B, shows the relationship between the scale values of NaCl on the saltiness scale and the scale values of NaCl on the total taste intensity scale. These data were analyzed in the same way as the data discussed in the two previous paragraphs. The straight line through the origin has a R squared value of 0.996. The multiplication factor between both sets of scale values is 0.67. After multiplying the scale values of NaCl on the saltiness scale with 0.67, ANOVA showed that the psychophysical functions for the saltiness and total taste intensity of NaCl are similar [  $F(3,39) = 1.39$ ,  $p = 0.26$  ].

It can therefore be concluded that although NaCl has a sweet side taste, it seems that only the saltiness determines the total taste intensity of NaCl. In this analysis it is assumed that NaCl has no side tastes, which are a constant fraction of the saltiness, and which add to the saltiness to form the total intensity.

Total taste intensity of sucrose/NaCl mixtures in relation to the sweetness and saltiness of the components tasted outside the mixture (Fig. 1: 9).

The adjustments of the scale values as described in the previous section has lead to equivalent units for sweetness, saltiness and total taste intensity. As was explained in the Theory section, knowing these scale values is a prerequisite for assessing the relationship between the total taste intensity of sucrose/NaCl mixtures and both the sweetness and the saltiness of the mixture's constituents.

These relationships need not be analyzed separately because they can be deduced from previous analyses. In the analysis above it was assumed that the sweetness intensity of sucrose is equal to the total intensity of sucrose and also that the saltiness intensity of NaCl is similar to the total taste intensity of NaCl. If these assumptions are correct then the relationship between the total taste intensity of the mixture and the

combination of the sucrose sweetness and NaCl saltiness is equal to the relationship between the total taste intensity of the mixture and the combination of sucrose total intensity and NaCl total taste intensity. The latter relationship was already discussed in one of the previous paragraphs and given in a visual form in the figures 5, 6, and 7.

Sweetness intensity and saltiness intensity of sucrose/NaCl mixtures in relation to the total taste intensity of sucrose/NaCl mixtures (Figure 1: 10).

As argued above multiplying the scale values on the sweetness scale with 0.56, and multiplying the scale values on the saltiness scale with 0.67, yields equivalent units of sweetness, saltiness, and total taste intensity. This standardization enables a further study of the taste integration of the sweetness and saltiness of sucrose/NaCl mixtures when forming the total taste intensity of sucrose/NaCl mixtures.

The relationship between the total taste intensity and the sweetness and saltiness is investigated by using the summated response comparison. Table 1 shows the sweetness intensity, the saltiness intensity, the sum of these two and the total taste intensity of the experimental stimuli in equivalent units. It appears that the sum of the sweetness and saltiness is a good approximation of the total taste intensity.

The average difference between the sum of the sweetness and saltiness to the observed intensities is 0.14; the average absolute difference is 3.77. The mean relative deviation  $[(\text{sweetness mixture} + \text{saltiness mixture}) - (\text{total taste intensity mixture}) / (\text{total taste intensity mixture}) * 100 \%$  is -1.60 %. The mean of the absolute values of the relative deviation is 7.61 %. Multiple linear regression through the origin, with the saltiness and sweetness as independent variables and the total taste intensity as dependent variable yields the regression equation  $\Psi_{\tau i} = 1.00 \Psi_{\alpha i} + 0.92 \Psi_{\beta i}$ , having a R squared value



Table 1. Sweetness intensity, saltiness intensity, the sum of the sweetness intensity and saltiness intensity and total taste intensity of Sucrose/NaCl mixtures.

Conc. sucrose (M)	Conc. NaCl (M)	Sweetness mixture	Saltiness mixture	Sum of sweetness and saltiness	Total taste intensity
0.125	0.125	12.0	5.8	17.8	17.6
0.125	0.250	13.3	10.2	23.5	26.8
0.125	0.500	8.9	28.8	37.7	41.6
0.125	1.000	5.0	55.9	60.9	62.8
0.250	0.125	19.4	4.1	23.5	31.7
0.250	0.250	22.8	12.8	35.6	36.8
0.250	0.500	19.4	25.1	44.5	43.1
0.250	1.000	14.4	51.6	66.0	65.5
0.500	0.125	37.1	3.7	40.8	44.4
0.500	0.250	36.5	9.1	45.6	46.8
0.500	0.500	36.6	27.7	64.2	57.5
0.500	1.000	26.5	51.8	78.2	71.0
1.000	0.125	52.5	6.3	58.8	55.2
1.000	0.250	51.4	8.2	59.6	64.8
1.000	0.500	47.0	24.2	71.1	71.2
1.000	1.000	42.7	50.7	93.3	81.7

of 0.993. The obtained regression equation suggests that the sweetness and saltiness have about equal weights in determining the total taste intensity.

## DISCUSSION

The methodology used in the present study resulted in validated scale values of the perceived sweetness, saltiness and total taste intensity of sucrose, NaCl and sucrose/NaCl mixtures. These scale values are a linear function of differences in perceived taste intensity. If it is assumed that water has a taste intensity of zero then the obtained scale values represent taste intensities on a ratio scale.

The present results are first discussed with reference to the

conceptual framework of Fig. 1. Subsequently they will be compared to the results of other studies.

The main conclusions to be drawn from the results of the present study are:

- 1) The psychophysical functions for the sweetness of sucrose (Fig. 1, 2A) and the saltiness of NaCl (Fig. 1, 2B) are positively accelerating at low concentrations and negatively accelerating at high concentrations (on linear-linear coordinates).
- 2) The same holds for the psychophysical functions for the total taste intensity of sucrose (Fig. 1, 3A) and the total taste intensity of NaCl (Fig. 1, 3B).
- 3) The psychophysical functions for the sweetness and total taste intensity of sucrose have a similar shape (Fig 1, 2A = Fig 1, 3A) and the same applies for the psychophysical functions of the saltiness and total taste intensity of NaCl (Fig. 1, 2B = Fig. 1, 3B). The data suggest that the sweetness intensity of sucrose is identical to the total taste intensity of sucrose (Fig. 1, 4A is an identity function), and that saltiness of NaCl is identical to the rated total taste intensity of NaCl (Fig. 1, 4B is also an identity function). The plausibility of the latter two suggestions depends on the assumption that the sucrose/NaCl mixtures do not elicit side tastes which are a constant fraction of the sweetness/saltiness and which add to the sweetness/saltiness to form the total taste intensity.
- 4) The sweetness of sucrose/NaCl mixtures is higher than the sweetness of the corresponding unmixed sucrose concentrations when both the sucrose concentration and the NaCl concentration are low. When either the sucrose concentration is high or the NaCl concentration is high, sucrose/NaCl mixtures are less sweet than unmixed sucrose (Fig. 1, 7A). The saltiness of sucrose/NaCl mixtures is lower than the saltiness of the corresponding unmixed NaCl concentrations. The saltiness of sucrose/NaCl mixtures

depends only on the NaCl concentration and not on the sucrose concentration (Fig. 1, 7B).

5) The psychophysical functions for the total taste intensity of sucrose (Fig. 1, 3A), NaCl (Fig. 1, 3B) and the sucrose/NaCl .50/.50 mixture (Fig. 1, 5) do not differ.

6) The total taste intensity of sucrose/NaCl mixtures is less than the sum of the total taste intensity (= sweetness) of the corresponding unmixed sucrose concentration plus the total taste intensity (= saltiness) of the corresponding unmixed NaCl concentration (Fig. 1, 8 and 9). The total taste intensity of a sucrose/NaCl mixture can be well predicted by the square root of the sum of the squared taste intensities of its unmixed components.

7) The total taste intensity of sucrose/NaCl mixtures is about equal to the sum of the sweetness and saltiness of sucrose/NaCl mixtures (Fig. 1, 10). Sweetness and saltiness have about equal weights in determining the total taste intensity.

The comparison of the present results with the results of other studies will focus on two issues:

1) the sweetness of sucrose and saltiness of NaCl compared to the sweetness and saltiness of sucrose/NaCl mixtures [Fig. 1, 7A and 7B: ( $\psi_{\alpha 1} \longleftrightarrow \psi_{\alpha L}$ ,  $\psi_{\beta 1} \longleftrightarrow \psi_{\beta L}$ )], and,

2) the interrelationships among the total taste intensity of sucrose/NaCl mixtures, the sweetness and saltiness of those mixture and the total taste (= sweetness) intensity of the constituent sucrose concentration tasted alone and the total taste (= saltiness) intensity of the constituent NaCl concentration tasted alone (Fig. 1: 8, 9, 10: [ $\psi_{\tau 1} \longleftrightarrow (\psi_{\tau L}, \psi_{\tau 2})$  or ( $\psi_{\alpha L}, \psi_{\beta L}$ ), and ( $\psi_{\tau 1} \longleftrightarrow \psi_{\alpha L}, \psi_{\beta L}$ )]).

Sweetness and saltiness of sucrose and NaCl compared to the

sweetness and saltiness of sucrose/NaCl mixtures.

The conclusions of the present study are in broad agreement with the results of various other studies (e.g., Beebe-Center *et al.*, 1959; Frank & Archambo, 1986; Indow, 1969; Pangborn, 1962). When the results are examined in more detail, however, discrepancies can be seen. These will be discussed below, and possible explanations for the differences in the results obtained by various studies will be examined.

It is a well established fact, that the magnitude of the difference between the sweetness of a sucrose/NaCl mixture ( $\Psi_{\text{M}}$ ) and the sweetness of sucrose ( $\Psi_{\text{S}}$ ) depends on both the sucrose concentration and the NaCl concentration. The present results suggest that the mixture is sweeter than unmixed sucrose when both the sucrose and the NaCl concentration is lower than 0.50 M. The mixture is less sweet than unmixed sucrose when either the sucrose or the NaCl concentration is high (i.e., 1.00 M). These results are in agreement with the results obtained by Frank & Archambo (1986) and Indow (1969).

Similar trends can also be noticed in the results of other studies. Beebe-Center *et al.* (1959), Kamen *et al.* (1961) and Pangborn (1962) concluded that sucrose/NaCl mixtures with low concentrations of sucrose and low concentrations of NaCl are sweeter than unmixed sucrose and that highly concentrated sucrose/NaCl mixtures are less sweet than unmixed sucrose. However, the concentrations of both substances at which the mixture shifts from being sweeter to being less sweet than sucrose, are substantially lower than found in the present study. For instance, Pangborn (1962) found that a mixture of 0.20 M sucrose and 0.17 M NaCl was less sweet than 0.20 M sucrose tasted alone. For just-above-threshold NaCl concentrations, Kamen *et al.* (1961) noted that the shift from enhancement towards suppression occurs between 0.015 M and 0.18 M sucrose. In line with these latter results, Bartoshuk (1975), Kroeze (1979), and Lawless (1982) observed that a mixture of 0.32 M NaCl and 0.32 M sucrose is less sweet than 0.32 M sucrose tasted alone.

With respect to the saltiness of sucrose/NaCl mixtures, the present results suggest that the saltiness of sucrose/NaCl mixtures is lower than the saltiness of corresponding NaCl solutions. This general conclusion is in line with the observations of Bartoshuk (1975), Beebe-Center et al. (1959), Frank & Archambo (1986), Kroeze (1979), Lawless (1982), and Pangborn (1962). Indow (1969) and Kamen et al. (1961) obtained different results. They reported that the saltiness of sucrose/NaCl mixtures was approximately equal to the saltiness of corresponding NaCl solutions.

However, when the results of the studies are examined more closely, differences between the various results emerge. The outcome of the present study suggests that the saltiness of sucrose/NaCl mixtures depends on the NaCl concentration only and not on the sucrose concentration. The results of Beebe-Center et al. (1959) suggest that the difference between the saltiness of the mixtures and unmixed NaCl increases with increasing concentrations of NaCl and with increasing concentrations of sucrose. Frank & Archambo (1986) reported that this difference was largest at the highest sucrose concentrations (0.30 and 1.00 M sucrose) and at the intermediate NaCl concentrations (0.21 - 0.34).

The differences between the results of the various studies can be reconciled by referring to several factors, two of these will be discussed below. One reason may be variance in samples of subjects whilst another may be that different perceptual and/or cognitive processes have occurred in different experiments.

Some support for the first explanation can be found in the observations of Pangborn (1962), and Kroeze (1982b) who noted that there are large differences between subjects with respect to mixture suppression. Kroeze (1982b) observed that although the average sweetness response to 0.32 M sucrose and 0.32 M NaCl was lower than the average sweetness response to 0.32 M sucrose tasted alone, about 20 % of his subjects perceived the mixture as being equally sweet or sweeter than the unmixed sucrose. Another

Illustration of the large differences in individual responses to taste mixtures can be found in the data of Kroeze (1979). Averaged over the responses of 12 subjects in that experiment, the saltiness of a mixture of 0.32 M sucrose and 0.32 M NaCl is 59.1 % lower than the saltiness of 0.32 M NaCl. However, there was one subject who perceived the mixture as being saltier than the unmixed NaCl. Another subject judged the saltiness of the mixture nine times less strong than the saltiness of the unmixed NaCl.

Since the results of most studies are based on the data of ten subjects or less (Bartoshuk, 1975: 9 Ss.; Beebe-Center et al., 1959: 2 Ss.; Indow, 1969: 8 Ss.; Kroeze, 1978: 6 Ss.; Lawless, 1982: 10 Ss.; Pangborn, 1962: 10 Ss.) it is possible that differences between samples of subjects have contributed to the different results obtained.

