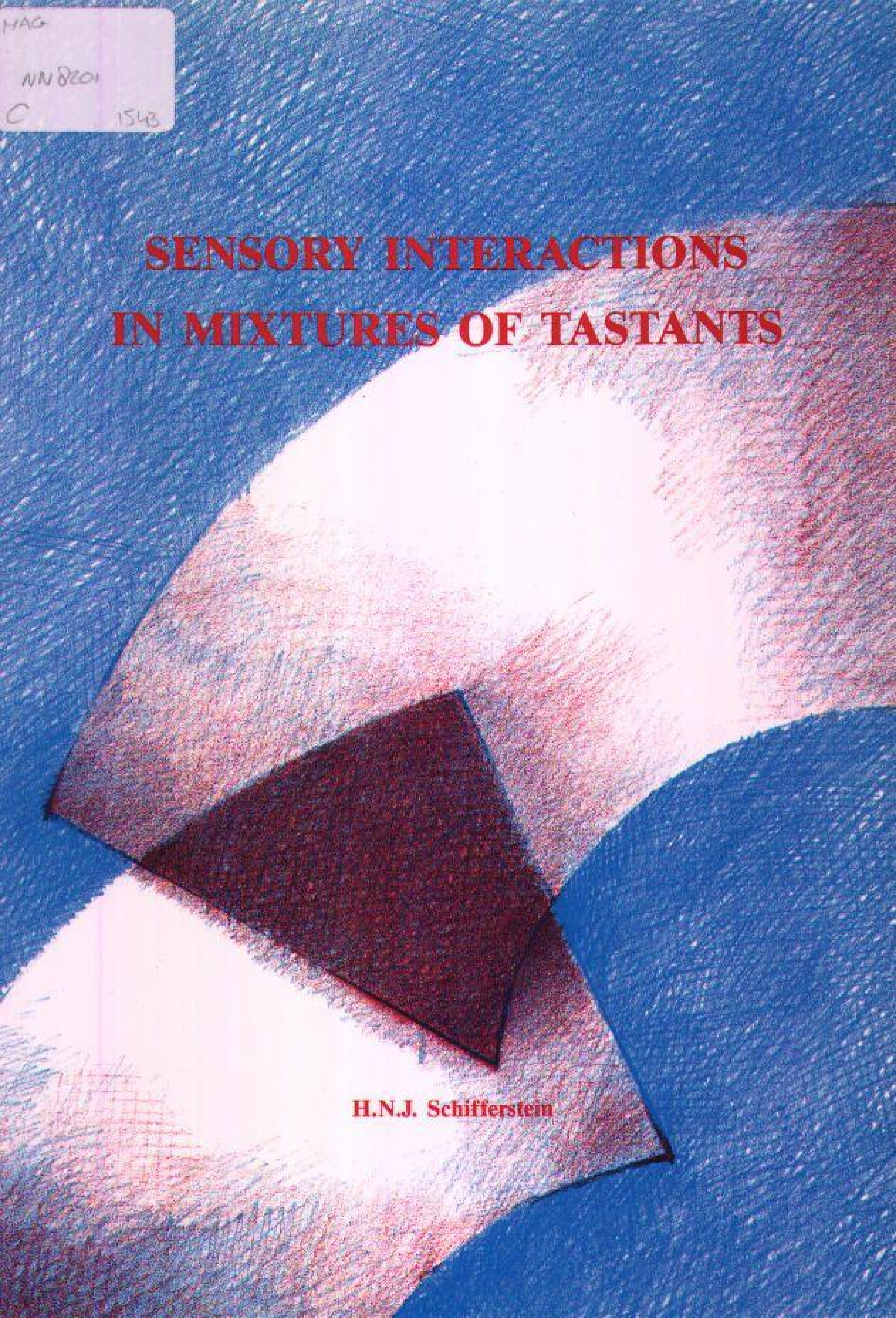
SENSORY INTERACTIONS IN MIXTURES OF TASTANTS

H.N.J. Schifferstein



STELLINGEN

1. In mengsels die centrale mengonderdrukking vertonen spelen de waargenomen sensaties een grotere rol bij het tot stand komen van sensorische interacties dan de concentraties van de smaakstoffen die deze sensaties hebben opgewekt.
Dit proefschrift

2. De smaaksterkte van een mengsel wordt bepaald door de combinatie van specifieke smaaksensaties die door het mengsel worden opgewekt en niet door de intensiteiten van de ongemengde componenten.
Dit proefschrift

3. De conclusie dat de gevoeligheid voor PTC-achtige verbindingen gerelateerd is aan de waargenomen intensiteit van chemisch niet aan PTC verwante stoffen is mogelijkerwijs een gevolg van het gebruik van een verkeerde statistische toets of een verkeerde classificatie-procedure.
Dit proefschrift

4. Afhankelijk van de aan de proefpersonen gegeven taakinstructie, kunnen bepaalde mengsels een patroon van mengonderdrukking of van mengversterking vertonen.
Frank, R.A., van der Klaauw, N.J. en Schifferstein, H.N.J. Both perceptual and conceptual factors affect taste-odor and taste-taste interactions. Ongepubliceerd manuscript.

5. De constatering dat er bias is opgetreden bij het vaststellen van de numerieke waarde van een parameter is eerder het gevolg van het gebruik van een incompleet conceptueel schema dan van een gebrek inherent aan de meetmethode.

6. Indien een therapie de mortaliteit ten gevolge van een bepaalde ziekte verlaagt, is dit op zich nog geen reden om over te gaan tot het toepassen van deze therapie.

7. De kans op toekenning van een reisbeurs is omgekeerd evenredig met de hoeveelheid tijd die nodig is voor het formuleren van de aanvraag.

8. Indien de NRC week-editie voor het buitenland in Nederland verkrijgbaar zou zijn, zou dit onder Nederlandse managers de meest gelezen krant zijn.

stellingen behorend bij het proefschrift van
Hendrik N.J. Schifferstein
Sensory interactions in mixtures of tastants
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Hendrik Nicolaas Jozef Schifferstein

SENSORY INTERACTIONS IN MIXTURES OF TASTANTS

Promotor: dr. J.E.R. Frijters, bijzonder hoogleraar in de sensorische en psychologische aspecten van voeding en voedsel.

Hendrik Nicolaas Jozef Schifferstein

SENSORY INTERACTIONS IN MIXTURES OF TASTANTS

Proefschrift
ter verkrijging van de graad van doctor
in de landbouw- en milieuwetenschappen
op gezag van de rector magnificus,
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VOORWOORD

Het proefschrift dat nu voor u ligt is het resultaat van vier jaar onderzoek, verricht bij de Sectie Sensorisch Onderzoek, Vakgroep Levensmiddelentechnologie, van de Landbouwuniversiteit te Wageningen. Het onderzoek is als het projekt "Sensorische Integratie in Smaakstoffenmengsels" (Nr. 560-262-032) gedurende de hele periode gesubsidieerd door de stichting PSYCHON van de Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).

Degene die zonder meer het meest aan dit proefschrift heeft bijgedragen is mijn promotor, Jan Frijters. Hij is degene die mij de kans gegeven heeft om mij enkele jaren te verdiepen in het vakgebied der psychofysica. In talloze besprekingen heeft hij, met behulp van talrijke anecdotes, de relaties aangegeven tussen ons waarnemingsonderzoek en de andere gebieden van de psychologie, de filosofie, de statistiek en het dagelijkse leven. Daarnaast is zijn begeleiding van groot belang geweest bij het verbeteren van mijn wetenschappelijke schrijfstijl. Tevens kan ik op deze plek beamen dat zijn voorspelling is uitgekomen dat door middel van een handtekening onder een arbeidscontract mijn promotie een feit is.

Vervolgens wil ik Liesbeth Hijwegen bedanken die de nodige oplossingen voor mij gemaakt heeft en de nodige bekertjes heeft gevuld. Daarnaast speelde zij van tijd tot tijd een cruciale rol bij het openhouden van communicatie-kanalen binnen en buiten onze sectie.

Veel van het hier gepresenteerde onderzoek was nooit tot stand gekomen zonder de inzet en het enthousiasme van doctoraalstudenten en onderzoeksassistenten. Ik denk hierbij met name aan Marjon Theunissen, Hilda Smit, Joke de Vries en Céline Porcheron. Ik heb met hen allen met veel plezier samengewerkt.

Tijdens mijn studiereis in de Verenigde Staten heeft het onderzoek van Bob Frank mij de beperkingen van mijn eigen onderzoek laten inzien. Ook zeer aangenaam waren de laatste maanden van mijn vier-jarig OIO-bestaan, toen ik samen met Nicolette van der Klaauw en Ralf Kleykers de grenzen van het mengselonderzoek heb verkend.

Last but not least wil ik hier ook alle mensen bedanken die mijn persoonlijke leven een stuk verrijkt hebben tijdens deze periode. Een speciale plaats daarbij wordt ingenomen door Toine Hulshof, een vriend die tevens de rol van collega vervulde en mijn al dan niet gevraagde mening steeds erg heeft gewaardeerd.

Natuurlijk kan een proefschrift als dit niet tot stand komen zonder financiële steun. Naast de stichting PSYCHON heeft de Suikerstichting Nederland de nodige bijdragen geleverd.

Mijn reis naar de Verenigde Staten werd mede mogelijk gemaakt door de Landbouwuniversiteit en door beurzen van de stichting "Fonds Landbouw Export Bureau 1916/1918" (LEB-Fonds) en de European Chemoreception Research Organization (ECRO).

Rick Schifferstein

ABSTRACT

This dissertation focuses upon the interrelationships between physical and psychological variables involved in the human perception of mixtures of dissimilar tasting substances. Mixture interactions are complex, asymmetrical, and they can have a central or peripheral origin, depending on the nature of the mixture components. Two regularities only seem to hold for all pairs of dissimilar tasting substances in taste mixture research. First, dissimilar tasting components generally suppress each other's taste intensity. Second, the total taste intensity of a binary mixture is well predicted by the sum of the two specific taste intensities within the mixture percept.

In addition to mixture interactions, differences in research methodology are addressed, which appear to affect the outcomes of taste interaction research.

Chapter 1

GENERAL INTRODUCTION

This chapter starts out with a brief introduction into taste mixture research. First, mixture interactions between similar tasting substances at threshold and supra-threshold level are discussed. Second, various aspects of mixtures of dissimilar tasting substances are discussed: intensity changes, quality changes, and the locus of the mixture suppression mechanism. Subsequently, the factors affecting the complexity of the mixture percept are discussed and are linked to the results of multidimensional scaling studies on complex taste stimuli.

In the second part of the chapter, the conceptual framework and the scaling procedures used in this dissertation are discussed. The last part of the chapter focuses upon the aim and structure of the dissertation.

A BRIEF INTRODUCTION INTO TASTE MIXTURE RESEARCH

In assessing interactions between different tastants, two types of mixtures should be distinguished. In the first mixture type, all components used for mixture composition elicit similar taste qualities. If such a mixture is tasted, it leads to the formation of a homogeneous percept, consisting of only one taste sensation. In the second mixture type, dissimilar tasting substances are mixed, leading, in most cases, to the formation of a heterogeneous percept in which several taste qualities can be identified.

The locus of the mechanism responsible for the interaction between two substances *A* and *B* may, in principle, reside anywhere in the pathway from aqueous solution to the overt behavior (response). The substances may react chemically, forming new compounds, or physicochemically, forming complex structures. Furthermore, they may interact biophysically in the periphery of the sensory system, on their way to the receptor or in competing for receptor sites (peri-receptor events, e.g. Birch, 1980; Lawless, 1982; Carr *et al.*, 1989). In addition, they may interact at the level of the receptor cell, in the afferent nerve bundles, in the central nervous system or at the level of conscious experience, i.e. the percept (Kroeze, 1978, 1979; Lawless, 1979; De Graaf and Frijters, 1989).

Mixtures of similar tasting substances

In binary mixtures of similar tasting substances, both compounds contribute to the intensity of the sensation perceived, and interactions between substances can best be described by terms like hypo-addition, addition, and hyper-addition (Berglund *et al.*, 1976).

Hahn and Ulbrich (1948) determined taste thresholds for many combinations of similar tasting substances. Two substances *A* and *B* were defined to behave additively if the threshold concentration for *AB* mixtures equalled p times the threshold concentration of A and $1\text{-}p$ times the threshold concentration of B [$0<p<1$]. For some 200 combinations of bitter, salty, sweet, and sour substances, the mixture components were found to behave additively. For such components, the concentrations in a mixture allowing detection are lower than the concentrations of the unmixed substances necessary to allow detection.

Similar tasting substances are frequently found to cross- adapt (e.g. Lawless and Stevens, 1983), implying that similar tasting substances are often mutually dependent at the level of the peripheral sensory system (Frijters and Oude Ophuis, 1983). One possible explanation for this dependency is that similar tasting components compete for the same set of receptors. In addition to shared receptor sites, the components may have additional binding mechanisms, which might account for the hyperaddition sometimes found (e.g. De Graaf and Frijters, 1986). The observed hyperaddition can also be described by a model stating that different numbers of molecules react with one receptor and/or by a model stating that different numbers of substance-receptor complexes compete for one transducer (Ennis, 1989, 1991).

Intensity changes in mixtures of dissimilar tasting substances

In mixtures of dissimilar tasting substances, one component does not contribute to the intensity of the sensation elicited by the other component. The phenomenon that the intensities of the component sensations within and outside the mixture are equal is called independence. If the intensity in the mixture percept is higher than the intensity outside the mixture, this is called synergism or mixture enhancement. The converse is called antagonism or mixture suppression (Berglund *et al.*, 1976; Frijters, 1987).

In the presence of 0.9 times the threshold concentration of substance *A*, the threshold concentration of a dissimilar tasting substance *B* is either equal to or lower than the threshold concentration for unmixed *B* (Hahn and Ulbrich, 1948). If a suprathreshold concentration of a dissimilar tasting component is added, threshold concentrations for HCl, NaCl, and sucrose increase (Heymans, 1899). In general, the presence of one component raises both the detection as well as the recognition threshold for the other component. However, adding quinineHCl at suprathreshold levels lowers the thresholds for tartaric acid, and adding tartaric acid lowers the thresholds for glucose (von Skramlik, 1962) .

Fabian and Blum (1943) investigated the effect of sub-recognition threshold concentrations of one substance upon the intensity of a suprathreshold concentration of a dissimilar tasting substance using a matching procedure. NaCl was found to reduce the sourness of acids, but to increase the sweetness of sugars. Acids mostly enhance the saltiness of NaCl. The sweetness of sugars, however, is sometimes suppressed and sometimes enhanced. Sugars generally decrease the saltiness of NaCl and the sourness of acids. Kremer (1917) obtained matches and numerical intensity ratings of similar mixture types. He found that subthreshold concentrations of NaCl and HCl enhance sucrose sweetness. QuinineHCl, however, was found to decrease sucrose sweetness.