Another explanation might be that differences occurred in the perceptual and/or cognitive processing of the intensities of single taste qualities in mixtures. With respect to the perceptual and/or cognitive processing of taste mixtures there appears to be one central factor, that is the attention to the specific taste intensities in taste mixtures. Kuznicki et al (1983) noted that "...selectively attending to a single taste in a mixture is a difficult task..". Kroeze (1982c) showed that the degree of sucrose-sweetness suppression by NaCl could be manipulated by habituating the subjects to NaCl. After habituation the suppressing effect was weakened and the sweetness of the mixture was restored to some extent. This means that the degree of mixture suppression may vary with the degree of habituation. Kroeze (1982b) also showed that habituating to sucrose can eliminate the suppressive effect of sucrose. After habituation to sucrose the sweetness of sucrose in the sucrose/NaCl mixtures lost its significance so that subjects judged the saltiness of the mixture as being about equal to the saltiness of unmixed NaCl. The evidence put forward by Kroeze indicates that the perceptual processing of the specific taste intensity in taste mixtures can be manipulated by habituating the

subjects to one component.

Sweetness, saltiness, of sucrose, NaCl, and sucrose/NaCl mixtures  
in relation to the total taste intensity of sucrose/NaCl mixtures

The relationship between the sweetness, saltiness, and total taste intensity of sucrose/NaCl mixtures is determined by the way in which perceived sweetness and perceived saltiness are integrated to form perceived total taste intensity. It is important to note that the integration of sweetness and saltiness is a perceptual and/or cognitive process which does not depend on the psychophysical functions for sucrose and NaCl. The sweetness and saltiness of sucrose/NaCl mixtures are the product of the psychophysical functions of sucrose and NaCl and the mutual interactive effects of sweetness on saltiness and vice versa. After these sources of sensory information have arrived centrally, some form of integration between the sweetness and saltiness of a mixture occurs.

The present results suggest that the total taste intensity of sucrose/NaCl mixtures is equal to the sum of the sweetness and saltiness of these mixtures. The sweetness and saltiness contribute about equally to the total taste intensity. For example, the total taste intensity of a mixture of 1.0 M sucrose and 0.50 M NaCl has a total taste intensity of about 71 units. The sweetness accounts for 47 units, which is about 66 % of the total taste intensity. The saltiness accounts for the remaining 24 units, that is 34 % of the total taste intensity.

In the Theory section it was noted that Bartoshuk (1975), McBurney & Bartoshuk (1973), and Moskowitz (1972) assumed that the total taste intensity of a complex taste percept is the sum of the specific taste intensities of that percept. The present results support this assumption. The observation that the total taste intensity of NaCl is equal to the saltiness of NaCl, in spite of the sweet side taste of NaCl, appears to be contradictory to this conclusion. We do not have an adequate explanation for this.

In the Results section it was concluded that the total taste intensity of sucrose/NaCl mixtures is always less than the sum of the sweetness (= total taste intensity) of the corresponding unmixed sucrose concentration tasted alone, and the saltiness (= total taste intensity) of the corresponding unmixed NaCl tasted alone. This implies that some taste intensity is "lost" when sucrose and NaCl are mixed; the whole is less intense than the sum of the intensities of the parts. The results discussed above, and the conceptual framework of Fig. 1 can give an indication as to where this taste intensity is "lost".

It appears that the relationship between the total taste intensity of a mixture and the specific taste intensities of the unmixed constituents (Fig. 1, 8 and 9) is made up of two separate relationships. These being the relationship between the specific taste intensities of the unmixed compounds and the specific taste intensities of the mixture (Fig. 1, 7A, 7B), and the relationship between the total taste intensity of a mixture and its sweetness and saltiness (Fig. 1, 10). The results discussed above suggested that the total taste intensity of a mixture is about equal to the sum of the sweetness and saltiness of that mixture. Thus the integrative process between the sweetness and saltiness of a mixture when forming the total taste intensity of a mixture cannot be responsible for the observed loss in perceived taste intensity. The logical consequence of this conclusion is that the loss of taste intensity is located in the other relationship, that is the relationship between the sweetness and saltiness of a mixture and the sweetness and saltiness of unmixed sucrose and NaCl. The results have shown that the saltiness of sucrose/NaCl mixtures is lower than the saltiness of unmixed NaCl. Obviously, some taste intensity is lost here. Another source of "losing" taste intensity is that sucrose/NaCl mixtures containing either a high sucrose concentration or a high NaCl concentration are perceived as being less sweet than the corresponding unmixed sucrose solutions.



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## CHAPTER TEN

### SOME ADDITIONAL ANALYSES

1. INTRODUCTION
2. WEBER FRACTIONS AND ACCUMULATED JND-SCALES FOR GLUCOSE AND FRUCTOSE
3. INTERRELATIONSHIPS AMONG THE RESULTS OF PREVIOUS STUDIES
  - 3.1. Numerical ratings and matching
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      - 3.2.1.3. Comparison of psychophysical sucrose functions obtained by De Graaf & Frijters (1987b) and by De Graaf & Frijters (1987e)
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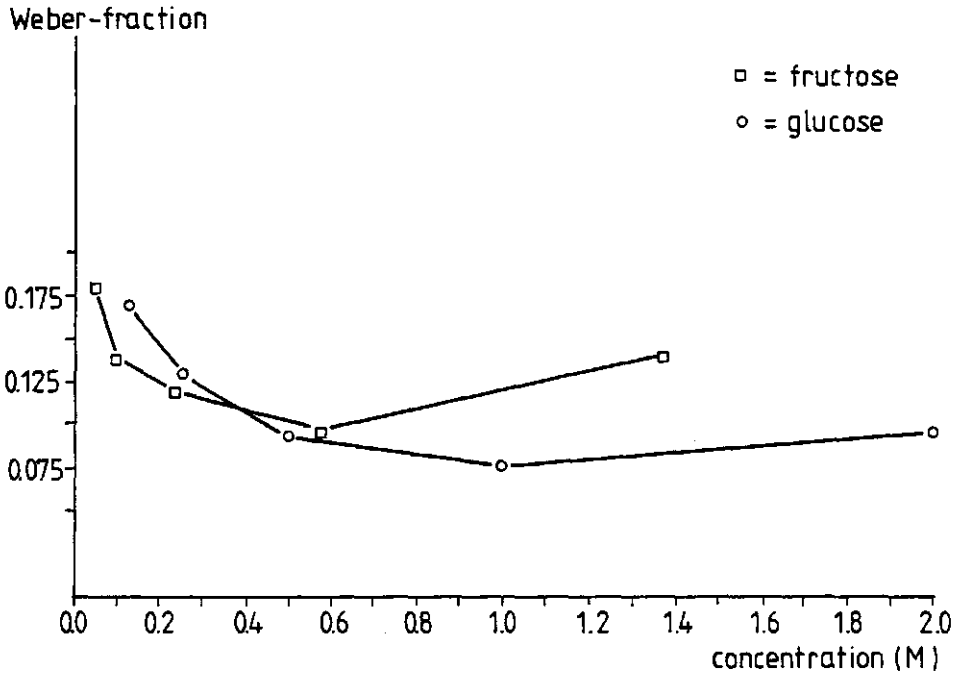
the fructose concentration.

The purpose of the present analysis is to test the internal consistency of accumulated JND scales for the sweetness intensity of glucose and fructose. These scales are consistent when the glucose concentration corresponding to a particular number of JNDs on the glucose-JND-scale matches the sweetness intensity of the fructose concentration that corresponds to the same number of JNDs on the fructose-JND-scale.

A previous analysis of the internal consistency of JND-scales for sweeteners (Lemberger, 1908) showed that a particular number of JNDs on a sucrose-JND-scale was considerably sweeter than the same number of JND's on a saccharine-JND-scale. Apparently one JND on the sucrose-JND-scale represented a larger difference in sweetness intensity than one JND on the saccharine-JND-scale. From these results it can be concluded, that Lembergers JND-scales cannot be considered as valid sensory scales for sweetness intensity.

The accumulated JND-scales presented below were determined on the basis of the data derived from control experiments in the study made by De Graaf & Frijters (1986). The reader is referred for details to this paper. Using the method of constant stimuli, five series of geometrically spaced glucose concentrations (denoted as comparison stimuli) were matched in sweetness to five glucose standards. The concentrations of the glucose standards, which varied from near threshold to near physical saturation, were 0.125, 0.25, 0.50, 1.00 and 2.00 M. In other similarly designed experiments five series of seven geometrically spaced fructose stimuli were matched in perceived sweetness intensity to five fructose standards. The concentrations of the fructose standards which were equal in perceived sweetness intensity to the glucose standards were 0.0485, 0.1027, 0.2374, 0.5790, and 1.3828 M.

The Weber fractions at each of the ten standard concentration were calculated on the basis of ten fitted lines, obtained by a weighted linear regression procedure after Bock &



**Figure 1. Weber fractions of glucose and fructose plotted as a function of their molar concentrations. The Weber fractions were determined on the basis of the results of the control experiments of De Graaf & Frijters (1986).**

Jones (1968). These lines relate the log concentration of the series of comparison stimuli with the z-score corresponding to the percentage sweeter than the standard judgments. The log concentration which would yield a change in predicted z-score of 0.6745 was then determined. The value of z of 0.6745 corresponds to 75 % of the area under the cumulative standard normal distribution. The Weber fraction was defined as the antilogarithm of the required change in log concentration minus one.

Figure 1 shows the Weber fractions of glucose and fructose as a function of their molar concentration. It shows that the value of the Weber fraction is not constant but that it reaches a minimum at the middle concentration range. The Weber fraction

increases at low and high concentrations. This observation is in line with the conclusions of other investigators (Holway & Hurvich, 1937; Lemberger, 1908; McBride, 1963; Schutz & Pilgrim, 1957).

In order to construct accumulated JND-scales for glucose and fructose beginning at the lowest standard concentration, it is necessary to know all the values of the all the Weber fractions over the entire range of concentrations. The Weber fractions of the concentrations which lay in between the concentrations of which the Weber fractions were experimentally determined were obtained by graphical estimation from the plots in Figure 1.

The following examples illustrate the construction of the JND-scale for glucose. The Weber fraction at 0.125 M glucose is 0.168. The glucose concentration corresponding to the sweetness of one JND above the sweetness of 0.125 M glucose is  $0.125 + 0.125 \times 0.168$  which is equal to 0.146 M. The value of the Weber fraction at this concentration was estimated from the plot in Figure 1. Its numerical value is 0.1625. The concentration corresponding to the sweetness intensity two JND's above the sweetness of 0.125 M glucose is thus  $0.146 + 0.146 \times 0.1625 = 0.17$  M. These calculations were proceeded until 2.00 M glucose. Similar calculations were performed to construct the JND scale of fructose.

Figure 2 shows the JND-scales for glucose and fructose. From this Figure it can be seen that the sweetness intensities of 0.125 and 0.25 M glucose differ by about 5 JNDs on the JND-scale of glucose. The difference between the corresponding fructose concentrations (0.0485 and 0.1027 M fructose, respectively) is also 5 JNDs. It takes about 28 JNDs to go from the lowest glucose concentration, which is not far above threshold, to the highest glucose concentration, which is not far from physical saturation. It also takes 28 JNDs to go from the lowest to the highest fructose concentration. As the lowest and highest glucose and fructose concentrations were equal in perceived sweetness intensity, it can be concluded that one JND on the glucose-JND-

number of JND<sub>s</sub> from 0.0485 M fructose,  
and 0.125 M glucose.

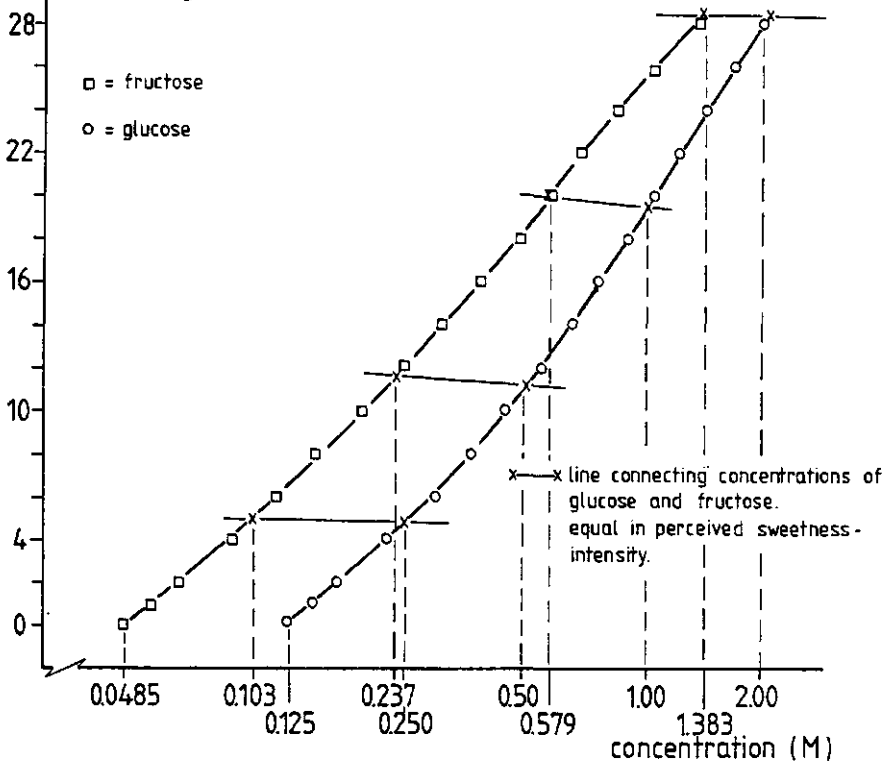


Figure 2. JND-scales for glucose and fructose, determined from the data in Figure 1.

scale represents the same difference in perceived sweetness intensity as one JND on the fructose-JND-scale.

The main conclusion to be drawn from these results is that the JND-scales for glucose and fructose, derived from the data of De Graaf & Frijters (1986), are internally consistent.



### 3. INTERRELATIONSHIPS AMONG THE RESULTS OF PREVIOUS STUDIES

During recent years several experiments were carried out with the same taste substances. The fact that the same tastants were used in makes a comparison of the results from different experiments possible. The results of such comparisons give insight to the validity of the sensory scales developed in the previous studies.

Of all sugars glucose, fructose, and mixtures of these substances were most frequently investigated. These substances were used by Frijters & Oude Ophuis (1983), De Graaf & Frijters (1986), and De Graaf, Frijters & Van Trijp (1987). De Graaf & Frijters (1987b) used sucrose, fructose, and mixtures of these substances. De Graaf & Frijters (1987c) used unmixed fructose only. De Graaf & Frijters (1987d) used unmixed sucrose and unmixed NaCl, and De Graaf & Frijters (1987e) used sucrose, NaCl and mixtures of sucrose and NaCl. In total there were five experiments which yielded data on unmixed fructose, three experiments with data on unmixed glucose, three experiments with unmixed sucrose and three experiments with data on the sweetness of GluFru 0.75/0.25, GluFru 0.50/0.50, and GluFru 0.25/0.75. In addition there are two experiments in which data on the total taste intensity of unmixed sucrose and unmixed NaCl were obtained.

The first analyses in this section the numerical scale values obtained by direct scaling techniques will be related to the sensory equalities obtained by matching. The second part of this section will discuss further on the psychometric properties of the data obtained.

#### 3.1. Numerical ratings and matching

One criterion for the validity of sensory scales is that the responses obtained by direct scaling must concur with the results on concentrations which have equal perceived taste intensity, as

obtained matching.

In the past three years two matching experiments were carried out, one by De Graaf & Frijters (1986) on the sweetness intensity of glucose, fructose and three equiratio mixtures types of glucose and fructose, and one by De Graaf & Frijters (1987d) on the taste intensity of unmixed sucrose and unmixed NaCl. The results of De Graaf & Frijters (1986) can be compared to the results of Frijters & Oude Ophuis (1983) and to the results of De Graaf, Frijters, & Van Trijp (1987). The results of De Graaf & Frijters (1987d) can be compared to the results of De Graaf & Frijters (1987e). These comparisons will be made in two separate paragraphs below.

3.1.1. PSEs of glucose, fructose and mixtures as determined  
from magnitude estimation, compared to PSEs obtained  
by matching

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The results of the study of De Graaf, Frijters & Van Trijp (1987) have already been compared to the results of De Graaf & Frijters (1986) in the paper of De Graaf, Frijters, & Van Trijp (1987). In the latter paper it was shown that the results of both experiments concurred. The concentrations of fructose and the three equiratio mixtures which are equal in sweetness to 0.125, 0.250, 0.500, 1.00, and 2.00 M glucose, as calculated from fitted psychophysical functions from the direct scaling experiment, were similar to those concentrations obtained by direct matching. From this result it can be concluded that the direct scaling method applied by De Graaf, Frijters & Van Trijp (1987) meets the validity criterion of sensory scales.

A similar analysis can also be carried out for the data of Frijters & Oude Ophuis (1983). Frijters & Oude Ophuis (1983) obtained magnitude estimates of the perceived sweetness intensity for each of the concentrations of 0.125, 0.25, 0.50, 1.00 and 2.00 M for each of the stimulus types glucose, fructose, GluFru

**Table 1. Comparison of Points of Subjective Equality (PSEs) determined using the method of constant stimuli\* and PSEs calculated from the data of Frijters & Oude Ophuis (1983)**

Concentration of glucose (M)	Type of Comparison Stimulus	PSE determined from matching (M)	PSE determined from data F & O (1983)	Difference in % (PSE <sub>F&amp;O</sub> -PSE <sub>met</sub> )
0.125	Fructose	0.0485	0.0700	44.3
0.125	GF .25/.75	0.0540	0.0844	56.3
0.125	GF .50/.50	0.0650	0.0942	44.9
0.125	GF .75/.25	0.0873	0.0951	8.9
0.250	Fructose	0.1027	0.1144	11.4
0.250	GF .25/.75	0.1206	0.1337	10.7
0.250	GF .50/.50	0.1439	0.1520	5.6
0.250	GF .75/.25	0.1817	0.1867	- 8.3
0.500	Fructose	0.2374	0.2270	- 4.4
0.500	GF .25/.75	0.2682	0.2551	- 4.9
0.500	GF .50/.50	0.3118	0.2952	- 5.3
0.500	GF .75/.25	0.3639	0.3512	- 3.5
1.000	Fructose	0.5790	0.5736	- 0.9
1.000	GF .25/.75	0.5920	0.6162	3.3
1.000	GF .50/.50	0.6550	0.7072	8.0
1.000	GF .75/.25	0.7729	0.8610	11.4
2.000	Fructose	1.3828	1.3388	- 3.2
2.000	GF .25/.75	1.4007	1.4136	0.9
2.000	GF .50/.50	1.4552	1.4908	2.4
2.000	GF .75/.25	1.6310	1.6458	0.9
Mean absolute deviation				12.0

\*From Frijters & Oude Ophuis (1983)

0.75/0.25, GluFru 0.50/0.50, GluFru 0.25/0.75 and fructose. For fructose and the three equiratio mixture types, psychophysical functions were fitted with the log-concentration and (log-concentration)\*\*2 as independent variables and the logarithm of the obtained geometric means as dependent variable. The obtained regression equations were set equal to the logarithm of the geometric mean of the glucose stimuli. The resulting quadratic equations were resolved for the logarithm of the required

concentration.

Table 1 shows that the PSEs calculated on the basis of the data of Frijters & Oude Ophuis (1983) generally concur with the PSEs obtained by matching except at the level of 0.125 M glucose. The mean absolute deviation is about 12 % which is about one JND. When the data of the the PSEs to 0.125 M glucose were omitted, the mean absolute deviation was 5.3 %.

The large deviations at the levels of 0.125 M glucose may have been caused by the statistical estimation procedure employed. The geometric mean of the responses to 0.125 M glucose in the experiment of Frijters & Oude Ophuis was 0.58. The geometric mean of all other stimuli were higher than 0.58. Consequently the value of 0.58 lies outside the range of the fitted functions of the other stimulus types. The PSEs of the other stimulus types were thus assessed by equating the fitted functions to a value outside the domain in which these functions were originally determined. This would have resulted in less accurate predictions.

The results in Table 1 show, that numerical ratings obtained by magnitude estimation concur with sensory equalities obtained by matching.

### 3.1.2. PSEs of sucrose and NaCl obtained by functional measurement compared to PSEs obtained by matching

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As the data in the literature on the concentrations of sucrose and NaCl which are equal in perceived taste intensity appeared to be contradictory, De Graaf & Frijters (1987d) carried out an experiment in which the taste intensity of NaCl was matched to the taste intensity of 0.125, 0.25, 0.50, 1.00, and 1.25 M sucrose. The results of this study suggested that the taste intensities of sucrose and NaCl are about equal when the molar concentration of sucrose is 1.5-1.75 times the molar concentration of NaCl.

In a direct scaling experiment De Graaf & Frijters (1987e)

**Table 2. Comparison of PSEs of NaCl to four sucrose solutions, obtained by matching (De Graaf & Frijters, 1987d), and obtained by direct scaling (De Graaf & Frijters, 1987e).**

Concentration of sucrose standard (M)	PSE NaCl obtained by matching (M)	PSE NaCl obtained by direct scaling (M)	Difference (%) (PSE <sub>dir</sub> -PSE <sub>met</sub> )
			PSE <sub>met</sub>
0.125	0.065	0.135	107.7
0.250	0.136	0.230	69.9
0.500	0.327	0.379	15.9
1.000	0.558	0.757	35.7

determined the total taste intensities of 0.125, 0.25, 0.50 and 1.00 M of both unmixed NaCl and unmixed sucrose. These latter data can be compared to the data of the matching experiment. This comparison was made in a similar manner to those mentioned in the previous section (section 3.1.1.). The relationship between the concentration of NaCl and its total taste intensity was estimated by a second order polynomial regression equation with (log-concentration) and (log-concentration)\*\*2 as independent variables, and the log of the total taste intensity as dependent variable. The obtained regression equation was set equal to the log of the scale values of 0.125, 0.25, 0.50, and 1.00 M sucrose and resolved for the logarithm of the required NaCl concentrations.

The data in Table 2 show that PSEs of NaCl obtained by direct scaling are substantially higher than the PSE's determined by matching. The molar concentration of the PSE's of NaCl equal in taste intensity to 0.125 and 0.250 M sucrose are about equal to the molar concentrations of sucrose themselves. This observation is in line with observations of Kuznicki et al. (1983), and Bartoshuk (1975) who found that sucrose and NaCl have about equal perceived taste intensities when their molar concentrations are about equal. These results however are not in line with the conclusions of the matching experiments of Beebe-Center et al. (1955) and De Graaf & Frijters (1987c).

It is surprising that the results of the functional measurement

experiment and the matching experiment do not concur with each other. In the analysis of the results of the direct scaling experiment, it was shown that the scale values of the total taste intensity of sucrose and NaCl were assessed on a linear scale of perceived taste intensity. The matching experiment was carried out with the method of constant stimuli, generally considered to be one of the most reliable and precise psychophysical methods for the determination of the PSEs. Therefore, it was to be expected that the results of both experiments would concur. At present, there does seem to be no adequate explanation for the discrepancies obtained.

### 3.2. Interrelationships among the scale values obtained in previous studies

The first part of this section compares scale values obtained by direct scaling. In the second part the scale values of the JND scales of glucose and fructose are compared to the scale values of glucose and fructose obtained by De Graaf, Frijters, & Van Trijp (1987).

#### 3.2.1. Comparison of scale values obtained by functional measurement

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In most of the previous experiments it was assumed that subjects judged the difference in perceived sweetness intensity between the two stimuli of each pair. As the judgment function appeared to be linear, it was concluded that the marginal means of the response matrices were linear with perceived sweetness intensity differences. In all the direct scaling experiments, these difference judgments were made relative to the difference in the perceived sweetness intensity of a standard pair. This standard pair was different in each experiment. If it is assumed that all the difference judgments were proportional to the differences in the standard pair then the obtained scale values represent ratio scales of perceived sweetness intensity differences. The validity of this assumption will be tested

below.

Before the results of these analyses are introduced it seems useful to review the scale values obtained in each of the previous experiments.

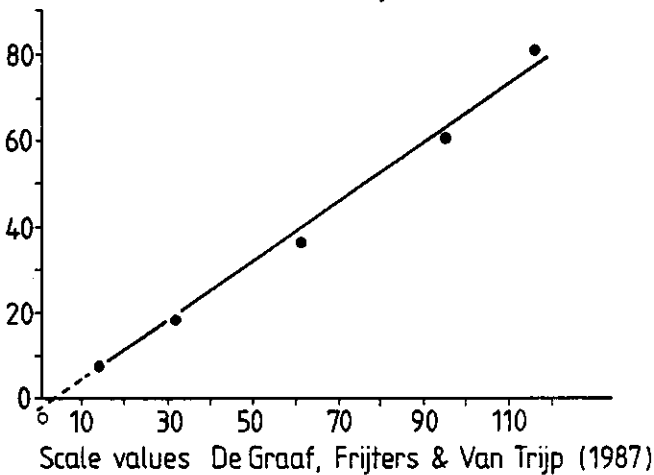
In the experiments of De Graaf, Frijters & Van Trijp (1987), De Graaf & Frijters (1987b) and De Graaf & Frijters (1987c), water was incorporated in the factorial design, and the scale value of water was set equal to zero. The scale values of the other experimental stimuli were calculated as the difference to the scale value of water. In the experiment of De Graaf & Frijters (1987c) the scale value of 0.125 M fructose was set equal to zero and the scale values of the other five fructose concentrations were calculated as the difference between their scale values and the scale value of 0.125 M fructose. There are thus three experiments, in which scale values were obtained relative to water, and one experiment in which the scale values represent sweetness intensity differences to the sweetness intensity of 0.125 M fructose.

If these scales are ratio scales of perceived sweetness intensity differences, then the scale values of the different studies can differ with a multiplicative constant only. This implies that the relationship between both sets of scale values is to be described by a straight line through the origin. Another implication is that apart from the multiplicative constant, the psychophysical functions in the different studies must be similar. The psychophysical function for fructose in the experiment of De Graaf, Frijters, & Van Trijp (1987) for example should have a similar shape to the psychophysical fructose function obtained in the experiment of De Graaf & Frijters (1987b).