For weak sucrose/citric acid mixtures, Gregson and McCowen noted that the individual type of mixture interaction (suppression or enhancement) depends mainly upon the idiosyncratic type of response behavior. Kamen *et al.* (1961) found decrements in category ratings for some specific taste intensities when a second substance was added to a solution (e.g. caffeine bitterness ratings decreased when sucrose was added), but increments for other substance combinations (caffeine and citric acid). Pangborn (1960), however, reported that sucrose, NaCl, caffeine, and citric acid all mutually suppress each other's taste intensity. The only exception to this rule is NaCl, which appears to enhance the sweetness of sucrose at low concentration levels. According to Kroeze (1982b), the degree of mixture suppression or taste enhancement is related to the intensity of side tastes of the unmixed components. For example, if NaCl elicits a sweet taste, a NaCl/sucrose mixture may be sweeter than the unmixed sucrose, due to the sweetness of NaCl.

Another notable feature of mixtures of dissimilar tasting substances is that the total taste intensity of the mixture is lower than the sum of the total taste intensities elicited by the unmixed components (Pfaffmann *et al.*, 1971).

<u>Qualitative changes in mixtures of dissimilar tasting substances</u>

At threshold level, mixtures of dissimilar tasting substances may elicit sensations that are not typically associated with the substances in the mixture. For example, Gregson (1966b) noted that a sucrose/NaCl mixture was often called 'acidic'. This is not surprising, given the fact that NaCl may be judged as sweet, sour, salty, or bitter near threshold level (Bartoshuk *et al.*, 1964).

For two dissimilar tasting substances *A* and *B* that are mixed in successively different intensity ratios, Hambloch and Püschel (1928) described five stages in the evolution of the perceptual experience. Beginning with a mixture where the quality elicited by substance *A* has a high intensity, whilst the concentration of *B* is low, the quality elicited by *B* is totally suppressed. This can be the case even though the concentration of *B* is readily perceptible when presented unmixed. When, subsequently, the concentration of *A* is decreased whilst that of *B* is increased, the quality of *B* may not yet be recognizable but the presence of *B* changes the character of the mixture percept. The mixture percept seems to remain homogeneous in this second range. However, the mixture can be discriminated from a solution of unmixed *A* on the basis of taste quality. In the third stage, both components can be discriminated and can be attended to. After a further decrease of the *A*/*B* ratio, the quality elicited by *A* is no longer recognizable, but the quality of the mixture differs from that of a solution of unmixed *B*. Finally, in the fifth stage, the taste of *A* is fully suppressed by the presence of substance *B*. The extensions of the five stages discussed above depend upon the two substances that are investigated (Hambloch and Püschel, 1928). The description of changing mixing ratios between substances *A* and *B* clearly shows that intensity and quality are two attributes that are heavily interdependent, and that both attributes depend upon both solute concentrations.

The locus of mixture suppression

Dissimilar tasting substances virtually do not cross-adapt, implying that they do not share common receptor sites (McBurney and Bartoshuk, 1973). According to Kroeze (1978, 1979), mixture suppression and adaptation are two separate phenomena to be accounted for by different processes. Kroeze showed that adaptation and mixture suppression have different locations in the taste system and, also, that mixture suppression is more centrally located than adaptation. The fact that adaptation and mixture suppression are separate phenomena does not imply that they do not affect each other. For example, adaptation to one of a mixture's components has been shown to release the intensity elicited by the other component from suppression (e.g. Lawless, 1979; Gillan, 1982). This phenomenon has been called 'suppression release'. Release from mixture suppression has also been demonstrated after blocking the perception of sweetness using *Gymnema sylvestre* (e.g. Lawless, 1979) and after habituation to one of the mixture's component sensations (Kroeze, 1982a, 1983).

Since there are no structural elements of the neural part of the taste system that connect the two sides of the tongue before the thalamic level (Norgren and Leonard, 1973), Kroeze and Bartoshuk (1985) carried out a split-tongue experiment to gain information about the locus of mixture suppression. These authors argued that the decrease in bitterness intensity has a central origin in quinineHCl/sucrose mixtures, but results from both central and peripheral mechanisms in quinineHCl/NaCl mixtures.

The complexity of the mixture percept

In studying the perception of mixtures of tastants, it is important to know whether the sensations elicited by a mixture of two dissimilar tasting substances are perceived separately (analysis), or whether they are combined into one new mixture sensation (synthesis). If the taste sensations synthesize into a new, homogeneous sensation $\Psi_{\gamma ij}$, it is impossible to scale the specific taste intensities of the component sensations within the mixture percept ($\Psi_{\alpha i}$ and $\Psi_{\beta j}$), since no separate sensations can be distinguished within a homogeneous percept. The controversy between those who argue that the taste modality functions analytically and those who state that it is a synthetic sense goes back to the nineteenth century (Öhrwall, 1891; Kiesow, 1894). More recently, McBurney and colleagues (e.g. McBurney, 1974; McBurney and Gent, 1979) have defended the analytical position, whilst Schiffman and Erickson (1971, 1980) have argued in favour of the synthetic view.

A strictly analytical position does not seem to hold, since unmixed 'primary' stimuli are not consistently judged as singular (homogeneous percept) and mixtures are not consistently perceived as being 'more-than-one' (heterogeneous percept). No one-to-one relationship exists between physical and perceptual complexity (Erickson and Covey, 1980; Erickson, 1982). The degree of complexity of a mixture percept varies with the number of physical components, and with the ratio and the absolute concentration levels of the physical components present (O'Mahony *et al.*, 1983). These results are not only incompatible with a strictly analytic point of view, they also argue against a strictly synthetic point of view. A purely synthetic view implies that each combination of specific taste sensations produces a new, homogeneous sensation. The studies cited above, however, have shown that mixtures and unmixed substances may elicit heterogeneous percepts.

The processes involved in mixture perception carry features of analysis and synthesis and cannot be identified with either one of these two types of processes (e.g. McBurney, 1986). In order to describe the processes involved in mixture perception and mixture judgment, a systematical analysis of all processes involved in the perception of complex stimuli is necessary.

Through a top-down approach, the factors determining the heterogeneity of a mixture percept become apparent. According to Kubovy's (1981) Theory of Indispensable Attributes, the perceived numerosity (heterogeneity) of a discrete stimulus depends upon whether the stimulus elements vary on an indispensable attribute or not. Without (detectable) variation on such an indispensable attribute, the reported perceived numerosity deviates from the physical numerosity. Kubovy (1981) stated that spatial location and event time are indispensable attributes for the sense of vision. For audition, auditory frequency and event time are indispensable. In determining the indispensable attributes for the sense of taste, one attribute that can be postulated to be indispensable is, similar to the senses of audition and vision, *event time*. If two taste sensations are perceived one after the other, the subjects are likely to conclude that the overall percept consisted of two elements. Since time manifests itself through all of the senses (Marks, 1978, p.32) event time could be regarded as an indispensable attribute for every sense modality.

A second indispensable attribute for the sense of taste, however, is harder to find. It could be suggested that *taste quality* is the second indispensable attribute for the sense of taste. However, the use of taste quality as an attribute leads to two new problems. First, taste quality has no corresponding entity in the physical world. Chemically entirely different substances may elicit similar taste sensations (e.g. sucrose and aspartame), whilst chemically more similar substances may elicit entirely different taste sensations (e.g. HCl and NaCl). Second, mixing two dissimilar tasting substances usually results in mixture interactions affecting the intensities and/or qualities elicited by both compounds. Therefore, the component sensations of a mixture percept deviate substantively from the sensations elicited by the unmixed components.

Using a bottom-up approach, an attempt can be made to describe all processes involved in transforming a physical stimulus into an observable judgmental response. In such an attempt we can make use of Garner 's (1974) distinction between primary and secondary processes involved in the perception of complex stimuli. Primary processes are processes that occur under time constraints, whilst secondary processes require more processing time.

Primary processes

Primary processes lead to the formation of a mixture percept as perceived spontaneously under time constraints. According to Kuznicki and Ashbaugh (1979, 1982), subjects are incapable of selectively attending to one individual taste sensation in a mixture percept without noticing the other sensation(s) in the percept. In addition, the authors noted that the presence of irrelevant tastes resulted in a quality shift in the target sensation. These findings show that afferent input is integrated to form a percept during the primary processes (Kroeze, 1990). The final mixture percept consists of a pattern of sensations, integrated over space and time. The complexity of the mixture percept, therefore, depends upon the properties of each of the specific taste sensations forming the mixture percept.

According to Boring (1942), Külpe (1893) listed *intensity*, *quality*, and *duration* as the attributes of sensations for all five senses. He added the attribute *extension* to this list for the senses of vision and touch. A gustatory analogue to the attribute of extension can be found in the gustatory experience of space by variation in stimulated area of the tongue and the oral cavity. Two attributes of sensations (intensity and quality) have already been discussed. The other two are discussed below.

The reaction times for various substances are found to differ, leading to a separation in time for the component sensations of the heterogeneous mixture percept. According to Hambloch and Püschel (1928), the sequence in increasing reaction times for representatives of the four taste qualities is NaCl < sucrose < tartaric acid < quinine hydrochloride. Kuznicki and Turner (1986) reported the detection time sequence NaCl < HCl < sucrose < quinine sulphate for equi-intense solutions of these four substances. If the time interval between the specific taste sensations increases noticeably, this will lead to an increase in the complexity of the mixture percept, since event time is an indispensable attribute for the sense of taste.

According to von Békésy (1964), spatial separation of tastants on the human tongue may affect the complexity of the taste percept. When bitter and sweet or salty and sour stimuli are applied to the two different sides of the tongue, the two sensations interact and the percept is localized in the middle of the tongue. However, for the other four possible combinations (bitter-salty, bitter-sour, sweet-salty, and sweet-sour), there are separate sensations on each tongue half. Therefore, the nature of the stimulus and the tongue area stimulated may affect the heterogeneity of the overall percept.

Apart from the properties of the specific taste sensations within the percept, the structure of the organization of the different sensations within the mixture percept may affect the perceived mixture complexity. If all specific taste sensations are high enough in intensity to be separately recognizable, the degree of dissimilarity between the separate sensations is likely to affect the complexity of the mixture percept. For example, if the component sensations are easily confused, the percept is likely to be more homogeneous than if all component sensations are never confused. In a psychophysical multidimensional scaling study, Schiffman and Erickson (1971) showed that subjects experienced the sweet stimuli as a group of stimuli rather distinct from the other samples. One of the four subjects reported that he made a dichotomous 'sweet' versus 'non-sweet' classification before he made any more specific judgments. Although 'sweetness' may be easily discriminated from other sensations, subjects have been shown to confuse 'sourness' and 'bitterness' (e.g. Gregson and Baker, 1973; O'Mahony *et al.*, 1979), which may imply that 'sweet-sour' mixture percepts may be more heterogeneous than 'sour-bitter' percepts. Apart from dissimilarity, perceptual organization processes (grouping, figure-ground segregation, and Gestalt formation) may operate in forming a mixture percept

Secondary processes

If the subject has more processing time available to attend to the mixture percept, cognitive processes come into play. If the subject wants to retain the percept elicited by a stimulus, the information in the sensory buffer has to be encoded in order to be stored in the short-term memory. Stimulus dimensions that were integral in a primary sense and thus unanalyzable, can be analyzable in a secondary sense as more processing time is available (Garner, 1981). Every percept following the presentation of a multidimensional stimulus can then be analyzed into its component sensations (Lockhead, 1966). During the analysis of a pattern of taste sensations, attention shifts between the different parts of the percept (Kroeze, 1990). In analyzing the mixture percept, the subjects make their judgments on the basis of decisional separability (i.e. the subjects select the sensation they are expected to judge without considering the other sensations during the judgmental process). Decisional separation processes are easier to implement in some cases than in others (Ashby and Maddox, 1990). The effort required in analysis depends heavily upon the outcomes of the primary processes: the complexity of the percept, the degree of organization, and the locus of the integration process (Kroeze, 1990).

If the subject is instructed to judge the total taste intensity of a mixture percept, this task may require the subject to perform an integrative operation instead of an analytic operation during the judgmental process. If the mixture percept is clearly heterogeneous, a total taste intensity instruction demands the subject to integrate all specific taste sensations perceived in order to give the appropriate response.

Perceptual integration (primary processes) and decisional separation or integration (secondary processes) are supposed to be independent processes (Ashby and Townsend, 1986). Decisional separation or integration are optional strategies that can be chosen depending on the experimental task, whilst the perceptual processes are considered to be mandatory. It should be noted that the distinction between primary and secondary processes for taste perception research is somewhat artificial, since primary processes will often be confounded with secondary processes. The reaction time differences for several tastants are considerable (0.7 s for NaCl and quinine sulphate; Kuznicki *et al.*, 1983), so that secondary processes can already be operating before all components have been perceived.

Since secondary processes are cognitive and decisional, it is not surprising that they are largely affected by task instructions. Several investigations on taste mixtures have demonstrated that the experimental task influences the degree of analysis of the mixture percept and/or the degree of interaction between the different sensations (e.g. Gregson and McCowen, 1963; Lawless and Schlegel, 1984; Kuznicki and Turner, 1988).

An example of an experiment in which the experimental task influenced the degree of analysis of the mixture percept can be found in O'Mahony *et al.* (1990). In this experiment, one group of subjects were instructed to use combinations of the descriptors 'sweet', 'salty', 'sour', 'bitter', and 'other' in describing percepts resulting from mixed and unmixed stimuli, whilst subjects in a second group were required to describe each stimulus in their own words. In the first group, the number of descriptors more often matched the number of physical stimulus compounds than in the second group. In addition, the number of unique descriptions (descriptions used for one stimulus only) was much larger in the 'unrestricted' group than in the 'restricted' group. These results show that if subjects are not forced to analyze the mixture percept into a limited number of components, an overall descriptor may be used that captures the whole percept in one word.

The mixture percept in multidimensional scaling studies

The nature of the secondary processes involved in taste perception may help to elucidate the seemingly conflicting results concerning the metric structure of the space in which taste stimuli can be represented. The following discussion shows that these results can be brought into agreement, assuming that both 'analytical' task instructions and intensity differences in the stimuli induce an analytical way of stimulus processing. A 'synthetic' task instruction used to investigate equi-intense stimuli will lead to synthetic processing of stimulus information.