#### 3.2.1.1. Scale values of fructose from De Graaf, Frijters & Van Trijp (1987) compared to scale values from De Graaf & Frijters (1987b)

Figure 3 shows the the relationship between the scale values of fructose from De Graaf, Frijters, & Van Trijp (1987) and the

Scales values De Graaf & Frijters (1987 b)



**Figure 3, Relationship between the scale values of the sweetness of fructose obtained by De Graaf, Frijters & Van Trijp (1987), and those values obtained by De Graaf & Frijters (1987b).**

scale values of fructose obtained by De Graaf & Frijters (1987b). The straight line through these points was fitted by orthogonal regression (Hampton, 1983). The intercept of this line does not deviate significantly from zero [ $t(3) = 2.05$ ,  $p > .10$ ] (Kendall & Stuart, 1961, p. 389).

The relationship between the two sets of scale values was further tested using analysis of variance. This procedure tested whether or not the psychophysical functions in both experiments were identical after normalization for the difference in the magnitude of the scale units. The normalization factor is the value of the multiplicative constant. The value of this constant was estimated using the formula  $\sum XY / \sum X^2$  (Snedecor & Cochran, 1973; p.170) where X represents the scale values from the experiment of De Graaf, Frijters & Van Trijp (1987), and Y represents the scale values from the experiment of De Graaf & Frijters (1987b). The value of this multiplicative constant was 0.659. Each of the 50 individual scale values (i.e., 10 subjects  $\times$  5 scale values) from the experiment of De

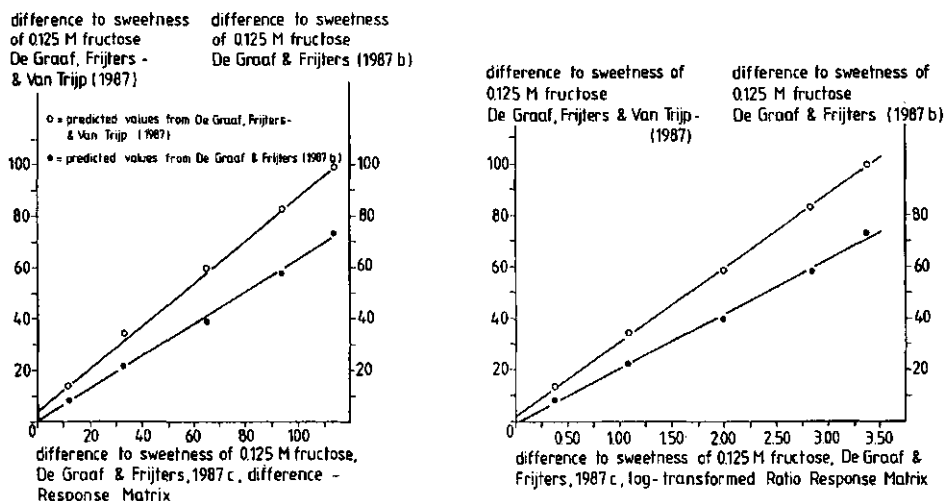


Graaf, Frijters & Van Trijp (1987) was multiplied by 0.659. ANOVA showed that the psychophysical functions in both experiments did not differ significantly [  $F(4,72) = 1.78$ ;  $p > 0.10$  ]. This outcome further supports the validity of the assumption that the obtained scale values are measured on a ratio scale of perceived sweetness intensity differences.

3.2.1.2. Scale values of fructose from De Graaf & Frijters (1987b), and De Graaf, Frijters & Van Trijp (1987) compared to scale values from De Graaf & Frijters (1987c)

In the experiment of De Graaf & Frijters (1987c) the molar concentrations of fructose were 0.125, 0.218, 0.379, 0.660, 1.149 and 2.00 M. De Graaf, Frijters & Van Trijp (1987), and De Graaf & Frijters (1987b) used stimuli of 0.125, 0.25, 0.50, 1.00, and 2.00 M fructose. For the two latter sets of scale values second order polynomial regression equation functions were fitted with the (log-concentration) and (log-concentration)\*\*2 as independent variables and the log of the obtained scale values as dependent variable. Using the fitted regression equations, the scale values for 0.218, 0.379, 0.660, and 1.149 M fructose were estimated. Once these estimated scale values were obtained the difference between these scale values and the scale value of 0.125 M fructose was calculated. These latter scale values were plotted against the scale values of the difference response matrix and the log-transformed ratio response matrix of the experiment of De Graaf & Frijters (1987c).

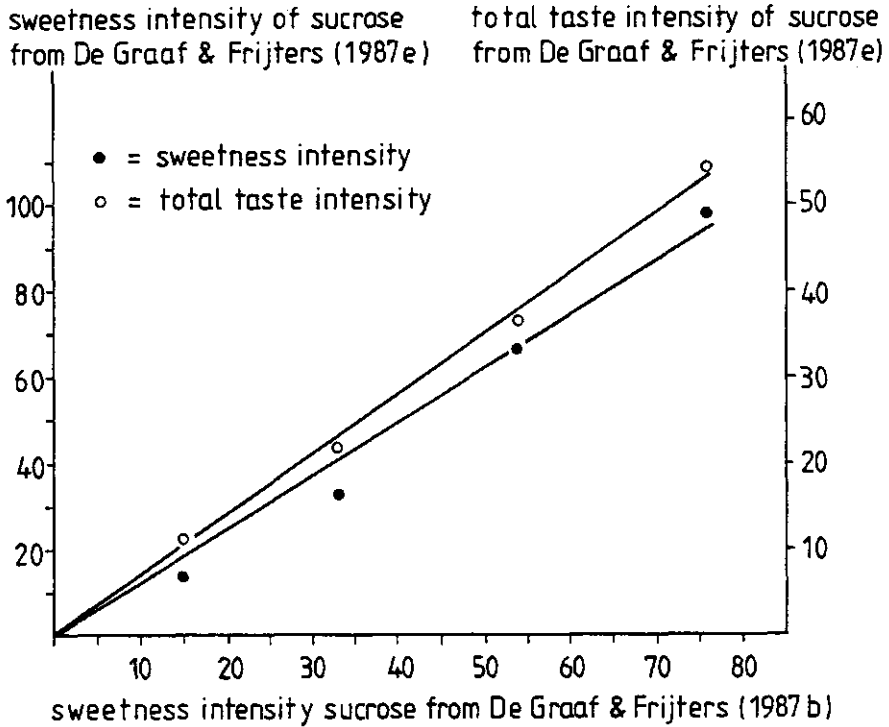
Figure 4, panels A and B, shows the relationships between the different sets of scale values. The four straight lines fitted through these points were obtained by orthogonal regression. The lowest of the four values of  $R^2$  was 0.994. The largest intercept was obtained for the line which was fitted through the points relating the scale values of the difference response matrix of De Graaf & Frijters (1987b) to the scale values determined from the data De Graaf, Frijters, & Van trijp (1987). A statistical test showed



**Figure 4. Panel A: Relationship between difference in sweetness to sweetness of 0.125 M fructose obtained from the "difference" response matrix of De Graaf & Frijters (1987c), and 1) (open points) sweetness differences to sweetness of 0.125 M fructose as predicted from the data of De Graaf, Frijters & Van Trijp (1987), and 2) (closed points) sweetness differences to sweetness of 0.125 M fructose predicted from the data of De Graaf & Frijters (1987b). Panel B shows similar relationships as panel A, except that the sweetness differences of the De Graaf & Frijters (1987c) were obtained from the log-transformed "ratio" response matrix, instead of the "difference" response matrix.**

that this intercept does not deviate significantly from zero [ $t(3) = 1.08$ ,  $p > 0.10$ ]. The intercepts of the other three fitted lines were virtually identical to zero.

It is concluded that the scale values obtained by De Graaf & Frijters (1987c) differ only with a multiplicative constant from the scale values determined from the data of De Graaf, Frijters & Van Trijp (1987), and from the data De Graaf & Frijters (1987b).



**Figure 5. Relationships between scales values of 1) the total taste intensity of sucrose (open points), 2) the sweetness of sucrose (closed points), as determined by De Graaf & Frijters (1987e), and the scale values of the sweetness of sucrose as obtained by De Graaf & Frijters (1987b).**

3.2.1.3. Comparison of psychophysical sucrose functions  
obtained by De Graaf & Frijters (1987b) and by De  
Graaf & Frijters (1987e)

In the experiment of De Graaf & Frijters (1987b) the concentrations of the unmixed sucrose stimuli were 0.125, 0.25, 0.50, 1.00 and 2.00 M. In the experiment of De Graaf & Frijters (1987e) the concentrations of the unmixed sucrose stimuli were 0.125, 0.25, 0.50, and 1.00 M. Figure 5 shows the relationship between the scale values of sucrose obtained in the experiment of De Graaf & Frijters (1987b)

and the scale values obtained by De Graaf & Frijters (1987e) for the total taste intensity of sucrose and for the sweetness intensity of sucrose.

The two straight lines fitted through the data of this Figure were obtained by linear regression through the origin. The slopes of these lines were used as the normalization factor to account for the difference in the magnitude of the scale units for each of the three scales.

Each individual scale value (i.e., 40 values = 10 subjects \* 4 concentrations) of the sweetness of sucrose from De Graaf & Frijters (1987b) was multiplied with the numerical value of the obtained normalization factor (1.24). ANOVA showed that the difference between the psychophysical functions for the sweetness of sucrose obtained by De Graaf & Frijters (1987b) and De Graaf & Frijters (1987e) was statistically marginally significant [ $F(3,66) = 2.99$ ,  $p = 0.04$ ].

The numerical value for the normalization factor between the sweetness of sucrose of De Graaf & Frijters (1987b) and the total taste intensity of sucrose of De Graaf & Frijters (1987e) was 0.70. After multiplying the individual scale values of De Graaf & Frijters (1987b) with 0.70, ANOVA showed that the psychophysical function for the sweetness of sucrose (De Graaf & Frijters (1987b) does not differ from the psychophysical function for the total taste intensity of sucrose (De Graaf & Frijters, 1987e).

#### 3.2.1.4 Summary

The previous analyses showed that the scale values of fructose obtained in the studies of De Graaf, Frijters, & Van Trijp (1987), and De Graaf & Frijters (1987b), differ from the fructose scale values of De Graaf & Frijters (1987c) with a multiplicative constant only. The shape of the psychophysical fructose function obtained by De Graaf, Frijters, & Van Trijp (1987) does not differ from the shape of the psychophysical fructose function obtained by De Graaf & Frijters (1987b). The shape of the psychophysical function of the total taste intensity of sucrose (De Graaf & Frijters, 1987e) does

not differ from the shape of the psychophysical function of the sweetness of sucrose (De Graaf & Frijters, 1987b).

Summarizing the results of the above analyses it can be concluded that there is substantial support for the assumption that the scale values obtained in the previous experiments represent sweetness intensity differences measured on a ratio scale level.

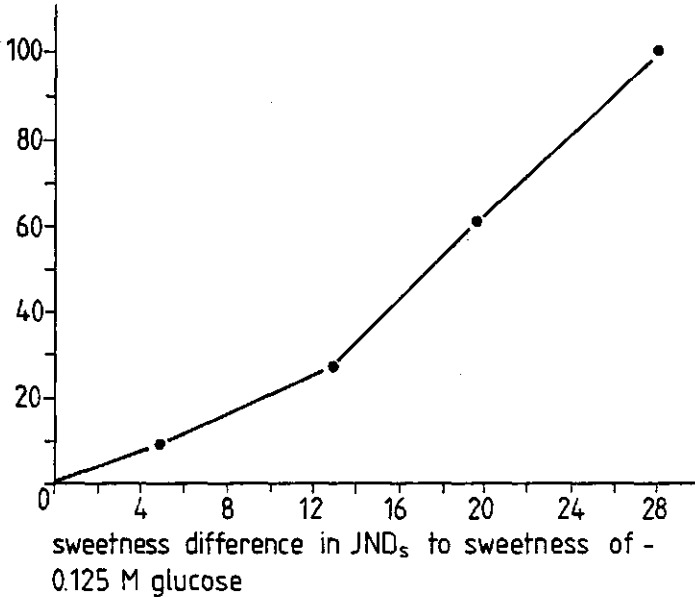
### 3.2.2. A comparison of glucose scale values obtained by functional measurement and glucose scale values obtained by accumulating JNDs

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As Birnbaum (1980) noted one of the most puzzling issues in psychophysical measurement has been the failure of different scaling techniques to provide one single scale of sensation. Scale values obtained by magnitude estimation, scales obtained by category scaling and scale values obtained by accumulating JNDs, have a nonlinear relationship with each other. Sometimes however the different scale types converge. In taste psychophysics McBride (1983) claimed that an accumulated JND scale of sucrose converges with scales values of sucrose on a category scale.

The analyses on the form of the judgment function in the previous experiments showed that the judgment functions in these studies were linear. The scale values were thus linear with perceived sweetness intensity differences. The analyses presented in the foregoing section also suggest that these scale values were measured on a ratio scale level. In addition these scale values were shown to be consistent with matching data. With respect to the JND scales of glucose and fructose the analysis in one of the previous sections (10.2) showed that these scales were internally consistent. So at first sight it appears that both the scales obtained from direct scaling and the scales obtained by indirect scaling are valid sensory scales. Additional analysis on the relationship between these two different types of scales can give further support for this suggestion.

sweetness difference to sweetness of -  
0.125 M glucose (De Graaf, Frijters, & Van Trijp, 1987)



**Figure 6. Relationship between sweetness differences to the sweetness of 0.125 M glucose as determined from the data of De Graaf, Frijters & Van Trijp (1987) and sweetness differences determined from the JND-scale in Figure 2 of the present chapter.**

In Figure 6 the sweetness differences between 0.25, 0.50, 1.00, and 2.00 M glucose and the sweetness intensity of 0.125 M glucose expressed in scale values obtained by De Graaf, Frijters & Van Trijp (1987) are plotted as a function of the same differences expressed in units of the JND-scale.

Visual inspection shows that the relationship between these two scale types is not linear. It seems that the sweetness differences expressed in JNDs are not directly proportional to sweetness differences expressed in the units of the scale used by De Graaf, Frijters & Van Trijp (1987). These data do not support the suggestion that both scales are linear scales of perceived sweetness intensity.

#### 4. RELATIONSHIPS OF THE SCALE VALUES OBTAINED IN PREVIOUS STUDIES WITH THE SCALE VALUES OBTAINED BY MCBRIDE

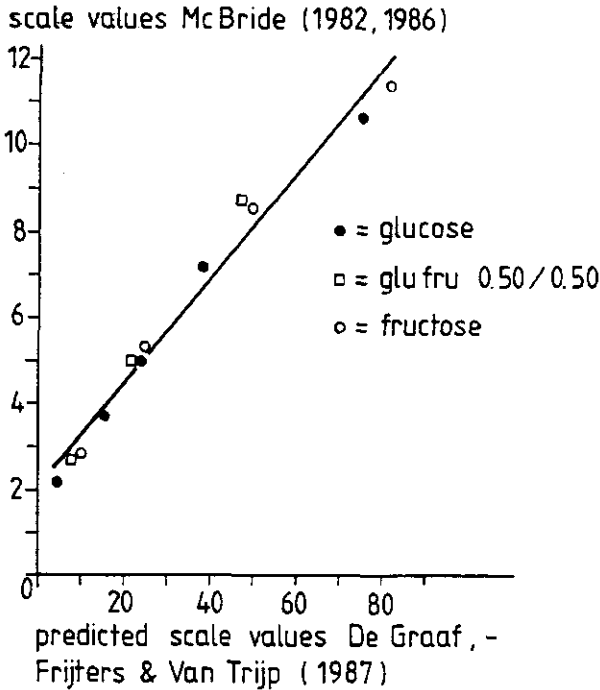
McBride (1983, 1986) used a category scale to assess the sweetness intensity of sucrose, glucose, fructose and their binary mixtures. This author took special precautions to exclude all kinds of biases. In addition, McBride (1983) claims that category scales and JND scales of sucrose sweetness converge. These findings suggest that the sensory scales developed by McBride (1982, 1983, 1986) are valid sensory scales of sweetness intensity. The scales developed in the previous studies of De Graaf and Frijters were shown to be valid scales of sweetness intensity. Both the studies of McBride and the studies of De Graaf & Frijters used glucose, fructose, sucrose and binary mixtures of these substances, which enabled a comparison between the results of their studies.

If both McBride (1982, 1983, 1986) and De Graaf & Frijters developed valid sensory scales then the relationship between these scales must be linear. The purpose of the present analysis is to investigate whether or not a linear relationship exists.

Three analysis have been carried out. In the first analysis the data of De Graaf, Frijters & Van Trijp (1987) of the sweetness intensity of glucose, fructose and glucose-fructose mixtures have been compared to the results of McBride (1982, 1986) on the same substances and mixtures. The second analysis focused on the data on the sweetness of sucrose, fructose, and sucrose-fructose mixtures (De Graaf & Frijters, 1987b; McBride, 1982, 1983, 1986). The third analysis compares the JND-scales for glucose and fructose to the category scales for the same substances of McBride (1982).

##### 4.1. Data on glucose, fructose and mixtures: a comparison between the data of McBride (1982, 1986) and De Graaf, Frijters & Van Trijp (1987)

McBride (1982, 1986) assessed the responses to the sweetness intensity of 0.0971, 0.1943, 0.3885 and 0.7771 M fructose, 0.1500,



**Figure 7. Relationship between scale values for the sweetness of glucose, fructose, and mixtures obtained by McBride (1982, 1986), and scale values as predicted from the data of De Graaf, Frijters, & Van Trijp (1987).**

0.300, 0.400, 0.600 and 1.200 M glucose, and 0.111, 0.222 and 0.444 M of the GluFru .50/.50 equiratio mixture type. The average responses to each of these stimuli were graphically estimated from Figures 20 and 21 of McBride (1982) and Figure 5 of McBride (1986).

De Graaf, Frijters & Van Trijp (1987) obtained scale values of the sweetness intensity of 0.125, 0.250, 0.500, 1.000 and 2.000 M of glucose, fructose and the GluFru .50/.50 equiratio mixture type. For each of these three stimulus types second order polynomial regression equations were fitted. The log concentration and (log-concentration)\*\*2 were the independent variables and log of the mean scale value served as the dependent variable. The obtained regression



equations were used to predict the scale values of the stimuli used by McBride.

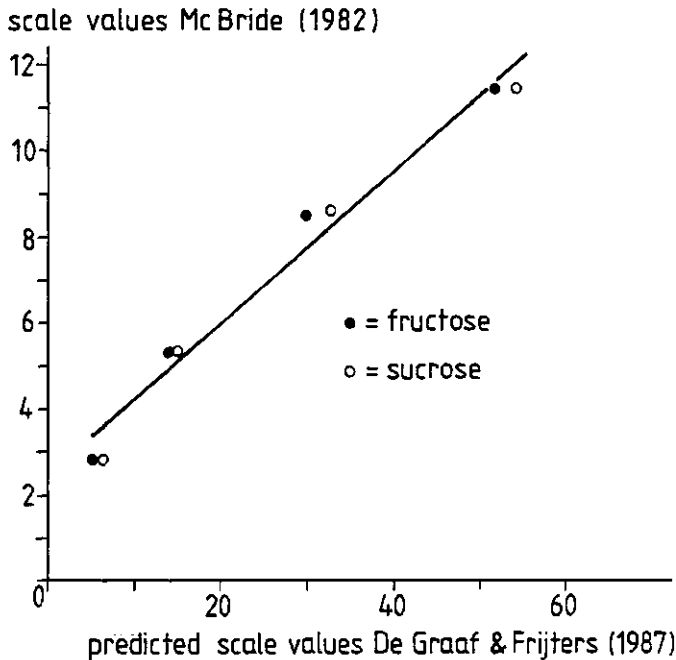
Figure 7 shows the relationship between the scale values obtained by McBride (1982, 1986) and the scale values predicted from the data of De Graaf, Frijters & Van Trijp (1987). Although the straight line fitted through the points in Figure 7 has an high  $R^2$ -value (0.975), there appear to be some deviations from linearity.

#### 4.2. Data of sucrose, fructose: a comparison between the data of McBride (1982) and De Graaf & Frijters (1987b).

McBride (1982) obtained estimates for the sweetness intensity of 0.0625, 0.125, 0.2500 and 0.500 M sucrose, and 0.0971, 0.1943, 0.3885 and 0.7771 M fructose. The numerical values for the mean of the responses to these stimuli were graphically estimated from Figures 14 and 20 presented by McBride (1982).

De Graaf & Frijters (1987b) obtained scale values for the sweetness intensity of 0.125, 0.25, 0.50, 1.00 and 2.00 M of both sucrose and fructose. Through these latter scale values second order polynomial regression equations were fitted with log-concentration and (log-concentration)\*\*2 as independent variables and the log of the scale values as dependent variables. The obtained regression equations were used to predict the scale values of the stimuli that McBride (1982) used.

Figure 8 shows the relationship between the scale values of McBride (1982) and the scale values predicted from the data of De Graaf & Frijters (1987b). Visual inspection shows that this relationship shows the same pattern as the relationship in Figure 8, and is also not linear.



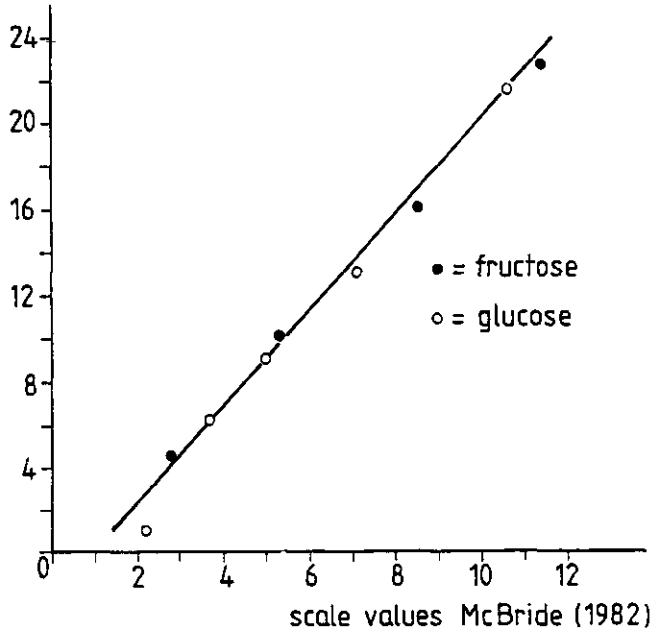
**Figure 8. Relationship between scale values for the sweetness of sucrose and fructose obtained by McBride (1982), and scale values predicted from the data of De Graaf & Frijters (1987b).**

**4.3. Comparison of JND-scales of glucose and fructose and the category scales for glucose and fructose as obtained by McBride (1982).**

McBride (1983) reported that a JND-scale of sucrose converged with a category scale of sucrose. The purpose of the present analysis is to investigate whether the JND-scale of glucose and fructose developed previously (section 2. of this Chapter) converges with the category scales of glucose and fructose such as developed by McBride (1982).

McBride (1982) obtained the sweetness responses to 0.0971, 0.1943, 0.3885 and 0.7770 M fructose, and to 0.150, 0.300, 0.400, 0.600 and 1.20 M glucose. The average responses to these stimuli were

number of JND<sub>s</sub> from 0.125 M glucose  
or 0.0485 M fructose.



**Figure 9. Relationship between scale values for the sweetness of glucose and fructose obtained by McBride (1982), and scale values obtained from the data of the JND-scales of glucose and fructose, as shown in Figure 2 of the present chapter.**

graphically estimated from the Figures 20 and 21 of McBride (1982). The scale values of these stimuli on the JND scale of glucose and fructose were graphically estimated from Figure 2 of this chapter.

Figure 9 shows the relationship between the number of JNDs and the scale values of McBride (1982). Except for the lowest point (for 0.15 M glucose) all points lie on a straight line. It is concluded that the JND scale of glucose and fructose developed previously converges with the category scales of glucose and fructose obtained by McBride (1982).

#### 4.4. Summary

The relationship between the scale values obtained by McBride's (1983) method of category scales, and the scale values obtained from the functional measurement approach of De Graaf & Frijters is not linear. The relationship between the category scales of McBride and the JND-scales of De Graaf and Frijters is in fact linear.

#### 10.5. THE GENERALIZED BEIDLER EQUATION FITTED FOR SINGLE SUGARS AND EQUIRATIO MIXTURE TYPES

Beidler (1959) suggested that his fundamental taste equation which was originally developed to describe the neural response to taste stimuli (Beidler, 1954), can be a valid description for the psychophysical function of taste substances. One of the arguments put forward by Beidler was based on a replot of the accumulated JND-scale for sucrose as constructed by Lemberger (1908). This replot of Lembergers JND-scale appeared to converge with his fundamental taste equation. Beidler's suggestion was not followed by other investigators of that time, probably because of the simultaneous development and application of Stevens method of magnitude estimation and the subsequent formulation of the power law as the "proper" description of any psychophysical function.

In recent publications of human psychophysical studies however, Beidler's taste equation reappears in the literature (Curtis, Stevens & Lawless, 1984; De Graaf & Frijters, 1986; McBride 1987). McBride (1987) suggests that Beidler taste equation is a valid description for the psychophysical functions of sucrose, fructose, glucose, NaCl, caffeine and citric acid.

Beidler's original taste equation reads,

$$R = \frac{K R_{\max} \cdot C}{1 + K C} \quad (1)$$

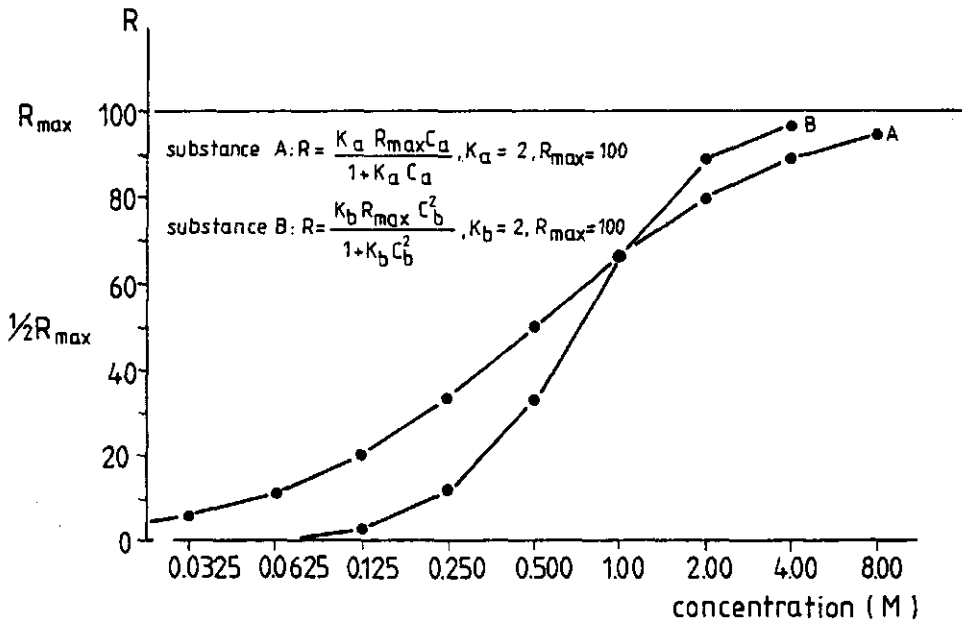
where  $R$  is the magnitude of the response,  $K$  is an association constant reflecting the degree of affinity of a taste substance molecule to its receptor site,  $C$  is the concentration in mol/L, and  $R_{max}$  represents the maximum response at very high stimulus concentrations. The relationship between log-concentration and response exhibits a symmetric sigmoidal function, asymptotically approaching the maximum response at high values of log-stimulus concentration (see Figure 10).