The first multidimensional scaling studies with taste stimuli were conducted by Gregson (1965, 1966a) and Russell and Gregson (1966). These authors presented subjects with three- or four- component mixtures and then requested them to judge the similarity with histograms representing these mixtures (cross-modal task) or the similarity with mixtures from the same set (intra-modal task). In these studies, the total intensities and the specific taste intensities varied between stimuli. In addition, the cross-modal task specifically asked for an analysis of the mixture percept in component sensations. When Gregson (1965) fitted his cross-modal data for three-component mixtures in a three-dimensional space, employing a non-metrical multidimensional scaling method, the goodness-of-fit index as given by the value of the Stress decreased with increasing values of r, the parameter of the Minkowski metric. For a two-dimensional space with a Minkowski metric, the distance (d) between stimulus x and the origin is given by:

$$d = (|x_A|^r + |x_B|^r)^{1/r} \qquad \text{(I)}$$

where x_A and x_B denote the coordinates of stimulus x on dimensions A and B respectively. According to Gregson, high r-values imply that 'the largest component in a mixture plays a disproportionately dominant role in determining its similarity with another mixture' (the Dominant Component concept e.g., McBride, 1989). With four-component mixtures, the best fit in a four-dimensional space was obtained when r=6 (Gregson, 1966a). In the study in which subjects had to indicate the degree of difference between the tastes elicited by two three-component mixtures, the three-dimensional solution was also optimal for r=6 (Russell and Gregson, 1966).

In Schiffman and Erickson's (1971) study, subjects were requested to judge the degree of similarity between two solutions of unmixed substances, eliciting about the same total taste intensity. Since the intensity of the experimental stimuli was about equal, judgments were made on the basis of overall quality differences. Schiffman and Erickson found a multidimensional space with an approximate Euclidean metric, a Minkowski metric with r=2.

De Graaf and Frijters (1989) determined the sweetness, saltiness, and total taste intensity of sucrose/NaCl mixtures. In this study, only one type of taste intensity was judged each session. Consequently, attention had to be directed to only one sensation, and every mixture percept had to be analyzed before a judgment could be made. These authors found that the sum of the specific taste sensations is a good approximation of the total taste intensity. These data can be represented in a multidimensional space, by using the formula:

$$d = |x_A| + |x_B| \qquad \text{(II)}$$

where total intensity is represented by the distance d, and the coordinates of stimulus x on dimensions *A* and *B* represent the specific taste intensities elicited by the mixture components. Equation II is identical to the one representing a Minkowski metric with r=1, the so-called 'City-block' metric. This metric is usually found for similarity relationships between analyzable percepts, whilst a Euclidean metric is found for those eliciting homogeneous percepts (Shepard, 1964, 1987).

Summarizing, three different metrical structures (r=1, r=2, and r=6 or more) have been found for multidimensional representations of taste stimuli. The finding of a Euclidean metric (r=2) has been used to argue that taste stimuli are perceived as wholes and that, therefore, the sense of taste functions as a synthetic system (Schiffman and Erickson, 1980). The finding of a City-block metric, however, argues in favour of an analytical sense of taste.

In order to account for these conflicting results, it should be noted that the processes involved in stimulus judgment are mostly optional (decisional separability; Ashby and Townsend, 1986). Melara, Marks, and Lesko (1992) have shown that the metric structure of the multidimensional space describing the relationships between integral, configural, and corresponding stimuli depends on task instructions. If the subjects are instructed to pay attention to the overall similarity between stimuli, a Euclidean metric is found. If subjects are instructed to concentrate on separate stimulus dimensions, a City-block metric underlies the multidimensional space. Therefore, Melara *et al.* concluded that the structure of the similarity space is largely determined by where the subjects focus their attention. Their findings demonstrate that the City-block metric is not unique for analyzable percepts (as stated by Shepard, 1987), but for percepts that are analyzed. In addition, these data show that if a percept is analyzable this does not imply that a stimulus cannot be perceived as a whole. Subjects appear to be able to analyze every multidimensional percept (Lockhead, 1966). Erickson (1977), for example, has shown that colour vision, the classical example of a synthetic sense, can be successfully described with only a few standard terms. Therefore, the metrical structure of a similarity space is not unique for a certain group of stimuli or for a sense modality, but is mainly determined by task instructions.

As noted before, in Schiffman and Erickson's study subjects were not requested to analyze percepts and, therefore, have made similarity judgments on the basis of whole percepts. In Gregson and Russell's studies, subjects were requested to analyze mixture percepts to some degree. As noted above, a multidimensional psychological space based on intensities (analysis only) would imply r=1, whilst a space based on qualitative dissimilarity (unanalyzed percepts only) would imply r=2. Since Gregson's studies involved stimuli differing both with respect to intensity and quality, an r-value between 1 and 2 would be the logical outcome if subjects try to compromise between judgments based on quality and judgments based on intensity. Surprisingly, Gregson (1965) reported that the Stress decreased with increasing values of r, which implies that the solution was optimal for r approaching infinity. Gregson (1966a) and Russell and Gregson (1966) reported an optimal r-value that equalled 6.

In order to account for these findings, it should be noted that Gregson (1965, 1966a) and Russell and Gregson (1966) calculated multidimensional solutions for integer values of r only. Mathematically, r can vary continuously and is not restricted to integer values. Gregson and Russell, however, could not find an optimal solution for $1<r<2$, since they did not calculate any solutions for these r-values.

The metric structure found in Gregson and Russell's studies does not deviate that much from the expected metric as may appear from the obtained r-values. Figure 1 shows isosimilarity contours in multidimensional spaces for three different values of r (Shepard, 1964). For increasing values of r, the isosimilarity contours change from rhombic (r=1), through circular (r=2) and approach the form of a square if r approaches infinity. If the two dimensions of Figure 1A (r=1) are rotated over an angle of 45°, the isosimilarity contours of panel A resemble those of panel C (r=6). A multidimensional space with a City-block metric, therefore, has the same metric structure as a multidimensional space with an infinitely large r-value if the dimensions are freely rotatable, as is the case in Gregson and Russell's studies (Shepard, 1974). Therefore, the multidimensional spaces obtained by Gregson (1965, 1966a) and Russell and Gregson (1966) are similar to the multidimensional space with a City-block metric usually found for analyzed stimuli (Shepard, 1987). Deviations from the City-block metric (r=1) or the Dominance metric ($r \rightarrow \infty$) may be attributed to the fact that the similarity judgments were not based on analytical taste intensity differences only, but may also have included quality differences.

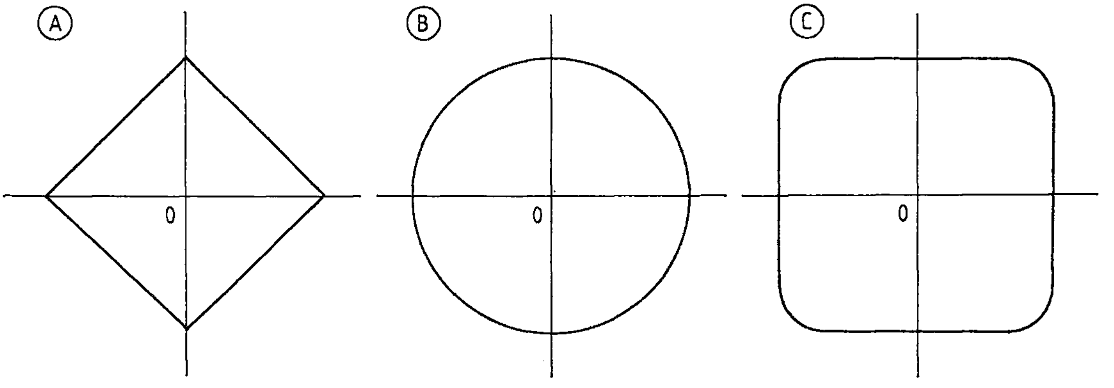

Fig. 1. Isosimilarity contours for three two-dimensional spaces with different Minkowski metrics. Panel A shows the form of the isosimilarity contours in spaces with a City-block metric (r=1), panel B for the Euclidean metric (r=2), and panel C for the metric found by Gregson (1966) and Russell and Gregson (1966) (r=6).

The discussion above concerning the effect of intensity and quality on similarity judgments bears some resemblance to Stevens and Galanter's (1957) distinction between prothetic and metathetic continua. On prothetic continua (e.g. loudness, heaviness, brightness) discrimination is based on additive mechanisms by which excitation is added to excitation. On metathetic continua (e.g. pitch, position) discrimination seems to behave as though based on a substitutive mechanism. The prothetic-metathetic distinction is related to the distinction between quantity and kind. Apparently, in experiments where intensity is not manipulated (metathetic continua, Schiffman and Erickson's experiment) other processes are involved in the judgment processes than in experiments in which the intensity dimension is involved (prothetic continua). During judgment, subjects use all possible cues in order to arrive at a response. If the taste intensity dimension is absent during an experiment, judgments will be based upon taste quality, aftertaste, persistence etc. in order to arrive at a judgment.

Summarizing, it can be stated that, if judgments are based on taste intensity only, the mixture percepts can be represented in a multidimensional psychological space with an approximate City-block or Dominance metric. If subjects do not analyze the percepts, a Euclidean metric is more appropriate. A task requiring a judgment based on qualitative and intensity aspects of the stimuli will yield a space with a metric structure that is a compromise between City-block or Dominance metric and Euclidean.

THE MEASUREMENT OF TASTE INTENSITIES WITHIN THE FRAMEWORK OF FUNCTIONAL MEASUREMENT

De Graaf and Frijters (1989) developed a conceptual framework describing the interrelationships among the physical and psychological intensity variables that play a role in the perception of mixtures of dissimilar tasting substances at suprathreshold concentration levels (Figure 2). Their notation is identical to that proposed by Frijters (1987), and will be used throughout this dissertation. The physical concentration of an unmixed stimulus is denoted by ϕ and the physical concentration of a component in a mixture by Φ. The taste intensities of single substances outside the mixture are denoted by ψ and the taste intensities of the mixture or its components within the mixture are denoted by Ψ. The Roman subscripts *a* and *b* refer to two dissimilar tasting chemicals, while the Greek subscripts α and β refer to the qualities of the specific taste sensations elicited by these two substances. The Greek subscript τ refers to the total taste intensity elicited by a solution. The subscripts *i* and *j* represent particular concentrations of the chemicals *a* and *b* in moles/l.

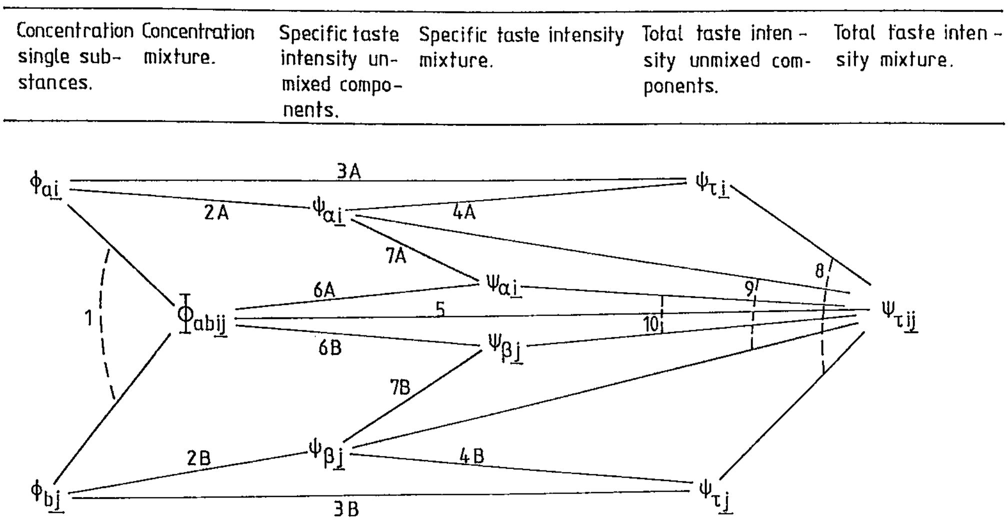

Fig. 2. Outline of interrelationships among concentration levels, perceived specific taste intensities, and perceived total intensities when two qualitatively dissimilar tasting substances are mixed (From De Graaf and Frijters, 1989).

In Figure 2, relation 1 describes the physical mixing of *i* moles A (ϕ_{ai}) and *j* moles B (ϕ_{bj}) to obtain the mixture Φ_{abij}. The lines connecting ϕ_{ai} and $\psi_{\alpha i}$ (2A), and ϕ_{bj} and $\psi_{\beta j}$ (2B), represent the psychophysical functions relating the physical concentrations of the unmixed substances to their corresponding specific taste intensities (e.g., sucrose concentration and sweetness intensity). The psychophysical functions relating stimulus concentrations (ϕ_{ai} and ϕ_{bj}) to total taste intensities ($\psi_{\tau i}$ and $\psi_{\tau j}$) are given by relation 3. Relation 4 relates the specific taste intensity elicited by a stimulus to its total taste intensity. If the substances under investigation elicit no side tastes, this relationship can be described by an identity function ($\psi_{\beta j}=\psi_{\tau j}$).

Each physical mixture Φ_{abij} evokes a total taste intensity $\Psi_{\tau ij}$ (5). In addition, the mixture elicits two specific taste sensations, $\Psi_{\alpha i}$ and $\Psi_{\beta j}$ (6). Relationship 7 gives the connection between the specific taste sensations inside ($\Psi_{\beta j}$) and outside ($\psi_{\beta j}$) the mixture. The total taste intensity of the mixture percept may be related to the total taste intensities (8: $\psi_{\tau i}$ and $\psi_{\tau j}$) or specific taste intensities (9: $\psi_{\alpha i}$ and $\psi_{\beta j}$) of the unmixed components, or to the specific taste intensities of the component sensations within the mixture percept (10: $\Psi_{\alpha i}$ and $\Psi_{\beta j}$).

In the use of the conceptual framework specified in Figure 2, the intensity of each sensation evoked by the mixture ($\Psi_{\alpha i}$, $\Psi_{\beta j}$, and $\Psi_{\tau ij}$) is measured as an attribute of the mixture percept. Relation 10 then investigates how the overall intensity of the mixture is related to the intensities of its component sensations. The specification of this relationship implies that the specific taste sensations are regarded as the elements of a larger construct, the percept. Since the framework is only used to determine the intensities of specific and total taste intensities, the present approach does not take into account that perception may be more than sensation since perception *'includes both a conception of the object perceived and also an immediate and irresistible conviction of the object's present existence'* (Thomas Reid, interpreted by Boring (1942)). In the present context, the mixture percepts result from tasting aqueous solutions of chemicals. Most of these solutions have never been tasted before by the subjects under real-life conditions, and are, therefore, unlikely to be associated to familiar objects. Consequently, the percepts are considered sensory in nature, and a structuralistic view is adopted in which specific taste sensations and total taste intensity are all regarded as attributes of the mixture percept.