One of the critical features of this function is that doubling the concentration always yields a less than double response. In other words, Beidler's taste equation predicts compressive psychophysical functions over the entire stimulus range.

The latter observation is not in agreement with the data obtained by Frijters, De Graaf and colleagues, who found that the psychophysical functions for glucose, fructose, sucrose, NaCl, and various equiratio mixture types of these substances are positively accelerating at low concentrations but negatively accelerating at high concentrations. In electrophysiological studies of glucose and fructose similar observation were made (Tateda & Hidaka, 1966; Morita & Shiraishi, 1968; Hiji & Imoto, 1980). In these latter studies a more general form of Beidler's taste equation was given. A similar more general equation was also formulated by Beidler (1978) himself. This equation reads

$$R = \frac{K R_{max} C^n}{1 + K C^n} \quad (2)$$

The difference between equation 1 and equation 2 lies in the exponent  $n$ , i.e. the Hill coefficient (Hill, 1910). According to Beidler, the exponent  $n$  reflects the number of molecules that must be adsorbed at a receptor site before a response is elicited. In the case of sucrose the value of  $n$  would be one indicating a monomolecular interaction between stimulus molecule and receptor



**Figure 10.** Log-linear plots of the generalized Beidler equation (see equation 2 in text), one for a function with an exponent of 1 (the original Beidler equation), and one for a function with an exponent of 2. The values of the other parameters ( $K$ , and  $R_{max}$ .) are supposed to be equal.

site. Figure 10 illustrates the difference between predictions from equation 1 and predictions from equation 2 when  $n$  has an assigned value of 2. This Figure shows that the slope of the function having the value of  $n = 2$  is steeper than the slope of the function having no exponent (or one might say that the exponent has a value of 1). Equation 2 predicts that at low concentrations the psychophysical functions are positively accelerating, whereas at high concentrations the psychophysical functions are negatively accelerating. This prediction is in line with the observations of Frijters and De Graaf.

For a more thorough and theoretical treatment of fitting the generalized taste equation the reader is referred to Maes (1985).

Equation 2 can be used to fit psychophysical functions for single substances as well as for equiratio mixture types. This provides a potential possibility for reparametrization of the

equiratio mixture model developed by Frijters & Oude Ophuis (1983). This model provided excellent predictions for the prediction of the sensory response to binary and physically more complex mixtures of sugars. The equiratio mixture model is an S-R model in which it is assumed that the power function as developed by Stevens is a valid description of the relation between concentration and response. Although this assumption may be valid it is clear that the relation between concentration and taste intensity is not a power function. Power functions with an exponent unequal to one are either compressing or expanding over the entire stimulus range. The data of the previous studies suggest that this is not the case.

Equation 2 was fitted through the data obtained by De Graaf, Frijters & Van Trijp (1987), De Graaf & Frijters (1987b) and De Graaf & Frijters (1987c). Equation 2 was also fitted through the data of De Graaf & Frijters (1987e) and the data on the accumulated JND-scales of glucose and fructose. The estimated parameters obtained from these latter analyses however had such a large standard error that they could not be considered to yield any meaningful interpretation. The results of these latter analyses are therefore not given here. All equations were fitted with an iterative non-linear regression procedure using the Gauss-Newton method (SAS, 1985).

The results of the present analyses must be interpreted with caution. The three estimated parameters are based on five points only. Five points in fact is too low to yield reliable estimates. Another reason for caution with the interpretation of the results of this analysis is that the estimates for the different parameters are not independent of each other. The estimated value of  $K$  for example has a drastic influence on the estimated value of  $n$ . It appeared that over the iterations in each analysis that the estimated values for each of the three parameters showed correlations close to + 1 or - 1.

Table 3 shows the estimated parameters for the fitted equations for the data obtained by De Graaf, Frijters & Van Trijp (1987).

The results given in Table 3 show that for glucose, fructose and the three equiratio mixtures types, the values of the exponent  $n$  and

Table 3. Estimated values of the parameters of equation 2, using the scale values obtained by De Graaf, Frijters, & Van Trijp (1987).

	Stimulus type				
	Glucose	GlFr.75/.25	GlFr.5/.5	GlFr.25/.75	Fructose
exponent $n$	1.53	1.44	1.51	1.39	1.44
constant $K$	0.68	1.28	1.81	1.73	2.31
$R_{max}$	157	143	135	140	135

the maximum responses do not differ to any great extent. The value of  $n$  lies between 1 and 2 in all cases. The parameters  $n$  and  $R_{max}$  of the mixtures do not lie in between the parameters of the unmixed substances. The response to 2.00 M fructose in this study was about 115, which is about 85 % of the estimated maximum response. The response to 2.00 M glucose was 104 which is about 66 % of the estimated maximum response.

The main difference between the parameters of the different stimulus types is the value of the association constant  $K$ . The values of  $K$  of the mixtures lie between the values of the unmixed compounds.

From these results however it is not clear whether the parameters of the mixtures can be predicted from the parameters of the unmixed compounds. From this observation it is concluded that it is not straightforward to reparametrize the equiratio mixture model on the basis of the generalized taste equation.

As mentioned above, Beidler (1978) noted that the value of  $n$  reflects the number of stimulus molecules which must be adsorbed before a response is elicited. These results may indicate that the adsorption of glucose and fructose to receptor sites is not a simple monomolecular process. This result is in agreement with the conclusions of other investigators (Hiji & Imoto, 1980; Morita & Shirahishi, 1968; Tateda & Hidaka, 1968). De Graaf & Frijters (1986) suggested that glucose and fructose have additional secondary binding



**Table 4. Parameter estimations of  $n$  and  $K$  of equation 2 for the psychophysical function of fructose as determined from the data of De Graaf & Frijters (1987c).**

	scale values from difference response matrix	scale values from log-transformed ratio response matrix
exponent $n$	1.65	1.64
constant $K$	2.15	2.53
$R_{max}$	141	4.2

mechanisms. The present results are also in line with this hypothesis.

Table 6 shows the estimated parameters for the psychophysical functions of fructose using the scale values obtained by De Graaf & Frijters (1987c). The parameters were estimated for the scale values derived from the "difference" response matrix and for the scale values derived from the log-transformed "ratio" response matrix. In this study water was not included so all scale values represented sweetness intensities on an interval scale without a specified zero point. In this case the response to water was estimated by inclusion of an additive constant in equation 2. The estimated value of the intercept (i.e. the estimated value of the additive constant) represented the estimated response to water. The estimated values of  $R_{max}$  are given as the distance to the estimated scale value of water.

Table 4 shows that the estimated value of  $n$  obtained from the difference response matrix is similar the value of  $n$  obtained from the log-transformed ratio response matrix. The obtained values of 1.64 and 1.65 are slightly higher than the value of  $n = 1.44$  obtained from the data of De Graaf, Frijters, & Van Trijp (1987). The value of  $K$  of 2.15 for "differences" differs somewhat from the value of  $K$  of 2.53 for log "ratios". The estimated value of  $K = 2.33$  obtained from the data of De Graaf, Frijters, & Van Trijp lies in between these two

**Table 5. Estimations of the parameters of equation 2 for fructose, sucrose and the SucFru .50/.50 mixture, using the scale values of De Graaf & Frijters (1987b)**

	Stimulus type		
	fructose	SucFru .50/.50	sucrose
exponent $n$	1.40	1.27	1.05
Constant $K$	1.71	2.08	1.22
$R_{max}$	98	113	144

estimates.

The difference between the estimated response to water and the response to 2.0 M fructose, was about 90 % of the difference of the estimated response to water and the estimated maximum response. The value of 90 % applied for both "differences" and log "ratios". This percentage is similar to the percentage obtained from the data of Frijters, De Graaf, & Van Trijp (1987), where 2.00 M fructose was estimated to account for about 85 % of the maximum response.

Table 5 shows the estimated parameters for the psychophysical functions of sucrose, fructose, and the SucFru .50/.50 equiratio mixture type. This table shows that the estimated value of  $n$  for sucrose is 1.05. This value is close to one and indicates that the psychophysical function of sucrose concurs with the simplest form of Beidler's taste equation, represented by Equation 1. This observation concurs with the conclusions of various electrophysiological studies (De Graaf & Frijters, 1986).

The value of  $n$  for fructose is 1.40 which is similar to the estimated value of  $n = 1.44$  as obtained from the data of De Graaf, Frijters & Van Trijp (1987) (see Table 6). The response to 2.00 M fructose was about 80 which is about 82 % of the estimated maximum response to fructose. This percentage concurs with the corresponding percentages obtained from the two previous analyses.

The estimated values of  $\bar{n}$  and  $R_{max}$  of the sucrose/fructose .50/.50 mixture lies in between the values of  $\bar{n}$  and  $R_{max}$  for unmixed sucrose and unmixed fructose.

The value of K of 1.71 for fructose is slightly lower than the estimated values for K in the Tables 3 and 4. Surprisingly the value of K for sucrose is substantially lower than the value of K for fructose. As sucrose is sweeter than fructose on a molar basis it was expected that the value of K for sucrose would be higher than the value of K for fructose. Probably the estimated values of K are interrelated with the estimated values of  $\bar{n}$  and  $R_{max}$ . Another unexpected result is the high value of K for the mixture. This value exceeds the estimated values for the unmixed components.

In conclusion, it can be said that the estimated values of  $\bar{n}$ ,  $R_{max}$ , and K for unmixed fructose show a large variation. It is most probable that more data-points must be known before any reliable estimates can be obtained with this procedure. On the basis of the present results it makes little to apply the rationale of the equiratio mixture model, to psychophysical functions having the form of the generalized Beidler equation form.

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## **CHAPTER ELEVEN**

### **GENERAL DISCUSSION**

In this thesis, the perception of taste substance mixtures was studied with reference to three central issues.

The first issue is the concept of equiratio taste substance mixtures which is to be considered as new paradigm which makes it possible to construct mixtures in an unprecedented way. This thesis pursues the consequences of the concept of equiratio taste substance mixtures in the study of taste interaction phenomena.

The second issue concerns rules currently in use regarding the comparison of the taste intensity of a mixture to the taste intensities of the mixture's unmixed compounds. This thesis investigates the consequences of application of these rules for the theories and hypotheses about the taste interaction in mixtures.

The third issue concerns fundamental measurement of taste intensities of mixtures and mixture's components. A recent structure for measuring mental states is functional measurement (Anderson, 1981). This research methodology incorporates specific rules and prescriptions to check the psychometrical status of verbal ratings.

It appears that the concept of equiratio taste substance mixtures is a powerful tool in the study of the taste interaction in mixtures. One of the main features of this concept is that it enables the physical dimension of stimulus concentrations in mixtures to be manipulated in a similar way as it is done for unmixed substances. This allows for the determination of psychophysical functions of taste substance mixtures.

Frijters & Dude Ophuis (1983) showed that the equiratio taste mixture model provided excellent predictions for the responses to the sweetness intensity of glucose-fructose mixtures. Frijters, De Graaf, & Koolen (1984) showed that the equiratio taste mixture model can also be applied for the prediction of the responses to the sweetness intensity of sucrose-sorbitol mixtures. This model was successfully extended to predict the sensory responses to complex mixtures of sugars and sugar alcohols (Frijters & De Graaf, 1987). Frijters & Stevens (1986) showed that this model can also be used for the prediction of the responses to the



sourness of binary equiratio acid mixtures. Results of future studies must decide whether or not the equiratio taste mixture model will also be successful in predicting the sensory responses to other types of mixtures.

The concept of equiratio taste substance mixtures also provided the basis for assessing the taste interaction according to the "equimolar comparison rule", which is described in the Chapters Four and Six. Application of this rule to the results of various other studies (Chapter Four) suggests that the taste interaction in all binary sugar mixtures follows two general principles. The first principle is that the sweetness intensity of a binary sugar mixture lies between the sweetness intensities of its components, when each is tasted alone at the same total molarity as the mixture (Chapter 4). The second principle is that the sweetness intensity of a binary sugar mixture approaches of the sweetness intensity of the sweetest unmixed compound, when the proportion of the sweetest compound in the mixture increases.

It is clear that equimolar comparison rule provided an excellent tool for assessing the taste interaction in binary sugar mixtures. However, application of this comparison rule is not so straightforward in the case of the taste interaction in mixtures of sugars and intensive sweeteners. It is not feasible to compare the sweetness intensity of sugars, intensive sweeteners, and mixtures of intensive sweeteners and sugars at equimolar concentrations. Future studies must show whether or not the equimolar comparison can be adjusted to describe the taste interaction in mixtures of sugars and intensive sweeteners.