A valid description of taste interaction phenomena requires that one scale value is derived for each sensation perceived. This value must represent a taste intensity on an interval or ratio scale. The stimulus-organism-response (S-O-R) paradigm of psychophysical judgment distinguishes between a psychophysical stage relating stimulus to sensation and a judgmental stage relating sensation to response. Whether or not the sensation scale derived from the responses has interval properties, depends on the linearity of the relationship between perceived intensities and overt responses. Since the judgmental operation is irrelevant to the peripheral psychophysical and central psychosensory interactions, a correct description of the sensory processes involved in the perception of taste mixtures can be achieved only by a measurement procedure that separates the sensory processes from the judgmental processes.

In most of the studies presented in this dissertation, taste intensities are assessed using a two-stimulus procedure based on functional measurement (e.g. Anderson, 1974, 1981). This approach was first applied in taste research by Klitzner (1975) in a study on hedonic integration and was introduced in taste mixture research by De Graaf *et al.* (1987). This methodology permits a separation of the sensory from the judgmental processes. After the linearity of the response scale in a particular experiment has been confirmed, scale values for the experimental stimuli can be calculated. These calculated scale values are valid estimates of the perceived taste intensity on an interval scale (Anderson, 1981) and can be regarded as the output from psychophysical and psychosensory processes.

AIM AND STRUCTURE OF THIS DISSERTATION

The present dissertation will try to describe systematically the taste interactions between substances eliciting dissimilar taste qualities using the conceptual framework of Figure 2. Apart from the relationships between concentrations and sensations (relations 2, 3, 5, and 6), the dissertation focuses upon relationships between the psychological constructs involved (relations 7, 8, 9, and 10). In Chapter 2, these relationships are studied for citric acid/sucrose mixtures and in Chapter 3 for quinine hydrochloride/NaCl mixtures. Chapter 5 focuses upon perceptual models that predict the total taste intensity of the mixture percept on the basis of the intensities of the unmixed components (relations 8 and 9) or on the basis of the specific taste intensities within the mixture percept (relation 10).

In addition to an investigation into taste interaction in citric acid/sucrose mixtures, Chapter 2 includes a study concerning the effectiveness of different sweeteners in suppressing citric acid sourness. The findings of this study have implications for the locus of the sourness suppressing mechanism.

Kroeze's (1982a, 1983) habituation paradigm enables a study of central mixture suppression mechanisms. Chapter 4 discusses the outcomes of three sip-and-spit experiments that have attempted to demonstrate the phenomenon of suppression release following repeated presentations of one of the mixture components.

Chapter 3 includes a study that investigates the relationship between the sensitivity to 6-*n*-propylthiouracil (PROP) and the taste perception of KCl, NaCl, and quinine hydrochloride. The ability to detect PROP is determined by hereditary factors and has been related to the perception of bitter and non-bitter substances. The effect of PROP-sensitivity on taste perception was studied in order to be able to decide whether this variable had to be controlled in the subsequent studies. In addition, Chapter 3 includes a methodological comparison between the one- and the two-stimulus procedure. Both these procedures have been applied in the assessment of taste intensities in taste mixture research, and the advantages and disadvantages of both methods are evaluated within the framework of functional measurement.

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Chapter 2

INVESTIGATIONS ON SWEET-SOUR MIXTURES

In this chapter, two studies are reported investigating taste interactions in mixtures of sweeteners with acids. The first study describes the taste interactions between sucrose and citric acid. The second one compares the sourness suppressing efficiency of different sweeteners. The results of this latter study have implications for the locus of the mixture suppression mechanism.

Sensory integration in citric acid/sucrose mixtures.
*Chemical Senses, **15**, 87-109, 1990*

The effectiveness of different sweeteners in suppressing citric acid sourness.
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Sensory integration in citric acid/sucrose mixtures

Hendrik N.J.Schifferstein and Jan E.R.Frijters
Wageningen Agricultural University, Department of Food Science, Bomenweg 2, 6703 HD Wageningen, The Netherlands

Abstract. The scale values of perceived sweetness, sourness and total taste intensity of unmixed sucrose, unmixed citric acid and several citric acid/sucrose mixtures were assessed, using a functional measurement approach in combination with a two-stimulus procedure. The data showed that the scale values obtained were linear with perceived taste intensity. It was demonstrated that citric acid suppresses the sweetness of sucrose and that, inversely, sucrose suppresses the sourness of citric acid. However, this suppressive effect was not symmetrical in the range of concentrations used. While the degree of sweetness suppression depended only on the citric acid level, the degree of sourness suppression depended on the sucrose as well as on the citric acid concentration. With regard to the perceived total taste intensity of citric acid/sucrose mixtures, it was shown that the sum of sweetness and sourness approximately equals the total taste intensity. The implications of the present findings for the analytic–synthetic controversy and for taste interaction theories are discussed.

Introduction

Previous research into taste interaction between sucrose and citric acid has produced some conflicting results, particularly where the sweetness of sucrose/citric acid mixtures at near threshold concentration levels was concerned. Fabian and Blum (1943) carried out a study in which a mixture of a suprathreshold concentration of a primary substance and a subrecognition threshold (but supradetection threshold) concentration of a secondary substance was matched to a series of solutions of suprathreshold concentrations of the primary substance. They reported that subthreshold concentrations of citric acid enhanced the sweetness intensity of sucrose. However, the description of the method they used does not make clear whether their subjects were instructed to judge a specific taste sensation (i.e. sweetness) or the total taste intensity of each stimulus. Pangborn (1960), using a modification of Fabian and Blum's method, reported that subthreshold levels of citric acid have a slightly depressing effect on the sweetness of sucrose. Both studies agreed that subthreshold concentrations of sucrose suppressed the sourness of citric acid.

Kamen *et al.* (1961) instructed their subjects to rate the sweetness and sourness of several citric acid/sucrose mixtures (threshold and suprathreshold concentrations) on a nine-point rating scale. They concluded that the addition of citric acid generally increased sweetness intensity. Pangborn (1961) repeated their investigation, but in contrast to Kamen *et al.*, she found that increasing quantities of citric acid generally decreased the sweetness intensity of sucrose. The solutions containing 0.007% (0.00036 M) citric acid were, however, given a higher sweetness rating than the control stimuli that contained no acid. This enhancing effect was not found when stimuli were presented in pairs instead of being presented individually. Both studies agreed that sucrose suppresses the sourness intensity of citric acid.

Gregson and McCowen (1963) studied the influence of experimental procedure on the perception of mixtures of threshold concentrations of sucrose and citric acid. They observed that sweetness and sourness can be both enhanced and suppressed. They concluded that 'in the near-threshold range of stimulus intensities, perceptual processes are as important as the stimulus identities or intensities themselves in determining what subjects will say they can taste in a mixture'.

Almost all the studies published since Gregson and McCowen agree that suprathreshold concentrations of citric acid suppress the sweetness intensity of sucrose (Pangborn and Chrisp, 1964; Pangborn and Trabue, 1964; Gordon, 1965; Pangborn, 1965; Frank and Archambo, 1986; McBride and Johnson, 1987; McBride, 1989; McBride and Finlay, 1989). Inversely, sucrose suppresses the sourness intensity of citric acid (Pangborn and Chrisp, 1964; Pangborn and Trabue, 1964; Curtis and Stevens, 1984; Frank and Archambo, 1986; McBride and Johnson, 1987; McBride, 1989; McBride and Finlay, 1989). Curtis and Stevens (1984) have additionally reported that the sweetness of sucrose/citric acid mixtures depends on the sucrose concentration only and not on the citric acid concentration, an effect not found in the other studies previously mentioned.

The total taste intensity of the mixture is usually higher than the sourness or the sweetness of the unmixed components. On the basis of a factorial plot comparison it has been claimed that sucrose and citric acid suppress each other's taste intensity (Curtis and Stevens, 1984; Frank and Archambo, 1986; McBride and Johnson, 1987; McBride, 1989; McBride and Finlay, 1989).

The present study was designed to investigate a number of specific relationships between the sweetness, sourness and total taste intensity of sucrose, citric acid and citric acid/sucrose mixtures. The procedure followed is similar to that of De Graaf and Frijters (1989), who investigated the taste interaction between sucrose and NaCl. The conceptual framework specifying these relationships is illustrated in Figure 1. For a detailed discussion of this framework, the reader is referred to De Graaf and Frijters (1989).

The notation used in the present paper is identical to that proposed by Frijters (1987).

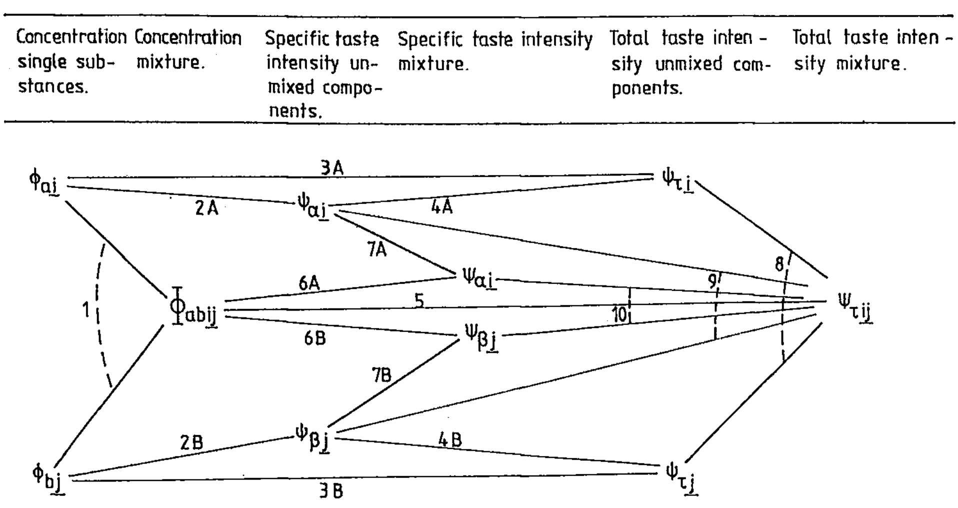

Fig. 1. Outline of interrelationships among perceived specific and total taste intensities when two qualitatively dissimilar taste substances are mixed. In the present context specific taste intensity refers to sweetness and/or sourness of sucrose, citric acid and citric acid/sucrose mixtures. (From De Graaf and Frijters, 1989.)

The physical concentration of an unmixed stimulus is denoted by ϕ and the physical concentration of a component in a mixture by Φ. The taste intensities of single substances outside the mixture are denoted by ψ and the taste intensities of the mixture or the compounds within the mixture are denoted by Ψ. The subscripts a and b refer to the chemicals sucrose and citric acid, while the subscripts α, β and τ refer to the sensations of 'sweetness', 'sourness' and 'total taste intensity' respectively. The subscripts i and j represent particular concentrations of sucrose and citric acid in mol/l.

A proper description of taste interaction phenomena requires that one scale value is derived for each stimulus presented. This value must represent a taste intensity on an interval or ratio scale. Whether or not the scale derived has interval properties depends on the assumption that the overt responses vary linearly with differences in perceived intensity (De Graaf *et al.*, 1987; De Graaf and Frijters, 1988).

The methodology used in the present investigation provides a tool to test whether this assumption is correct. It is based on a functional measurement paradigm in combination with a two-stimulus task (Anderson, 1974; Birnbaum, 1982). This framework permits a simultaneous evaluation of two cognitive processes. The first one is the comparison operation performed by the subjects on the basis of sensations elicited by two stimuli. The second one is the judgemental process that transforms the subject's impression into an observable response.

In the experimental procedure subjects were instructed to judge the magnitude of the difference between the perceived taste intensity of each 'row' (first) stimulus and each 'column' (second) stimulus. This type of design is called a *factorial judgement design* (De Graaf *et al.*, 1987; De Graaf and Frijters, 1988). Subjects perform a subtractive operation when they are instructed to judge a difference. The subtractive model predicts no interaction between row and column stimuli, assuming that the response scale is linear (e.g. Birnbaum, 1978; Birnbaum and Mellers, 1978). Therefore, testing the row $\times$ column interaction for significance provides the basis for testing the linearity of the response scale.

The linearity of the response scale is independent of the kind of taste interaction that has occurred or the shape of the psychophysical functions. For the assessment of taste interactions mixtures can be physically composed according to a *factorial mixing design* (McBride, 1986; De Graaf *et al.*, 1987). In a factorial mixing design each of a number of concentrations of one component is mixed with each of a number of concentrations of the other component. The term *factorial mixing design* refers to the physical composition of mixtures and should not be confused with the term *factorial judgement design* which refers to the presentation of pairs of (mixed and unmixed) stimuli to the subjects (De Graaf and Frijters, 1988).

Materials and methods

The study consisted of three similarly designed investigations. The first one assessed sweetness, the second one assessed sourness and the third assessed the total taste intensity of sucrose, citric acid and citric acid/sucrose mixtures (De Graaf and Frijters, 1989).

Subjects

Thirteen paid volunteers, nine women and four men, ranging in age from 20 to 38 years, served as subjects. They were students of the Agricultural University, Wageningen. All subjects had previous experience with psychophysical scaling experiments.

Stimuli

The stimuli were sucrose (Merck 7651), citric acid (Merck 244) and mixtures of these substances in demineralized water. Figure 2(A) shows the concentrations and composition of the experimental stimuli. The concentrations of the unmixed sucrose solutions were 0.00 (water), 0.125, 0.250, 0.500 and 1.000 M sucrose. For citric acid these were 0.00 (water), 0.00125, 0.0025, 0.005 and 0.010 M citric acid. The mixtures were constructed on the basis of a factorial mixing design. Each of the sucrose

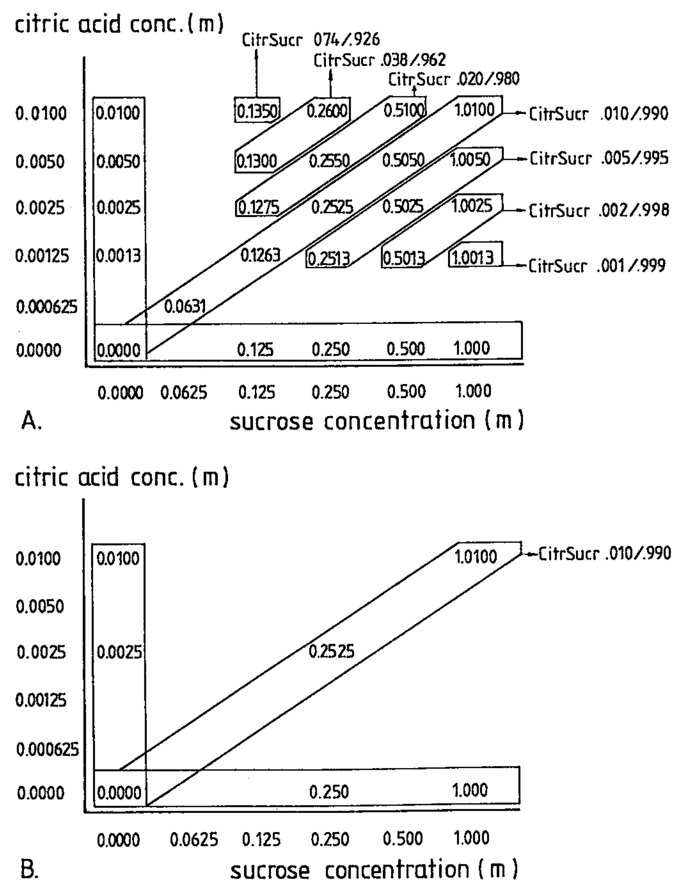

Fig. 2. (A) The total concentration and composition of the nine series of experimental stimuli. The series of unmixed sucrose, unmixed citric acid and the seven different equiratio mixture types are surrounded by solid lines. Water was included in each of the nine series. This is shown only for the series of unmixed sucrose, unmixed citric acid and the CitrSucr 0.010/0.990 equiratio mixture type. (B) The concentration and composition of the three series of stimuli to which each of the series of stimuli in (A) were compared. In the sweetness investigation the series in (A) were compared to the series of sucrose stimuli in (B). In the sourness investigation and the total taste intensity investigation each series in (A) was compared to the series of unmixed citric acid and the series of CitrSucr 0.010/0.900 equiratio mixtures in (B) respectively.

concentrations were mixed with each of the citric acid concentrations. In addition, a solution containing 0.000625 M citric acid and 0.0625 M sucrose was prepared.

For reasons of standardization, subjects were presented with reference pairs. The first stimulus of the reference pair was water in all three investigations. The second stimulus of the reference pair was 1.25 M sucrose in the 'sweetness' investigation, 0.0125 M citric acid in the 'sourness' investigation, and 2.2725 M of the CitrSucr 0.010/0.990 equiratio mixture (a mixture containing 0.0225 M citric acid and 2.25 M sucrose) in the 'total taste intensity' investigation.

Solutions were prepared at least 24 h before tasting and were stored at 4°C for no longer than 1 week.

Design

Since the designs for the 'sweetness', 'sourness' and 'total taste intensity' investigations are similar, the three investigations will be discussed simultaneously. Attention will be drawn to any specific differences.

The three investigations consisted of 18 experiments each. Every experiment was based on one factorial judgement design. A factorial judgement design implies that the subjects are presented with pairs of stimuli that originate from combining all stimuli from a series of first stimuli with all stimuli from a series of second stimuli. One possible way to construct an ordered series of mixtures is to use the concept of the *equiratio mixture type* (Frijters and Oude Ophuis, 1983). These mixtures have different total concentrations but a constant ratio of concentrations of constituent components (in mol/l). For example, a mixture of 0.005 M citric acid and 0.25 M sucrose, and a mixture of 0.010 M citric acid and 0.50 M sucrose both have the same concentration ratio (0.005/0.25 = 0.010/0.50), but they differ with respect to their total concentrations (i.e. 0.255 M and 0.510 M respectively).

In order to incorporate all the experimental stimuli in factorial judgement designs, nine series of stimuli were constructed, two series of single substances (sucrose and citric acid) and seven series of citric acid/sucrose equiratio mixtures (CitrSucr 0.074/0.926, 0.038/0.962, 0.020/0.980, 0.010/0.990, 0.005/0.995, 0.002/0.998, 0.001/0.999). These series are surrounded by solid lines in Figure 2(A). Water, which is the 0.00 M solution of each stimulus type, was included in each of the series.

In the 'sweetness' investigation each stimulus of each of the nine series of experimental stimuli was compared with three sucrose solutions: 0.00, 0.250 and 1.000 M sucrose (Figure 2B). Similarly, in the 'sourness' investigation each stimulus of each series was compared to 0.00, 0.0025 and 0.010 M citric acid, and in the 'total taste intensity' investigation each stimulus of each series was compared to 0.00, 0.2525 and 1.010 M of the CitrSucr 0.010/0.990 equiratio mixture type. In nine experiments the three comparison stimuli were presented as first stimuli; in nine other experiments they served as second stimuli.

In summary, the total study consisted of 54 experiments (three investigations of 18 experiments each). In every experiment each stimulus of one of the nine series of stimuli from Figure 2(A) was compared to each stimulus of one of the three series of comparison stimuli from Figure 2(B).

Procedure

Except for the instructions and response scale, the experimental procedure in each of the three investigations was similar. Only the experimental procedure for the 'sweetness' investigation is described and specific differences with the designs of the other investigations will be mentioned.

The subjects were instructed to judge the magnitude of the difference in perceived sweetness intensities (sourness, total taste intensity) between the first and second stimulus of each pair. The instructions emphasized that only the sweetness (sourness) intensity was to be judged and that the hedonic value and side tastes were to be disregarded. In the 'total taste intensity' investigation, subjects were instructed to judge the total taste intensity, irrespective of quality, and to include every quality they perceived.

The judgements 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' (sourness, total taste intensity) (De Graaf *et al.*, 1987; Figure 3). If the first stimulus was perceived as tasting sweeter (sourer, more intense) than the second stimulus, the subject placed a mark on the left side of the scale depending on the magnitude of the difference. The subject marked the right side of the scale when the second stimulus was perceived as being sweeter (sourer, more intense). The left end and the right end of the scale were labelled 'maximum difference'. In the instructions 'maximum difference' was defined as the difference in sweetness intensity (sourness, total taste intensity) between the stimuli of the reference pair, i.e. water as first stimulus and 1.25 M sucrose (0.0125 M citric acid, 2.2725 M CitrSuc 0.010/0.990) 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 >125 meant that the second stimulus was perceived as sweeter (sourer, having a higher total taste intensity) than the first one, and a value <125 indicated that the first stimulus was perceived as the sweetest (the sourest, 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 in polystyrene medicine cups. Each cup contained ± 10 ml of solution. The pairs 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, 24th and 36th pair of each session. The time interval between and within pairs was 40 s. Each of the 18 factorial judgement designs of every investigation were presented to each subject twice. The 18 experiments of each investigation were presented randomly. It took each subject 10 1-h sessions to complete each investigation so that 30 sessions were needed to complete the entire study.

Results

To quantify the relationships between sweetness, sourness and total taste intensity of each of the experimental stimuli, three separate scale values had to be derived. A procedure recently developed by De Graaf *et al.* (1987) and De Graaf and Frijters (1988) was applied to the present data. A brief outline of the psychometric properties of the response scale and an explanation of how scale values were derived is given in the next section.

Psychometric properties of response scale and derivation of scale values

The subjects were instructed to judge the difference between the perceived taste intensities within each pair of stimuli. Parallelism in a factorial judgement plot implies that the response function is linear with the perceived difference. Because individuals may vary in their judgement functions (linear or non-linear), or in their comparative operations (which may or may not be subtractive), individual analyses were performed first. The measure of the degree of non-parallelism, the row × column (first stimulus × second stimulus) interaction, was tested in an analysis of variance for statistical significance with the row × column × replicate interaction as an error term. At first, individual analyses were performed (54 experiments × 13 subjects = 702 analyses). Depending on the specified alpha level, 11 ($P < 0.01$), 37 ($P < 0.05$) or 78 ($P < 0.10$) row × column interactions were found to be significant. None of the subjects had more than two significant interactions at the $P < 0.01$ level. Averaged over subjects, experiments and investigations, the row × column interaction contained no more than 2.78% of the total sum of squares.

On group level, the row × column interaction was tested for significance against the row × column × subject interaction for each of the 54 factorial judgement designs. The interaction appeared to be significant in two ($P < 0.01$), three ($P < 0.05$) or five ($P < 0.10$) cases. The mean percentage of total sum of squares located in the row × column interaction was 0.22%.

The number of significant interactions deviates only slightly from the number that may be expected to reach significance given this number of analyses and the specified alpha levels. It can be concluded, therefore, that possible deviations from parallelism do not have a substantive effect on the scale values that are obtained. It is concluded that the assumptions concerning the subtractive comparative operation and the linear judgement function were met. Consequently, the marginal means of the row and column stimuli are considered to be valid estimates of the perceived taste intensity on an interval scale (Anderson, 1981).

If it is assumed that water has no taste, then scale values can be derived for each of the experimental stimuli by calculating the difference between the marginal mean for the experimental stimulus and the marginal mean for water in each of the 54 experiments. The final scale value for each stimulus was calculated by averaging the scale value for that stimulus tasted as first stimulus of each pair and the scale value when tasted as second stimulus of each pair. All data were averaged over subjects and replicates.

The sweetness of sucrose and the sourness of citric acid

Figure 3(A) and (B) shows the psychophysical functions for the sweetness of sucrose and the sourness of citric acid on a linear plot. These functions appear to be negatively accelerating for the whole range of concentrations.

It should be noted that the unit of the sweetness scale is not necessarily equal to the unit on the sourness scale. The unit on each scale depends on the taste intensity difference within the reference pair, which is different for each of the three investigations.

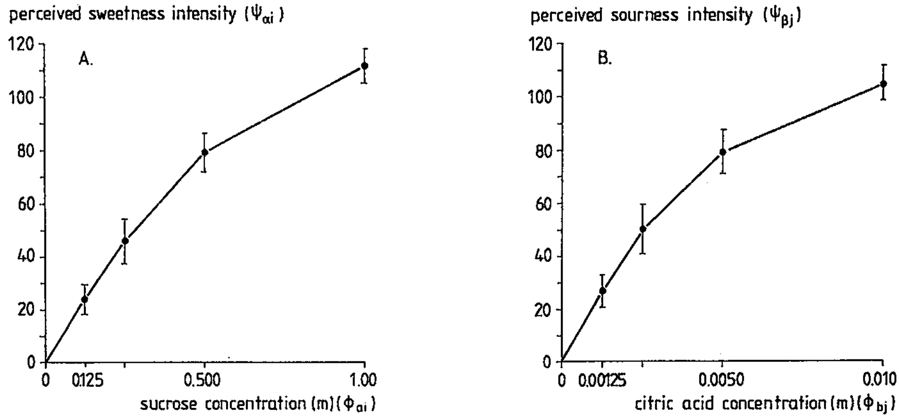

Fig. 3. (**A**) The psychophysical function for the sweetness of sucrose. (**B**) The psychophysical function for the sourness of citric acid. The error bars around each point represent the 95% confidence interval for each scale value. The units of the 'sweetness' scale and the 'sourness' scale are not equal.

Sweetness of sucrose and sourness of citric acid compared to the sweetness and sourness of citric acid/sucrose mixtures

Figure 4(A) shows the sweetness of sucrose, citric acid and the mixtures as a function of the sweetness of sucrose, with a separate function for each citric acid concentration. Visual inspection shows that the sweetness intensities of citric acid/sucrose mixtures are lower than the sweetness intensities of unmixed sucrose. The influence of the citric acid concentration on the suppression of the sweetness intensity of sucrose seems minimal. The four functions for the citric acid/sucrose mixtures differ only slightly and show several cross-overs. ANOVA of these results showed significant effects for sucrose [$F(4,48) = 264.23$, $P < 0.001$], citric acid [$F(4,48) = 12.73$, $P < 0.001$] and the sucrose × citric acid interaction [$F(16,192) = 2.14$, $P < 0.01$]. However, if the responses to the unmixed sucrose are omitted, the statistical significance of the sucrose × citric acid interaction disappears [$F(12,144) = 1.33$, $P > 0.1$]. These results suggest that the four mixture functions differ significantly but do not converge or diverge. The degree of suppression of the sweetness intensity appears to be independent of the sucrose concentration.

Figure 4(B) shows the sourness of citric acid, sucrose and citric acid/sucrose mixtures as a function of the sourness of citric acid. Visual inspection shows a diverging pattern of functions in which a higher concentration of sucrose obviously produces a greater sourness suppressing effect. In addition, the citric acid concentration influences the sourness and the degree of suppression. ANOVA shows statistically significant effects for citric acid [$F(4,48) = 144.74$, $P < 0.001$], sucrose [$F(4,48) = 100.65$, $P < 0.001$] an the sucrose × citric acid interaction [$F(16,192) = 18.26$, $P < 0.001$]. If the responses to the unmixed citric acid are omitted, all these effects remain significant ($P < 0.001$).

Total taste intensity of sucrose, citric acid and citric acid/sucrose mixtures

The nature of the taste interaction that occurs in taste mixtures depends to some degree on the form of the psychophysical functions of the mixture's components. If a substance

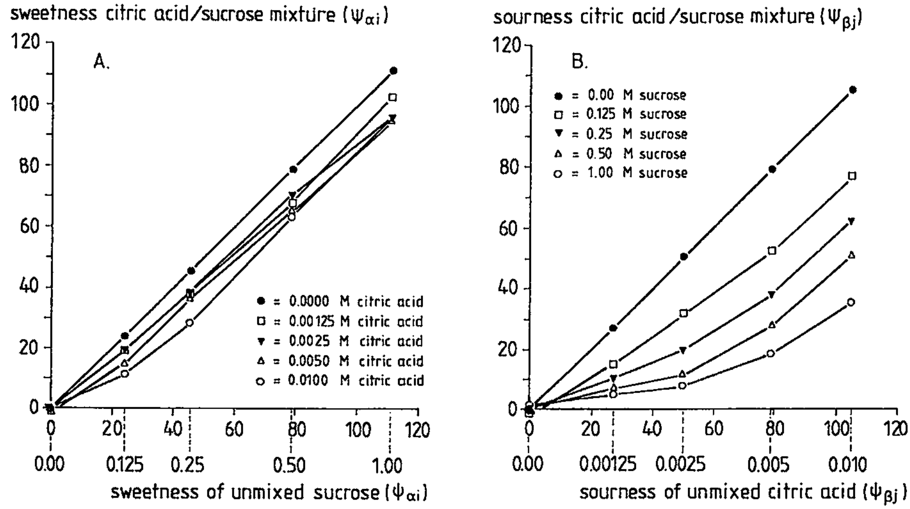

Fig. 4. (A) The sweetness intensity of sucrose, citric acid and the citric acid/sucrose mixtures as a function of the sweetness of sucrose with a separate curve for each citric acid concentration. (B) The sourness of citric acid, sucrose and the citric acid/sucrose mixtures as a function of the sourness of citric acid with a separate curve for each sucrose concentration. The units of the 'sweetness' scale and the 'sourness' scale are not equal.

produces a negatively accelerating psychophysical function, then a mixture of the substance with itself will show suppression. If this substance is mixed with a substance that has a similarly shaped psychophysical function and the same taste quality, then it might seem as if these substances show suppression, even if they elicit taste intensities that are additive (Bartoshuk, 1975; Bartoshuk and Cleveland, 1977). A proper description of the taste interaction *between* the two components of a mixture can be obtained only by separating it from the apparent taste interactions *within* the unmixed substances. Therefore, 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 (De Graaf and Frijters, 1988).