When the taste interaction between intensive sweeteners and sugars is considered, application of the two other comparison rules to assess the taste interaction, i.e., the summated response comparison rule and the factorial plot comparison rule, is straightforward. The concentrations of a sugars and intensive sweeteners can be manipulated according to a factorial mixture design, and the taste interaction can be specified according to these comparison rules. However, when assessing the taste

interaction according to the factorial plot or the summated response comparison, there is one additional issue that must be considered, i.e., the psychometric properties of the response scale.

As was shown in Chapter Five, the psychometric properties of the response scale have a drastic influence on the conclusions that are drawn on the basis of the summated response comparison. The same applies for conclusions about the taste interaction when using the factorial plot comparison rule. When the taste interaction is being assessed according to the factorial plot comparison rule, the taste intensities must be assessed on a interval scale, and when the summated response comparison is applied the taste intensities must be assessed on a ratio scale.

The results of the studies of this thesis suggest that the applied psychophysical scaling method, i.e., a functional measurement approach in combination with a two stimulus procedure, yielded interval scales of perceived taste intensity (Chapters Five, Six, Seven and Nine). The results of each of these experiments showed that the judgment function was linear in each study. The additional critical analyses in Chapter Ten of this thesis show that the interrelationships among the scale values obtained from different studies, concur with the hypothesis that the scale values represent taste intensities measured on a ratio scale.

The additional analyses in Chapter Ten showed that the scale values obtained from the functional measurement approach in combination with two stimulus procedure are not linear with the scale values on the category scale of McBride (1982, 1986). The JND scales of glucose and fructose as developed in Chapter Ten are also not linear with the scale values obtained from the functional measurement approach. However, the JND scales of glucose and fructose converge with the category scales of glucose and fructose as obtained by McBride (1982). A JND scale for sucrose also concurred with the category scale for sucrose, according to McBride (1983).

To summarize, JND scales for glucose, fructose, and sucrose concur with category scales for glucose, fructose and sucrose as obtained by McBride (1982, 1983a,b, 1986). However, the category scales and JND scales are not linear with the scale values obtained from the functional measurement approach. These latter scale values were shown to represent interval scales of perceived taste intensity. These scale values also concur with testable predictions for a ratio scale.

The question now arises as to which scale is linear with perceived taste intensity, the JND and category scales, or the scale values obtained from the functional measurement approach ?

McBride (1983a,b) claims that the scales that he obtained are interval scales of perceived taste intensities. He uses two arguments, i.e, 1) the category scale-JND scale convergence (McBride, 1983b), and 2) the agreement between category scales and matching data (McBride, 1983a). Both arguments are invalid. With respect to the first argument, it is noted, that when both the category scale and the JND-scale are not linear with perceived taste intensity, it may well be that the relationship between these two is in fact linear. Both types of scales may be nonlinear in the same way.

The second argument is invalid too. In Chapter Six of this paper, it was shown that the data obtained by functional measurement agree with the matching data obtained in Chapter Three. In Chapter Ten it was shown that the magnitude estimation data obtained by Frijters & Oude Ophuis (1983) also agree with the matching data in Chapter Three. As the data of McBride (1983b) are also in agreement with the matching data, we are now faced with at least three types of scales (McBride, 1983b; Frijters & Oude Ophuis, 1983; Chapter Six), which are all in agreement with matching data. However, these scales are interrelated in a non-linear way. Thus, the argument that a particular scale agrees with matching data is no evidence for a linear scale.

It is argued that the scale values obtained by the functional

measurement approach are linear with perceived taste intensity. The parallelism in the factorial plots in the Chapters Five, Six, Seven, and Nine show that the judgment function in each of these studies was linear. On the basis of the theory of information integration of Anderson (1981), it can thus be inferred that the derived scale values are linear with perceived taste intensity.

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## **CHAPTER TWELVE**

### **SUMMARY**

## CHAPTER ONE

The thesis deals with the human perception of taste substance mixtures. This subject matter is studied with reference to three central issues, 1) the concept of equiratio taste substance mixtures, 2) the way how the taste intensity of a mixture is compared to the taste intensities of the mixture's components, when tasted independently, and 3) the psychometric properties of the response scale.

## CHAPTER TWO

This chapter gives a review of the literature on the perception of taste substance mixtures until 1980. This review does not account for recent developments in psychophysical taste mixture research, and results in a description of the state of knowledge on the perception of taste substance mixtures as it existed at the end of the 1970's.

The study of the perception of taste substance mixtures is divided in two main areas i.e. the perception of qualitatively similar tasting substances and the perception of qualitatively dissimilar tasting substances.

The results of studies on the perceived taste intensity of mixtures of qualitatively similar tasting substances, showed that the intensity of a mixture exceeds the sum of the taste intensities of the mixture's unmixed components. However, most of these results can be explained on the basis of a model of Bartoshuk & Cleveland, which relates the taste interaction between substances to the forms of the psychophysical functions of the mixture's unmixed components.

The study of the taste interaction in mixtures of qualitatively dissimilar tasting substances focuses on two issues i.e. the perceived taste quality, and the perceived taste intensity.

One of the questions concerning the taste quality of

mixtures was already resolved in the middle of the nineteenth century. The taste qualities of the mixture's components can be identified in mixtures. For example, particular mixtures of sucrose and NaCl taste both sweet and salty. Another question concerning the taste quality of mixtures is whether or not new taste qualities emerge. The discussion on this issue started at the end of the nineteenth century, and continues until the present day. This question is still not resolved.

Whether or not the specific taste intensity of a particular taste substance is altered by the presence of another dissimilar tastant, has been investigated in a large number of studies. There appears to be little agreement between the results of various studies.

### CHAPTER THREE

Beidler formulated his taste mixture equation to describe the neural response to taste substance mixtures, of which the molecules of the components compete for adsorption at the same receptor sites. Later, this equation was generalized to a psychophysical level. The purpose of this chapter was to show that Beidler's mixture model can be tested appropriately with indirect psychophysical methods. Using the method of constant stimuli, concentrations of fructose, and three equiratio mixture types of glucose and fructose were matched in perceived sweetness intensity to five glucose standard concentrations. The results showed that Beidler's mixture equation describes accurately the taste interaction between glucose and fructose at low sweetness levels. At high sweetness levels the taste system operated in a more efficient way than could be expected on the basis of Beidler's mixture equation, because the experimentally determined mixture concentrations were lower than those predicted by this model. The findings suggest that glucose and fructose share common receptors, but that either one or both have additional secondary binding mechanisms.

## CHAPTER FOUR

This chapter discusses two rules currently in use for the assessment of the taste interaction in binary mixtures of qualitatively similar tasting substances. Usually, the taste interaction is assessed by comparing the response to a mixture to the sum of the responses of the mixture's components (i.e. "the summated response comparison rule"). The second rule discussed is the "equimolar comparison rule". When this rule is applied, the taste intensity of mixtures and single substances are compared at those concentrations where the mixtures and single compounds have equal molarities. The results of seven published studies were re-analyzed in order to enable application of the equimolar comparison rule. The results showed that the taste interaction in binary sugar mixtures follows two principles. The first principle is that the 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. The second principle is that the sweetness intensity of a binary sugar mixture gets near the sweetness intensity of the sweetest component, tasted alone and at the same molarity as the mixture, when the proportion of the sweetest component in the mixture increases.

## CHAPTER FIVE

In this chapter it is argued that the taste interaction in taste substance mixtures can only be studied properly by application of a psychophysical methodology, which separates the sensory processes from the judgmental processes. This is achieved by a functional measurement approach in combination with a two stimulus procedure. In this study, solutions of glucose, fructose, and three equiratio mixtures of glucose and fructose, were compared with glucose solutions for perceived



sweetness intensity. Parallelism in the obtained factorial plots showed that the judgment function was linear. From this result it was inferred that the marginal means of the response matrices represent perceived sweetness intensities on an interval scale. The results showed that the psychophysical functions of the three equiratio mixtures of glucose and fructose lie in between the psychophysical functions for unmixed glucose and fructose.

## CHAPTER SIX

In this chapter it is discussed how the taste interaction between two qualitatively similar tasting substances in mixtures can be assessed. The taste interaction can be assessed using the "equimolar comparison rule", the "factorial plot comparison rule", or the "summed response comparison rule". These rules were applied on the results of an investigation on the sweetness of sucrose, fructose, and sucrose-fructose mixtures. Each comparison rule arrived at a similar description of the taste interaction between sucrose and fructose, except for one phenomenon. From the results of the equimolar comparison rule it became apparent that the sweetness intensity of sucrose-fructose mixtures lies in between the sweetness intensities of unmixed sucrose and fructose. This was not evident from the results of the other comparison rules. The taste interaction between sucrose and fructose could be explained to a large extent, although not completely, by the apparent taste interactions within sucrose and within fructose. It is also argued that the taste interaction in binary sugar mixtures is synergistically at low sweetness levels, additive at intermediate sweetness levels, and suppressive at high sweetness levels.

## CHAPTER SEVEN

In this chapter it is investigated, whether or not subjects use one comparative operation between the absolute sweetness

intensities elicited by a pair of fructose stimuli, irrespective whether they are instructed to judge "ratios" or "differences" in perceived sweetness intensities. The pairs of fructose stimuli were constructed on the basis of a factorial judgment design. The results showed that judgments of "ratios" and judgments of "differences" were monotonically related. The marginal means of the log-transformed ratio responses were a linear function of the marginal means of the difference response matrix. These results indicate that subjects use only one comparative operation between perceived sweetness intensities. This comparative operation is to be described by algebraic subtraction.

#### CHAPTER EIGHT

This chapter concerns concentrations of sucrose and NaCl which are equal in perceived taste intensity. In some studies it was suggested that sucrose and NaCl have equal perceived taste intensities when their molar concentrations are about equal. Results of other studies suggest that sucrose and NaCl taste equally strong, when the molar sucrose concentration is 1.5-1.75 times the molar NaCl concentration. This issue was pursued in an experiment, where NaCl concentrations were matched in perceived taste intensity to five sucrose solutions (and vice-versa), using the method of constant stimuli. The results concurred with previous observations that sucrose and NaCl have an equal perceived taste intensity, when the molar concentration of sucrose is 1.5-1.75 times the molar concentration of NaCl.

#### CHAPTER NINE

This chapter concerns the interrelationships among the sweetness, saltiness and total taste intensity of unimixed sucrose, unimixed NaCl and sucrose/NaCl mixtures. These relationships are investigated according to a conceptual framework. The psychophysical scaling method used in this study

was similar to the method applied in the Chapters Five and Six. The results showed that the psychophysical functions for the sweetness of sucrose, and the saltiness of NaCl are expansive at low concentrations and compressive at high concentrations. The sweetness of sucrose was similar to the total taste intensity of sucrose, and the saltiness of NaCl was similar to the total taste intensity of NaCl. Sucrose/NaCl mixtures were sweeter than the corresponding unmixed sucrose solution, when both the NaCl and sucrose concentrations were low. When either the sucrose concentration or the NaCl concentration was high, sucrose/NaCl mixtures were perceived as less sweet than unmixed sucrose. The saltiness of sucrose/NaCl mixtures was lower than the saltiness of unmixed NaCl. The total taste intensity of sucrose/NaCl mixtures could be well predicted by the square root of the sum of the squared total taste intensities of the mixture's components when tasted alone. The total taste intensity of sucrose/NaCl mixtures was about equal to the sum of the mixture's sweetness and saltiness intensity.

## CHAPTER TEN

In this chapter some additional analyses were carried out. It appears that accumulated JND-scales of glucose and fructose, constructed on the basis of the results of Chapter Three are internally consistent. A comparison between the results of the Chapters Five, Six, Seven and Nine, shows that the scale values obtained in each of these studies differ with a multiplicative constant only. The scales obtained in these Chapters are not linear with the scales obtained by McBride. This chapter concludes with some attempts to fit a generalized Beidler function to the scale values obtained in the Chapters Five, Six, and Seven.

## CHAPTER ELEVEN

In the general discussion it is noted that the paradigm of equiratio taste substance mixtures appeared to be a powerful instrument in the study of taste interaction phenomena. The equiratio taste mixture model provided excellent predictions for the sensory responses to binary and complex mixtures of sugars and sugar-alcohols, and for binary mixtures of acids. The equimolar comparison showed that the taste interaction in binary sugar mixtures follows two general principles. Future studies must show whether or not the equimolar comparison rule can also be applied to mixtures of sugars and intensive sweeteners. This chapter concludes with a discussion on the psychometric properties of the scales obtained by McBride, and the scales obtained in this thesis. It is concluded that the scales obtained in this thesis are linear with perceived taste intensity, whereas the scales obtained by McBride are not linear with perceived taste intensity.

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**CHAPTER THIRTEEN**

**(HOOFDSTUK DERTIEN)**

**SAMENVATTING**

**(SUMMARY IN DUTCH)**

## HOOFDSTUK EEN

Dit proefschrift handelt over de perceptie van smaakstoffen mengsele. Hierbij komen met name drie centrale kwesties aan de orde, 1) het concept van equiratio smaakstoffen mengsele, 2) de wijze waarop de smaakintensiteit van een mengsel wordt vergeleken met de smaakintensiteiten van de ongemengde componenten van het mengsel, en 3) de psychometrische eigenschappen van de respons echaal.

## HOOFDSTUK TWEE

Dit hoofdstuk geeft een overzicht van de literatuur over de perceptie van smaakstoffen mengsele tot 1980. Dit overzicht gaat niet in op recente ontwikkelingen, en resulteert in een beschrijving van de kennis op het gebied van de perceptie van mengsele van smaakstoffen, zoals deze bestond aan het einde van de zeventiger jaren.