Figure 5 shows the total taste intensity of the experimental stimuli as a function of the total taste intensity of unmixed sucrose, with a separate curve for each concentration of citric acid. The curves show a convergent pattern where, in some cases, the total taste intensity of a mixture falls below the total taste intensity of unmixed sucrose. This is caused by the high degree to which the two substances suppress each other. ANOVA shows significant effects for sucrose [$F(4,48) = 61.53$, $P < 0.001$], citric acid [$F(4,48) = 134.26$, $P < 0.001$] and the sucrose × citric acid interaction [$F(16,192) = 24.21$, $P < 0.001$].

In order to obtain factorial plots for the apparent within-substance interactions, several scale values had to be estimated by interpolation because these had not been determined experimentally. The intensities of 0.375, 0.625, 0.75, 1.125, 1.25, 1.5 and 2.0 M sucrose and the intensities of 0.00375, 0.00625, 0.0075, 0.01125, 0.0125, 0.015 and 0.02 M citric acid were estimated by using second-order polynomials, in which the natural logarithm of the concentration and its squared value were the independent

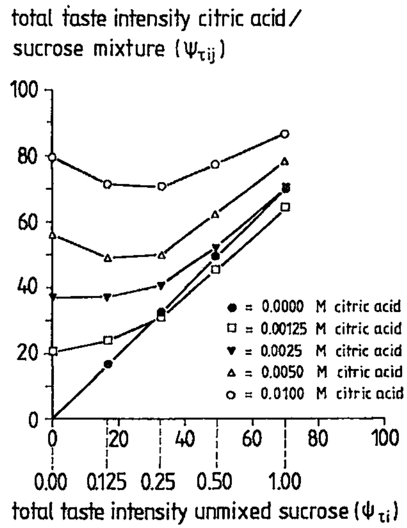

Fig. 5. The factorial plot comparison: the total taste intensity of sucrose, citric acid and the citric acid/sucrose mixtures as a function of the total taste intensity of sucrose, with a separate curve for each citric acid concentration.

variables and the natural logarithm of the obtained scale values was the dependent variable (De Graaf and Frijters, 1988). In view of the goodness of fit (the sucrose function had an R^2 of 0.9989, and that of citric acid had an R^2 of 0.9994) of the calculated polynomials, these were considered to be appropriate for the estimation of the intensities required.

Figure 6(A) and (B) shows the apparent taste interactions within sucrose and within citric acid. The solid points represent experimentally determined scale values, and the open circles are calculated estimates. Both panels show a set of converging lines, implying that the apparent taste interactions within both substances are suppressive at all concentration levels. Unfortunately there is no statistical criterion available for testing whether the degree of convergence in Figure 5 is significantly different from the degree of convergence in Figure 6. Visual inspection of the two figures reveals, however, that the convergence in Figure 5 is much more pronounced than the convergence in Figure 6. This implies that the taste interaction between sucrose and citric acid cannot be explained by the apparent taste interactions within the unmixed substances.

Figure 7 shows the relationship between the total taste intensities of the mixtures and the sums of the total taste intensities of its unmixed components according to the summated response comparison rule. From this figure it is evident that the total intensity of the mixture is always less than the sum of the total taste intensities of the unmixed components.

The summated response comparison for the unmixed substances (Figure 8A and B) exhibits a similar pattern. However, the points in Figure 7 systematically lie lower than the points in Figure 8. This analysis shows that the between-substances taste interaction exhibits a greater magnitude and frequency of suppression than do the within-substance taste interactions.

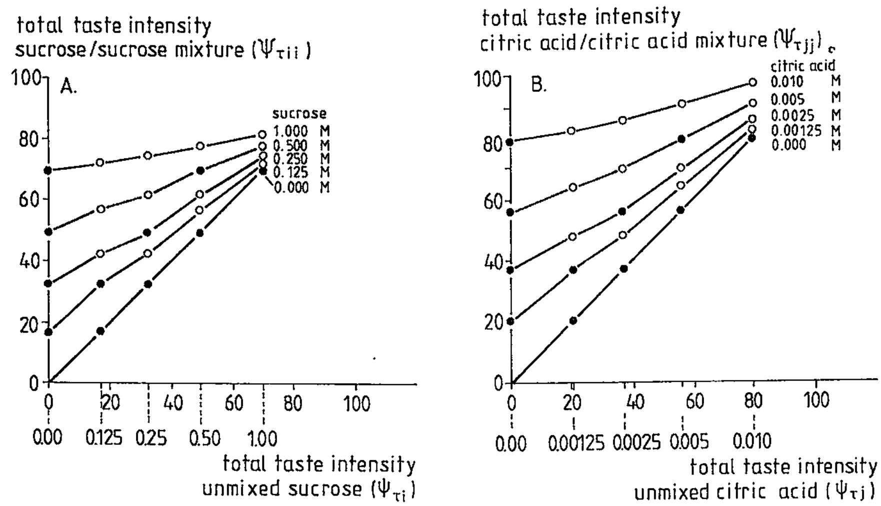

Fig. 6. Factorial plots for the apparent taste interactions within sucrose and within citric acid. In these plots the single substances are conceived as a mixture of the substance with itself. (**A**) Perceived total taste intensities of sucrose/sucrose 'mixtures' plotted as a function of the total taste intensity of 'unmixed' sucrose with a separate curve for each sucrose concentration that was 'added'. (**B**) Total taste intensities of citric acid/citric acid 'mixtures' plotted as a function of the total taste intensity of 'unmixed' citric acid with a separate curve for each 'added' citric acid concentration. The closed circles represent scale values obtained experimentally and the open circles represent scale values that were estimated by polynomial regression equations.

Frank and 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:

$$\Psi_{Tij} = (\psi_{Ti}^2 + \psi_{Tj}^2 + 2\psi_{Ti}\psi_{Tj} \cos \alpha)^{0.5} \tag{1}$$

where α represents the angle between the sucrose intensity and the citric acid intensity (both represented as a vector). This angle is supposed to reflect the degree of dissimilarity between the two taste qualities. In the present study this angle was estimated by orthogonal linear regression through the origin (Hampton, 1983), using the formula:

$$\Psi_{Tij}^2 - \psi_{Ti}^2 - \psi_{Tj}^2 = \cos \alpha(2\psi_{Ti}\psi_{Tj}) \tag{2}$$

and yielded a value of 110° ($R^2 = 0.956$), which agrees well with the value reported by Frank and Archambo ($\alpha = 115°$). Since $\alpha = 0°$ implies that two substances show complete addition and $\alpha = 180°$ means that they show complete subtraction, it can be concluded from this result that sucrose and citric acid exhibit a substantial amount of mixture suppression. It should be noted, however, that the use of the vector summation model to describe the relationship between the total taste intensity of a mixture and the total taste intensities of its components may not be justified, since this model was originally designed for homogeneous percepts.

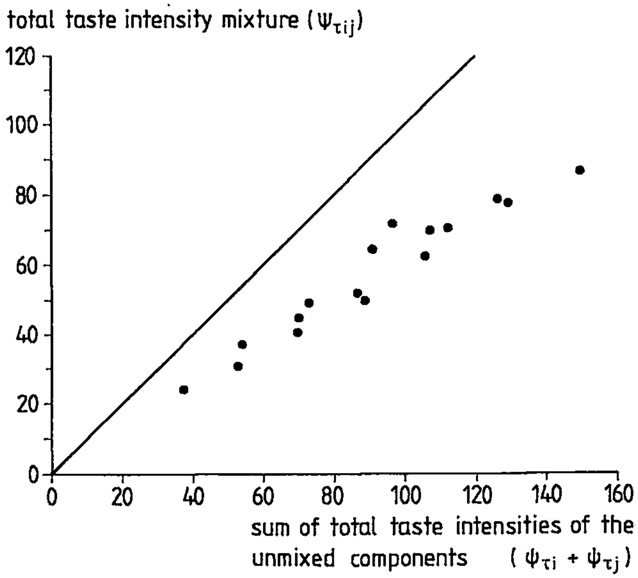

Fig. 7. The summated response comparison: the relationship between the total taste intensity of citric acid/sucrose mixtures and the sum of the total taste intensities of its unmixed components.

To summarize, taste interaction between sucrose and citric acid cannot be totally explained by the apparent taste interactions within the single substances themselves. Sucrose and citric acid suppress each other's taste intensity when they are mixed.

Sweetness and total taste intensity of sucrose and sourness and total taste intensity of citric acid

Figure 9(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. The scale values on these two scales seem to differ by a multiplicative constant only. Orthogonal linear regression through the origin yielded a value of 0.65, with an R^2 value of 0.95 for the fitted line. It appears that the total taste intensity of sucrose does not differ from its sweetness intensity.

Figure 9(B) shows the relationship between the scale values of citric acid on the 'sourness' scale and the scale values of citric acid on the 'total taste intensity' scale. In this case orthogonal linear regression yielded a multiplicative constant of 0.75, with an R^2 value of 0.92. It seems that only the sourness intensity determines the total taste intensity of citric acid.

The above reasoning would be incorrect only if sucrose or citric acid elicit side tastes that are a constant fraction of the specific taste intensity (sweetness or sourness). It is assumed that this is not the case.

Sweetness intensity and sourness intensity of sucrose, citric acid and citric acid/sucrose mixtures in relation to their total taste intensity

By multiplying the scale values on the 'sweetness' scale by 0.65 and multiplying the scale values on the 'sourness' scale by 0.75, equivalent units of sweetness, sourness

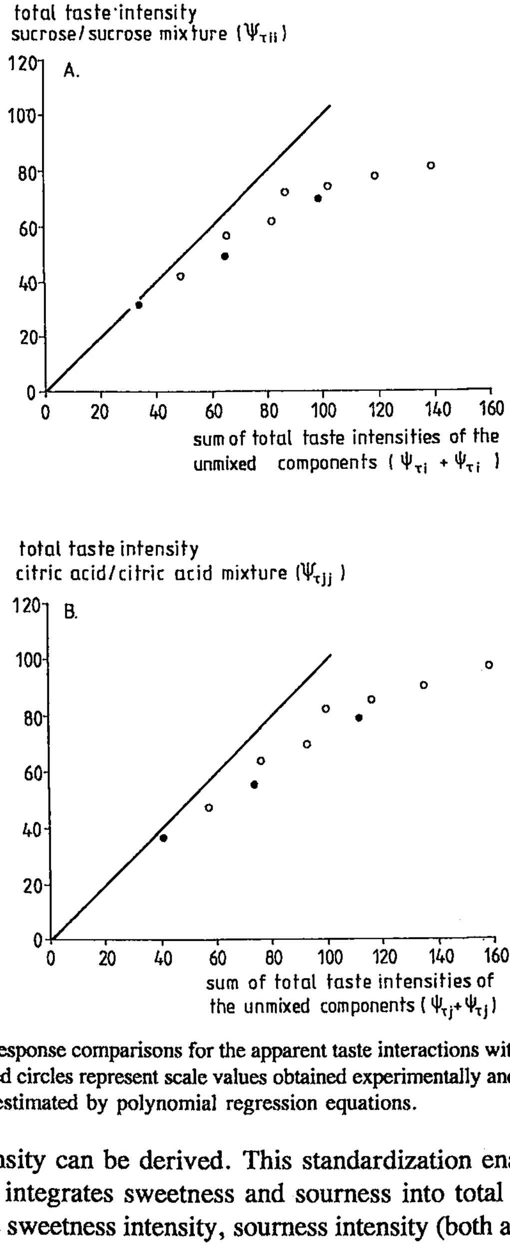

Fig. 8. The summated response comparisons for the apparent taste interactions within sucrose (A) and within citric acid (B). The closed circles represent scale values obtained experimentally and the open circles represent scale values that were estimated by polynomial regression equations.

and total taste intensity can be derived. This standardization enables a further study of the process that integrates sweetness and sourness into total taste intensity.

Table I shows the sweetness intensity, sourness intensity (both after standardization), the sum of these two and the total taste intensity of the experimental stimuli. The sum of sweetness and sourness appears to be a good approximation of the total taste intensity (Pearson $r = 0.992$). Multiple linear regression through the origin, with the sweetness and sourness as independent variables, yields the regression equation:

$$\Psi_{\tau ij} = 0.95\ \Psi_{\alpha i} + 1.07\ \Psi_{\beta j} \tag{3}$$

having an R^2 of 0.998. This implies that sweetness and sourness have about equal weights in determining total taste intensity.

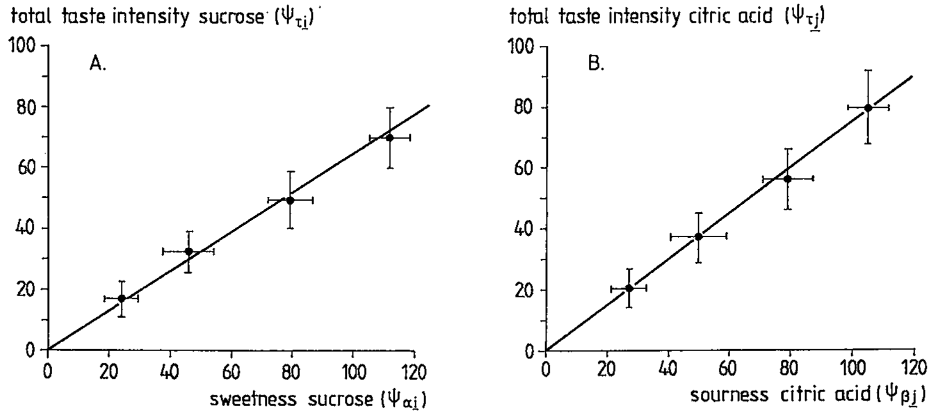

Fig. 9. (**A**) The relationship between the sweetness and total taste intensity of sucrose. (**B**) The relationship between the sourness and total taste intensity of citric acid. The straight lines were obtained by linear orthogonal regression through the origin. The error bars parallel with the ordinate represent the 95% confidence interval for the scale values of the total taste intensity. The error bars parallel with the abscissa represent the 95% confidence intervals for the scale values of sweetness and sourness respectively.

The sweetness and the sourness of a citric acid/sucrose mixture may be represented by two vectors. If these two vectors are summated, the resultant vector represents the total taste intensity. The angle between the two vectors is assumed to be related to the difference in importance of the two specific taste sensations in determining the total taste percept. This model can be described by the following equation:

$$\Psi_{\tau ij} = (\Psi^2_{\alpha i} + \Psi^2_{\beta j} + 2\Psi_{\alpha i}\Psi_{\beta j}\cos\alpha)^{0.5} \qquad (4)$$

This vector summation model is different from the model proposed by Berglund *et al.* (1973) because it is not the total taste intensities of the unmixed components ($\psi_{\tau i}$ and $\psi_{\tau j}$) but the specific taste intensities of the components within the mixture ($\Psi_{\alpha i}$ and $\Psi_{\beta j}$) that determine the total taste intensity of the mixture. Fitting equation (4) to the present data using orthogonal linear regression through the origin yields $\cos\alpha = 1.0$ ($R^2 = 0.922$). From this result it follows that the angle between the sourness intensity and the sweetness intensity is equal to 0°, which implies that sourness intensity and sweetness intensity add together to form the total taste intensity.