De studie naar de perceptie van mengsele van smaakstoffen is verdeeld in twee hoofdgebieden, de perceptie van mengsele van kwalitatief gelijkmakende stoffen, en de perceptie van mengsele van kwalitatief ongelijkmakende stoffen.

De resultaten van studies naar de waargenomen smaakintensiteit van mengsele van kwalitatief gelijkmakende stoffen lieten zien, dat de smaakintensiteit van een mengsel groter is dan de som van de smaakintensiteiten van de ongemengde componenten van het mengsel. Het grootste deel van deze resultaten kan echter verklaard worden op grond van een model van Bartoshuk & Cleveland, dat de smaak-interactie in mengsele in verband brengt met de vorm van de psychofysische functies van de ongemengde componenten.

De studie naar de smaak-interactie in mengsele van kwalitatief ongelijkmakende stoffen richt zich op een tweetal kwesties, namelijk, de waargenomen smaakkwiteit, en de waargenomen smaakintensiteit.

Een van de vragen over de smaakkwaliteit van mengsels van kwalitatief ongelijk smakende substanties is reeds beantwoord in het midden van de negentiende eeuw. De individuele smaakkwaliteiten kunnen in een mengsel geïdentificeerd worden. Bijvoorbeeld, bepaalde mengsels van tafelsuiker en keukenzout smaken zowel zoet als zout. Een andere vraag over de smaakkwaliteit van mengsels is of er een nieuwe smaakkwaliteit ontstaat. De discussie hierover begon aan het einde van de vorige eeuw, en zet zich voort tot de dag van vandaag. Deze vraag is nog steeds niet beantwoord.

Of de specifieke smaakintensiteit van een smaakstof beïnvloed wordt door de aanwezigheid van een andere kwalitatief ongelijk smakende stof, is het onderwerp geweest van vele studies. Het blijkt echter dat er weinig overeenstemming bestaat tussen de resultaten van de verschillende studies.

## HOOFDSTUK DRIE

Beidler formuleerde zijn meng-vergelijking voor de beschrijving van de neurale respons op mengsels van smaakstoffen, waarvan de moleculen van de componenten competitie plegen voor adsorptie aan dezelfde receptor plaatsen. Later werd deze mengvergelijking gegeneraliseerd naar psychofysisch niveau. Het doel van dit hoofdstuk was aan te tonen, dat Beidler's mengmodel op een adequate manier getoetst kan worden met behulp van indirecte psychofysische methodes. Gebruik makend van de methode van constante stimuli, werden concentraties van fructose, en drie equiratio mengsels van glucose en fructose, gematched in waargenomen zoetheidsintensiteit tot vijf standaard glucose oplossingen. De resultaten lieten zien dat Beidler's mengmodel de smaakinteractie tussen glucose en fructose accuraat beschrijft op lage zoetheidsniveaus. Echter, op hoge zoetheidsniveaus opereert het smaakzintuig efficiënter dan men op grond van Beidler's mengformule had kunnen verwachten. De experimenteel bepaalde mengsel concentraties waren lager dan de concentraties zoals het

model ze voorspelde. De bevindingen suggereren dat glucose en fructose dezelfde receptoren hebben, maar dat een of beide nog additionele bindingemechanismen hebben.

#### HOOFDSTUK VIER

In dit hoofdstuk worden twee regels besproken die gebruikt worden om de smaakinteractie in mengsels van kwalitatief gelijkmakende stoffen vast te stellen. Gewoonlijk wordt de smaakintensiteit vastgesteld door de respons op het mengsel te vergelijken met de som van de responsies op de ongemengde componenten (de "gesommeerde respons vergelijking"). De tweede regel die wordt besproken is de "equimolaire vergelijking". Wanneer deze regel wordt toegepast worden de smaakintensiteiten van mengsels en ongemengde componenten vergeleken bij die concentraties, waarbij de ongemengde stoffen en de mengsels gelijke molariteiten hebben. De resultaten van zeven gepubliceerde studies werden opnieuw geanalyseerd, zodanig dat de smaakinteractie vastgesteld kon worden met behulp van de equimolaire vergelijking. De resultaten van deze heranalyse toonden aan dat de smaakinteractie in tweewaardige suikermengsels verloopt volgens twee eenvoudige principes. De eerste regel is dat de zoetheidsintensiteit van een tweewaardig suikermengsel tussen de zoetheden ligt van de componenten, wanneer elk van de ongemengde componenten en het mengsel bij een gelijke molariteit geproefd worden. De tweede regel is, dat wanneer de proportie van de zoetste suiker in het mengsel toeneemt, dat de zoetheid van het mengsel de zoetheid van de zoetste component benadert.

#### HOOFDSTUK VIJF

In dit hoofdstuk wordt betoogd dat de smaakinteractie in een mengsel van smaakstoffen alleen maar goed bestudeerd kan worden door de toepassing van een psychofysische methodologie, die de sensorische processen scheidt van de beoordelingsprocessen. Deze



scheiding wordt bewerkstelligd door de toepassing van een "functional measurement" benadering in combinatie met een twee-stimulus procedure. In deze studie werden oplossingen van fructose, en drie equiratio mengsels van glucose en fructose vergeleken met betrekking tot waargenomen zoetheidsintensiteit met een aantal glucose oplossingen. Paralelliteit in de verkregen factoriële plots liet zien dat de respons functie lineair was. Uit dit resultaat werd afgeleid dat de marginale gemiddeldes van de response matrices, waargenomen zoetheidsintensiteiten op een interval schaal representeren. De resultaten toonden eveneens aan dat de psychofysische functies van equiratio mengsels van glucose en fructose tussen de psychofysische functies van ongemengde glucose en ongemengde fructose liggen.

## HOOFDSTUK ZES

In dit hoofdstuk wordt besproken hoe de smaakinteractie in mengsels van kwalitatief gelijkmakende stoffen vastgesteld kan worden. De smaakinteractie kan worden vastgesteld met behulp van de "gesommeerde respons vergelijking", de "factoriële plot vergelijking", en de "equimolaire vergelijking". Deze vergelijkingeregels werden toegepast op de resultaten van een onderzoek naar de zoetheid van saccharose, fructose, en saccharose-fructose mengsels. Elke vergelijkingeregel resulteerde in een gelijksoortige beschrijving van de smaakinteractie tussen saccharose en fructose. Echter, één fenomeen kwam alleen maar naar voren door de toepassing van de equimolaire vergelijking en niet door toepassing van de andere vergelijkingeregels. Dit was het verschijnsel dat de zoetheidsintensiteit van saccharose-fructose mengsels tussen de zoetheidsintensiteiten van de ongemengde componenten ligt. De smaakinteractie tussen saccharose en fructose kon voor een groot gedeelte, ofschoon niet helemaal, verklaard worden door de "blijkbare" smaakinteractie binnen saccharose en fructose als ongemengde stoffen. Er wordt betoogd dat de smaakinteractie binnen elk suikermengsel synergistisch is op lage

zoetheid niveaus, additief is op gemiddelde zoetheideniveaus, en onderdrukkend is op hoge zoetheideniveaus.

## HOOFDSTUK ZEVEN

In dit hoofdstuk wordt onderzocht of proefpersonen al dan niet één vergelijkende operatie gebruiken, om twee absolute zoetheidsintensiteiten (opgewekt door paren fructose stimuli) te vergelijken, ongeacht of ze nu gevraagd worden om "verschillen" of "verhoudingen" te beoordelen. De paren van de fructose stimuli werden geconstrueerd op basis van een factorieel beoordelings-schema. De resultaten lieten zien dat de beoordelingen van "verhoudingen" een monotone functie waren van de "verschil" beoordelingen. De marginale gemiddeldes van de log-getransformeerde ratio responsmatrix waren een lineaire functie van de marginale gemiddeldes van de respons matrix van verschil beoordelingen. Deze resultaten suggereren dat proefpersonen slechts één vergelijkende operatie gebruiken, wanneer zij twee zoetheidsintensiteiten met elkaar vergelijken. Deze vergelijkende operatie wordt beschreven door algebraïsche subtractie.

## HOOFDSTUK ACHT

Dit hoofdstuk handelt over concentraties van saccharose (tafelsuiker) en NaCl (keukenzout) die een gelijke smaakintensiteit opwekken. In sommige studies is gesuggereerd dat saccharose en NaCl oplossingen even sterk smaken, wanneer de molaire sucrose concentratie gelijk is aan de molaire NaCl concentratie. De resultaten van andere studies suggereren dat sucrose en NaCl oplossingen even sterk smaken als de molaire sucrose concentratie 1.5-1.75 keer de molaire NaCl concentratie is. Deze kwestie is uitgewerkt in een experiment, waarbij NaCl concentraties in smaakintensiteit gematched werden tot vijf sucrose oplossingen, en vice versa. Het matchen werd uitgevoerd

met behulp van de methode van constante stimuli. De resultaten kwamen overeen met de observaties van eerdere studies, namelijk dat sucrose en NaCl oplossingen even sterk smaken, wanneer de molaire sucrose concentratie gelijk is aan 1.5-1.75 keer de molaire NaCl concentratie.

## HOOFDSTUK NEGEN

In dit hoofdstuk wordt nader ingegaan op de onderlinge relaties tussen de zoetheid, zoutheid, en totale smaakintensiteit van ongemengde sucrose, ongemengde NaCl en sucrose/NaCl mengsels. Deze relaties worden bestudeerd aan de hand van een conceptueel schema. De psychofysische schaalmethode die in dit experiment is gebruikt is gelijk aan de methode zoals gebruikt in de hoofdstukken vijf en zes. Deze studie liet zien dat sucrose/NaCl mengsels zoeter smaken dan ongemengde sucrose oplossingen, indien zowel de sucrose als NaCl concentratie laag is. Wanneer of de sucrose concentratie of de NaCl concentratie hoog is, dan wordt een sucrose/NaCl mengsel als minder zoet waargenomen dan de ongemengde sucrose oplossing. De zoutheid van sucrose/NaCl mengsels is lager dan de zoutheid van ongemengde NaCl. De totale smaakintensiteit van een sucrose/NaCl mengsel kon goed worden voorspeld door de wortel te nemen uit de som van de gekwadrateerde intensiteiten van de ongemengde componenten. De totale smaakintensiteit van een sucrose/NaCl mengsel was ongeveer gelijk aan de som van de zoetheid en zoutheid van het mengsel.

## HOOFDSTUK TIEN

In dit hoofdstuk worden enkele additionele analyses uitgevoerd. Het blijkt dat geaccumuleerde JND-schalen (JND = Just Noticeable Difference) van glucose en fructose intern consistent zijn. Deze schalen werden geconstrueerd op basis van de resultaten van hoofdstuk drie. Een vergelijking van de resultaten van de hoofdstukken vijf, zes, zeven en negen liet zien, dat de

schaalwaardes die in elk van deze studies zijn verkregen, allen met een multiplicatieve constante van elkaar verschillen. De verkregen schalen zijn niet lineair met de schalen die door McBride verkregen zijn. Tenslotte worden enige pogingen gedaan om de parameters van een gegeneraliseerde Beidler vergelijking te schatten met behulp van de schaalwaardes verkregen in de hoofdstukken vijf, zes en zeven.

## HOOFDSTUK ELF

In de algemene discussie wordt opgemerkt dat het paradigma van equiratio smaakstoffen mengsels een krachtig instrument is om de verschijnselen die optreden in mengsels van smaakstoffen te bestuderen. Het equiratio mengmodel voorzag in uittekende voorspellingen voor de sensorische respons op de waargenomen intensiteit van tweewaardige en complexe mengsels van suikers en suikeralcoholen en tweewaardige mengsels van zuren. De equimolaire vergelijkingregel liet zien dat de smaakinteractie in tweewaardige suikermengsels beschreven kan worden door twee eenvoudige principes. Toekomstige studies zullen moeten uitmaken of de equimolaire vergelijking ook kan worden toegepast op mengsels van suikers en alternatieve zoetstoffen. De algemene discussie wordt afgesloten met een bespreking van de psychometrische eigenschappen van de schaal zoals die door McBride is ontwikkeld, en de schaal zoals die in dit proefschrift is ontwikkeld. Gekonkludeerd wordt dat deze laatste schaal lineair is met waargenomen smaakintensiteit en dat de schalen door McBride zijn ontwikkeld niet lineair zijn met waargenomen smaakintensiteit.

## CURRICULUM VITAE

Cornelis de Graaf werd geboren op 27 juli 1965 te Alkmaar. Na het behalen van zijn Atheneum-B diploma aan de Rijkscholengemeenschap Noord Kennemerland, begon hij in 1974 met de studie Voeding aan de Landbouwniversiteit Wageningen. Na het behalen van zijn kandidaats examen maakte hij een reis naar Azië. In februari 1982 rondde hij zijn studie af met als hoofdvakken Voedingeleer, en Marktkunde en Marktonderzoek. Na afronding van deze studie heeft hij gedurende anderhalf jaar gereisd en gewerkt in Azië en Australië. Na terugkomst in Nederland werd begonnen met psychofysisch onderzoek. Van September 1984 tot September 1987 was hij verbonden als wetenschappelijk assistent aan de Vakgroep Humane Voeding van de Landbouwniversiteit Wageningen. Momenteel werkt hij als sensorisch onderzoeker op de vakgroep Levensmiddelentechnologie van de Landbouwniversiteit.