Discussion

The taste interaction between sucrose and citric acid

In citric acid/sucrose mixtures, each of the two components influence the perceived taste intensity of the other component. These effects do not appear to be symmetrical, however (Figure 4A and B). The degree of sweetness suppression depends only on the citric acid concentration, while the degree of sourness suppression depends both on the sucrose concentration and the citric acid concentration.

Tables II(A)–(C) give an overview of the outcomes of other studies reporting the

Table I. Sweetness, sourness, the sum of sweetness and sourness, and the total taste intensity of sucrose, citric acid and citric acid/sucrose mixtures

Sucrose conc. (M)	Citric acid conc. (M)	Sweetness intensity	Sourness intensity	Sum of sweetness and sourness intensity	Total taste intensity
0.000	0.00000	0.00	0.00	0.00	0.00
0.000	0.00125	0.45	20.33	20.78	20.53
0.000	0.00250	0.44	37.72	38.17	36.96
0.000	0.00500	−0.59	59.48	58.89	55.97
0.000	0.01000	−0.15	79.00	78.85	79.49
0.125	0.00000	15.51	−0.49	15.02	16.79
0.125	0.00125	12.62	11.14	23.75	24.23
0.125	0.00250	12.53	23.95	36.48	37.33
0.125	0.00500	9.93	39.25	49.18	49.34
0.125	0.01000	7.45	57.71	65.16	71.47
0.250	0.00000	29.68	0.20	29.88	32.37
0.250	0.00125	24.96	7.88	32.84	30.82
0.250	0.00250	25.04	14.91	39.95	40.78
0.250	0.00500	24.32	28.68	52.99	50.12
0.250	0.01000	18.54	46.90	65.44	70.59
0.500	0.00000	51.41	−0.58	50.83	49.40
0.500	0.00125	44.26	5.12	49.38	45.03
0.500	0.00250	45.98	9.04	55.02	51.78
0.500	0.00500	42.55	20.99	63.54	62.26
0.500	0.01000	41.46	38.26	79.72	77.47
1.000	0.00000	72.52	1.09	73.60	69.99
1.000	0.00125	66.83	3.87	70.71	64.24
1.000	0.00250	62.24	5.84	68.09	69.83
1.000	0.00500	61.82	13.86	75.67	78.52
1.000	0.01000	62.18	26.61	88.79	86.63

results of ANOVA in order to demonstrate the effects of one component on the taste intensity of the other component. The results of Pangborn and Chrisp (1964) and Pangborn and Trabue (1964) seem to deviate from the results of the other studies. It should be noted that these studies were not carried out in aqueous solution or in fruit juice but in canned tomato juice and in lima bean purée respectively. Furthermore, these investigators added only very small amounts of sucrose to their stimuli, up to 1.6 and 2.4% (w/v) respectively. If the results of these two studies are not taken into account, it can be concluded from these tables that: (i) the main effects are significant for the 'sweetness', 'sourness' and 'total taste intensity' judgements; (ii) the sucrose × citric acid interaction is significant for the 'sourness' and 'total taste intensity' judgements, but not for the 'sweetness' intensity judgements in some studies.

These results are in line with the results of the present study. They seem to demonstrate two different suppression phenomena. With regard to sweetness suppression, there seems to be a kind of 'maximum degree of suppression' for each citric acid concentration.

Table II(A). Summary of the results of ANOVA in previous research into the effect of citric acid upon the sweetness of sucrose in citric acid/sucrose mixtures

Effect	Significant	Not significant
Citric acid	Pangborn (1961) Pangborn and Chrisp (1964) Pangborn and Trabue (1964) Pangborn (1965) Gordon (1965) Frank and Archambo (1986) McBride and Johnson (1987) McBride (1989) McBride and Finlay (1989)	Curtis and Stevens (1984)
Sucrose	Pangborn (1961) Pangborn (1965) Gordon (1965) Curtis and Stevens (1984) Frank and Archambo (1986) McBride and Johnson (1987) McBride (1989) McBride and Finlay (1989)	Pangborn and Chrisp (1964) Pangborn and Trabue (1964)
Citric acid × sucrose	Pangborn and Chrisp (1964) Pangborn and Trabue (1964) Frank and Archambo (1986) McBride (1989) McBride and Finlay (1989)	Pangborn (1961) Pangborn (1965) Gordon (1965) Curtis and Stevens (1984) McBride and Johnson (1987)

Table II(B). Summary of the results of ANOVA in previous research into the effects of sucrose upon the sourness of citric acid in citric acid/sucrose mixtures

Effect	Significant	Not significant
Citric acid	Curtis and Stevens (1984) Frank and Archambo (1986) McBride and Johnson (1987) McBride (1989) McBride and Finlay (1989)	Pangborn and Chrisp (1964) Pangborn and Trabue (1964)
Sucrose	Pangborn and Chrisp (1964) Pangborn and Trabue (1964) Curtis and Stevens (1984) Frank and Archambo (1986) McBride and Johnson (1987) McBride (1989) McBride and Finlay (1989)	
Citric acid × sucrose	Curtis and Stevens (1984) Frank and Archambo (1986) McBride and Johnson (1987) McBride (1989) McBride and Finlay (1989)	Pangborn and Chrisp (1964) Pangborn and Trabue (1964)

Table II(C). Summary of the results of ANOVA in previous research into the total taste intensity of citric acid/sucrose mixtures

Effect	Significant	Not significant
Citric acid	Curtis and Stevens (1984) Frank and Archambo (1986) McBride and Johnson (1987) McBride (1989) McBride and Finlay (1989)	
Sucrose	Curtis and Stevens (1984) Frank and Archambo (1986) McBride and Johnson (1987) McBride (1989) McBride and Finlay (1989)	
Citric acid × sucrose	Curtis and Stevens (1984) Frank and Archambo (1986) McBride and Johnson (1987) McBride (1989) McBride and Finlay (1989)	

If the sweetness intensity of the sucrose concentration is high enough to permit this maximum suppression, increasing the sucrose levels does not influence the sweetness-suppressing effect of citric acid any more. With regard to sourness suppression, the citric acid concentration does have a major effect on the magnitude of the sourness suppression. The degree of suppression is proportional to both the citric acid and the sucrose concentration.

When McBride and Johnson (1987) omitted the bottom level of citric acid (0.45% = 0.023 M) from their analysis of the sourness ratings, the sucrose × citric acid interaction was no longer significant. This level aside, the degree of sourness suppression depended only upon the sucrose concentration. It should be noted that the citric acid concentrations in their investigation (0.023−0.095 M) were much higher than the concentrations used in the present experiment (0.00125−0.010 M). Their results suggest that the perceptual process that can describe the relationship between citric acid and sweetness suppression in the present study may also hold for sucrose concentration and sourness suppression at high citric acid levels. If this suggestion is correct, the curves in Figure 4(B) must run parallel to the straight top line at higher citric acid concentrations, similar to the curves in Figure 4(A).

The degree to which the total taste intensity in sucrose/citric acid mixtures is suppressed depends on both the citric acid concentration and the sucrose concentration. This is probably an effect that is mainly produced by the degree of sourness suppression since the degree of sweetness suppression does not depend on the sucrose concentration for the concentration levels used in the present study.

Additivity of specific taste intensities within a heterogeneous taste percept

The results of the present study show that the total taste intensity of a mixture is determined by the sum of the specific taste intensities of that mixture. De Graaf and

Frijters (1989) arrived at a similar conclusion in their study on sucrose/NaCl mixtures. Several authors have studied the taste qualities of tastants by instructing their subjects to give a numerical estimate of the perceived taste intensity of each test stimulus and subsequently divide this estimate among the appropriate taste qualities (e.g. Smith and McBurney, 1969; McBurney and Shick, 1971; McBurney and Bartoshuck, 1973; Bartoshuk, 1975; Settle *et al.*, 1986). This procedure is based on the assumption that the total taste intensity of a stimulus equals the sum of the specific taste intensities of that stimulus (Figure 1: 10). The results of the present study provide the first evidence for the validity of this assumption.

Taste as an analytic or synthetic system

For many years there has been controversy between investigators who claimed that the taste modality functions analytically (e.g. McBurney, 1974; McBurney and Gent, 1979) and those authors who claimed that taste functions synthetically (e.g.Schiffman and Erickson, 1971, 1980). The first group argued that when two gustatory stimuli are presented in a mixture, they maintain their individual qualities without the emergence of a new quality. They tried to demonstrate the existence of several 'primary' or 'basic' tastes. The second group proposed that the sense of taste can better be represented by a continuum, where sweet, sour, salty and bitter are familiar points, than by a number of distinctly separate processes. This view implies a degree of synthesis, new qualities arising when two stimuli are mixed. Kuznicki and Ashbaugh (1979, 1982) demonstrated that subjects were incapable of selectively attending to individual tastes in a heterogeneous taste mixture. The presence of irrelevant tastes resulted in a quality shift in the target sensation. Subjects could only give an unaffected response when the mixture components were separated in both space and time. This result is in line with the hypothesis that subjects perceive taste mixtures as a whole and do not analyse these complex stimuli during the perceptual process.

The present outcomes and De Graaf and Frijters' results could be regarded as additional proof for the hypothesis that taste is an analytic sense. However, for several reasons this type of conclusion does not seem appropriate. The fact that a stimulus can be analysed into its component sensations does not provide any proof for the fact that a stimulus is not perceived as a whole. According to Lockhead (1966) it is almost certain that subjects can analyse every multidimensional stimulus. Erickson (1977), for example, has shown that colour vision, the classical example of a synthetic sense, can be successfully described with only a few standard terms. In the present study the subjects were instructed to judge the magnitude of the sweetness, sourness or total taste intensity. In every investigation a quantitative judgement had to be given on a separate, specified dimension. Therefore, every stimulus had to be analysed before a judgement could be made. In the multidimensinal scaling studies of Schiffman and Erickson, subjects were not asked to analyse stimuli. They were just asked to judge the degree of dissimilarity between two solutions of about the same taste intensity. Since the total taste intensities of their experimental stimuli were about equal, the judgements were made on the basis of *quality* differences and not on the basis of, analytical, *intensity* differences. The consequence of using a multidimensional scaling procedure may therefore be that stimuli are judged as a whole and not as the resultant of a number of specific taste sensations.

Therefore, our results and the discrepancy with the results of Schiffman and Erickson may be explained by a difference in the experimental task the subjects had to perform, and does not necessarily have to be explained by a perceptual phenomenon. We agree, therefore, with Kuznicki and colleagues who argued that the degree to which subjects respond to individual elements in a taste mixture or to their configuration can be influenced by the nature of the task and the instructions (Kuznicki and Ashbaugh, 1982; Kuznicki *et al.*, 1983; Kuznicki and Turner, 1986, 1988).

Another reason why the conclusion that taste is an analytic sense does not seem appropriate here is the fact that the present findings cannot simply be extrapolated to conclude that in mixtures with several different taste qualities the specific taste qualities can always be summated to estimate the total taste intensity. Several investigators have noted that the sensation of sweetness appears to be more different from the other taste qualities than sourness, saltiness and bitterness (e.g. Doetsch and Erickson, 1970; Schiffman and Erickson, 1971; Moskowitz, 1972; Gregson and Baker, 1973). If the mutual relationships among the specific taste sensations are not psychologically identical, the process that integrates these sensations into a heterogeneous taste percept may not be identical either. Therefore, it remains to be seen whether sourness and saltiness or sourness and bitterness combine in an additive way as well.

Other taste interaction theories

The vector summation model, originally designed for the description of interactions in mixtures of odorants, was one of the first models that was able to estimate the total taste intensity of a mixture from the total taste intensities of its unmixed components. However, the model cannot handle asymmetrical interactions or the phenomenon of taste enhancement (Beglund *et al.*, 1973). In addition, Cain (1975) noted that α always lies between 105° and 130° for mixtures of odorants, so that the magnitude of this angle cannot be considered specific for the qualities of a pair of odorants. Moskowitz and Barbe (1977) noted that 'the vector model is not totally correct, since, in the case of an odorant added to itself, the vector model would predict an angular separation of around 107° if odor intensity is a power function of concentration (exponent = 0.5). The angular separation, however, should be zero.' This demonstrates that a major part of the angle between the intensities of two different substances can be explained by the within-substance interactions. The present study yielded $\alpha = 100°$ ($R^2 = 0.466$) and $\alpha = 97°$ ($R^2 = 0.412$) for unmixed sucrose and citric acid respectively. It should be noted that the values of R^2 are extremely low for the unmixed components, which implies a bad fit of the vector summation model. This is the more surprising since this model was designed for homogeneous percepts, while it seems plausible to assume that the total taste intensities of unmixed citric acid and unmixed sucrose are more homogeneous than the percept of a citric acid/sucrose mixture. Another feature of the vector summation model is that it compares two different parameters (the total taste intensity of a mixture with the total taste intensities of the unmixed components) without paying any attention to the underlying relationships between specific taste intensities and the total taste intensities of unmixed substances and their mixtures.

McBride (1989) proposed two different models to account for mixture phenomena in heterogeneous taste mixtures. One of these models, the *algebraic integration model*, states that the specific taste intensities of the components of a mixture influence the magnitude of each other's specific taste intensity. In fact, the algebraic integration model resembles the model we have used throughout this study (Figure 1). His second model, the *dominant component model*, implies that the total taste intensity of a heterogeneous mixture is determined by the total taste intensity of the subjectively dominant component in the mixture. McBride claims that when subjects are asked to judge the total taste intensity of a mixture, the subjects compare the total taste intensities of the mixture's components as if they were unmixed. The component with the highest intensity will then determine the total taste intensity of the mixture. McBride formulated this second model because he assumes that a significant sucrose × citric acid interaction in an ANOVA of the total taste intensity estimates implies that the total taste intensity is not equal to the simple sum of sweetness and sourness. This line of reasoning, however, is not correct. McBride confuses the sucrose × citric acid interaction with the sweetness × sourness interaction. He overlooks the difference between the physical concentrations of the components (physical parameters) and the specific taste sensations that are elicited by those substances (psychological constructs). The sucrose effect of a mixture of an ANOVA depends on the sucrose concentration only. Similarly, the citric acid effect depends solely upon the citric acid concentration. In contrast, the sweetness of a mixture depends on both the citric acid concentration *and* the sucrose concentration of that mixture. The same holds for the sourness intensity of a mixture. Therefore, the sucrose × citric acid interaction and the sweetness × sourness interaction are two completely different concepts.

The ANOVAs of the sweetness intensity estimates and the sourness intensity estimates both reveal a significant sucrose × citric acid interaction. Since, according to the present results, total taste intensity equals the sum of sweetness and sourness, it can be anticipated that in most cases the sucrose × citric acid interaction will also be significant for the total taste intensity estimates.

The dominant component model has one feature in common with the vector summation model in that it compares total taste intensities without paying attention to the underlying relationships between specific taste intensities inside and outside the mixtures. The only reason why the dominant component model is sometimes encountered in the psychophysical literature is because it provides a reasonably good fit to the data (e.g. Ganzevles and Kroeze , 1987). In neurophysiological literature it is encountered because electrophysiological recordings cannot be discriminated on the basis of the different taste sensations that are elicited. Therefore, the intensity of the specific taste sensations of a mixture cannot be assessed and so the relationship between the specific taste intensities and the total taste intensity cannot be revealed.

Frank and Archambo (1986, 1987) found that the sum of sweetness and sourness in citric acid/sucrose mixtures, just like the sum of sweetness and saltiness in sucrose/NaCl mixtures, was higher than the rated total taste intensity of these mixtures. They concluded that mixture suppression alone could not account for the 'sub-additivity' observed for the total intensity ratings. They stated that a correction for the effects of psychophysical compression could improve the estimates of the total intensity estimates. However, by adding the ratings for the specific taste intensities they tacitly assumed that in their experiment sweetness, saltiness, sourness and total taste intensity were all assessed on a ratio scale with equal units. In the present study the scale values on the sweetness scale and the scale values on the sourness scale were multiplied by a certain constant. This was necessary because the scale units on the sweetness, sourness and total taste intensity scale were not identical, but differed by a multiplicative constant (Figure 9). The sum of the corrected sourness and sweetness scale values gave good estimates of the total taste intensity of the citric acid/sucrose mixtures (Table I).

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The effectiveness of different sweeteners in suppressing citric acid sourness

HENDRIK N. J. SCHIFFERSTEIN and JAN E. R. FRIJTERS
Agricultural University, Wageningen, The Netherlands

The exact mechanism that causes taste suppression in a perceptually heterogeneous mixture, and the locus of that mechanism, are as yet unknown. The present study was designed to explore the idea that mixture suppression is a perceptual phenomenon and not the result of physical, chemical, or receptor-substance interactions. An investigation was carried out as to whether perceptually similar taste stimuli give rise to the same sensory interactions when mixed with a substance of a different taste quality. In the first study, five different sweeteners (sucrose, fructose, aspartame, saccharin, and sorbitol) were matched in perceived sweetness intensity, in order to obtain five perceptually similar stimuli. Every equisweet sweetener concentration was mixed with each of four citric acid concentrations. In a second study, the sourness-suppressing effects of two sweeteners, sucrose and aspartame, were compared at four different concentration levels. Sourness scale values of unmixed citric acid, the unmixed sweeteners, and the citric acid/sweetener mixtures were assessed with a functional measurement approach in combination with a two-stimulus procedure. The equisweet sweeteners were equally effective in suppressing the perceived sourness intensity of citric acid over the concentration range used. The side tastes of the sweeteners, if present, did not have a substantial effect on the degree of sourness suppression.

When two or more substances of qualitatively different tastes are mixed, the overall perceived taste intensity of the mixture is, in most cases, less than the sum of the intensities of the unmixed components (see, e.g., Bartoshuk, 1975). This phenomenon, called *mixture suppression*, is the result of a decrease of the specific taste intensities (sweetness, sourness, saltiness, bitterness) contributing to the overall intensity of the solution (De Graaf & Frijters, 1989; Schifferstein & Frijters, 1990). The suppression of one taste quality by the other in a binary mixture is usually mutual, but not necessarily symmetrical. For example, Schifferstein and Frijters (1990) found that in a mixture of 1.00M sucrose and 0.010M citric acid, the sweetness intensity of sucrose was suppressed by 11 units, while the sourness intensity of citric acid was suppressed by 52 units. The total taste intensities of the unmixed stimuli were comparable in strength, being 73 and 79 units, respectively.

The exact mechanism that causes mixture suppression and the locus of that mechanism are as yet undetermined. Kroeze (1978) has shown that two phenomena that can cause a decrease in taste intensity, mixture suppression, and self-adaptation are independent and have to be accounted for by different processes. He demonstrated that there is no relation between a subject's saltiness score when the subject is given a sucrose/NaCl mixture and the saltiness score when the subject is given a solution of unmixed NaCl after adaptation to NaCl. In addition, he demonstrated that adaptation to unmixed NaCl and adaptation to a sucrose/NaCl mixture, in which the saltiness intensity is suppressed by sucrose, both decreased the saltiness of NaCl to the same degree. Similar results were obtained for the sweetness of the NaCl/sucrose mixture (Kroeze, 1979). Kroeze concluded that self-adaptation and mixture suppression have different locations in the taste system and that mixture suppression is more centrally located than adaptation.

Since there are no structural elements of the neural part of the taste system that connect the two sides of the tongue before the thalamic level (Norgren & Leonard, 1973), Kroeze and Bartoshuk (1985) carried out a split-tongue experiment to gain information about the locus of mixture suppression. They compared two conditions. In the first one, a mixture was applied to one tongue half while the other tongue half was stimulated with deionized water. In the second condition, the two components were spatially separated by applying each substance to a different tongue half. In quinineHCl/sucrose mixtures, they demonstrated that mixing quinineHCl with sucrose on the same tongue half, or administering the unmixed substances to the two tongue halves separately, decreased the bitterness to the same degree. This result suggests that quinineHCl-

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bitterness suppression by sucrose resides in thalamic or higher neural structures. In contrast, however, there was a 23% decrease in bitterness intensity in the quinineHCl/NaCl mixture when quinineHCl and NaCl were applied separately to the two tongue halves, compared to 69% when both substances were applied to the same tongue half. Therefore, Kroeze and Bartoshuk concluded that the observed decrease in bitterness intensity in quinineHCl/NaCl mixtures results from both central and peripheral suppression mechanisms.

Gillan (1982) carried out an experiment in which he varied the distance between two areas of the human tongue stimulated by two substances of different taste qualities. He found that if the distance between the stimulated areas was enlarged, the decrease in taste intensity was diminished. This result shows that peripheral mechanisms are important in determining the degree of mixture suppression.

Several authors observed that after elimination or reduction of the taste intensity of one component, the taste sensation of the other component of a heterogeneous mixture is, to some degree, released from suppression. In some studies, this phenomenon was demonstrated with the use of a self- or cross-adaptation paradigm (e.g., Gillan, 1982; Kuznicki & McCutcheon, 1979; Lawless, 1979). In other studies, the sweetness perception was blocked with *Gymnema sylvestre* (e.g., Lawless, 1979).

Kuznicki and McCutcheon (1979) observed suppression release in a sucrose/HCl mixture after adaptation to sucrose following a pretreatment with *Gymnema sylvestre*. They concluded that mixture suppression and suppression release can apparently occur in HCl/sucrose mixtures without the involvement of the sweet taste system. It is possible, however, that the sweetness perception was not completely blocked in their experiment.

Kroeze (1982) used a habituation paradigm to study suppression release. He habituated subjects to the sweetness of sucrose or glucose and subsequently presented an NaCl/sucrose mixture. He demonstrated that the saltiness of the NaCl/sucrose mixture approximated the saltiness of the unmixed NaCl after repeated stimulation with sweet tasting stimuli. In a similar way, he demonstrated that the sweetness of sucrose in the sucrose/NaCl mixture was released from suppression after repeated stimulations with unmixed NaCl (Kroeze, 1983). Since habituation is a central event, the mixture suppression found is also taken to be of a central origin.

In the present instance, mixture suppression is studied in a way different from the approach in previous studies. Here, we shall try to demonstrate that mixture suppression is a perceptual phenomenon and not the result of physical, chemical, or receptor-substance interactions. The following reasoning forms the basis of our thinking: Suppose there are two substances, A and B, that elicit the same taste quality. If the taste intensity of a specified concentration of B is matched to that of a certain concentration of A, one has obtained two stimuli that give rise to the same taste sensation, irrespective of their chemical structures. Assume further that there is another taste substance, X, which tastes qualitatively different from A and B. If a certain concentration of X is mixed with each of the equi-intense stimuli A and B, one obtains two binary mixtures that are composed of perceptually similar components. If substance X interacts in exactly the same way, or does not interact at all with A and B at the physical, chemical, or receptor level, then both the X–A and the X–B mixture should give rise to the same taste sensations and the same sensory interactions. If A and B are two substances that differ with regard to chemical structure and concentration level, it does not seem likely that both substances will exhibit the same interactions in the mixture or at the receptor site. Therefore, it seems plausible to assume that if two chemically different, but perceptually similar stimuli give rise to the same sensory interactions, the locus of the interaction mechanism must reside in the afferent pathways, the central neural system, or at the level of conscious experience—that is, the percept.

In 1965, Pangborn reported the results of a study in which equi-intense stimulus concentrations were used to study mixture suppression. Specifically, she investigated the effect of four organic acids on the sweetness intensity of four sugars. The sugar concentrations were equivalent in sweetness intensity, and the acid concentrations were equivalent in sourness intensity. Pangborn reported that citric acid and acetic acid usually exhibited greater sweetness-suppressing action than did lactic and tartaric acids when they were mixed with one of the four sugars in a binary mixture. However, since it was not her objective to demonstrate that equisour acids produce the same degree of sweetness suppression in a sugar/acid mixture, she did not test whether the differences between these four acids were significant.

In the first study, the influence of five different sweeteners on the degree of sourness suppression in citric acid/sweetener mixtures was assessed. Citric acid/sweetener mixtures were chosen, because the sourness of a citric acid/sucrose mixture is highly dependent on both the citric acid and the sucrose concentration (Schifferstein & Frijters, 1990). The five sweeteners were chosen as representative of a range of chemically different substances: aspartame (dipeptide), saccharin (imide), sorbitol (sugaralcohol), fructose (monosaccharide), and sucrose (disaccharide). The five concentrations of sweeteners were preexperimentally equated, with regard to sweetness intensity, to obtain five perceptually similar stimuli. Subsequently, the obtained sweetener concentrations were used to construct five stimulus series. In each series of citric acid/sweetener mixtures, the citric acid concentration was the only variable, while the sweetener concentration remained constant.

A second study was carried out to investigate whether two sweeteners (aspartame and sucrose) suppressed the sourness of citric acid to the same degree at four different sweetener levels. Four sucrose concentrations were matched in perceived sweetness intensity to four aspartame levels, and the obtained concentrations were used to construct eight series of citric acid/sweetener mixtures. In every series, the citric acid concentration varied while the sweetener concentration remained constant.

For one to draw proper conclusions about the degrees to which the different sweeteners suppress sourness, one must assess the perceived sourness intensities on an interval or ratio scale. Whether or not the derived scale has interval properties depends on the validity of the assumption that the scale values derived from the overt responses vary linearly with the perceived taste intensities. This assumption can be verified with a functional measurement approach in combination with a two-stimulus procedure (De Graaf, Frijters, & van Trijp, 1987).

One of the main features of functional measurement is the use of factorial designs as a tool for the evaluation of the judgment function. Two different factorial designs can be distinguished: a factorial judgment design and a factorial mixing design. In a factorial *judgment* design, the subjects compare the sensory impression of each level of a column stimulus with the impression of each level of a row stimulus. Parallelism in the factorial plot of the obtained data does not depend on sensory interaction but on the nature of the comparative operation and on the form of the judgment function. If subjects are instructed to judge differences, the comparative operation between two sensory impressions can be best described with an algebraic subtractive rule. The subtractive model predicts no interaction between row and column stimuli, assuming that the response scale is linear (e.g., Birnbaum, 1978; Birnbaum & Mellers, 1978). Therefore, testing the row × column interaction for significance provides the basis for testing the linearity of the response scale. If the response scale is linear, the marginal means of the row and column stimuli are validated estimates of the perceived taste intensity of the corresponding row and column stimuli on an interval scale (De Graaf et al., 1987).

In a factorial *mixing* design (De Graaf et al., 1987; McBride, 1986), each level of the first factor (type of sweetener) is mixed with each level of the second factor (citric acid concentration). The stimuli resulting from the factorial mixing design can be incorporated in the factorial judgment designs. If the judgment function is linear, parallelism in a factorial plot of mixture components indicates that the components behave additively.

The term *factorial mixing design* refers to the physical composition of mixtures and should not be confused with the term *factorial judgment design*, which refers to the presentation of pairs of (mixed and unmixed) stimuli to the subjects (De Graaf et al., 1987).

In the present studies, it is assumed that tasting a citric acid/sweetener mixture leads to the formation of a heterogeneous percept. Subjects can reliably analyze this percept in order to give estimates of the perceived sourness intensity and the perceived sweetness intensity. Evidence for the validity of this assumption has been provided by Schifferstein and Frijters (1990), who demonstrated that the weighted sum of sweetness and sourness equals the total taste intensity of a citric acid/sucrose mixture.

EXPERIMENT 1

Method

Subjects. The subjects were 14 paid volunteers, 8 women and 6 men, ranging in age from 19 to 27 years. They were under-graduate students at the Agricultural University. All 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 citric acid (Merck 244), sucrose (Merck 7651), aspartame (Holland Sweetener Company), saccharin (Sigma S-1002), fructose (Merck 5321), and sorbitol (BDH 30242), as well as mixtures of these sweeteners with citric acid in demineralized water. The concentrations of citric acid were 0.00, 0.00125, 0.0025, 0.005, and 0.010 M citric acid.

In a preliminary experiment, aspartame, saccharin, fructose, and sorbitol were matched in perceived sweetness intensity to 0.25 M sucrose, using the method of constant stimuli (De Graaf & Frijters, 1986). Thirteen of the 14 subjects participated in this experiment. The concentrations that were determined as equisweet to 0.25 M sucrose were 0.0030 M aspartame (corrected for the water content), 0.0020 M saccharin, 0.3891 M fructose, and 0.8346 M sorbitol.

The mixtures were constructed on the basis of a factorial mixing design. Every sweetener was mixed with each of the citric acid concentrations.

For reasons of standardization, the subjects were presented with a reference pair. The first stimulus of the reference pair was water; the second was 0.0125 M citric acid.

All solutions were prepared at least 24 h prior to tasting and were stored at 4° C for a period not longer than 1 week.

Design. The investigation consisted of 12 experiments, each of which employed a factorial judgment design. A factorial judgment design implies that subjects are presented with pairs of stimuli. In each investigation, an $m \times n$ design is employed, where m and n denote the number of concentrations of the first (row) and second (column) stimulus. In order to incorporate all the experimental stimuli in factorial judgment designs, six series of stimuli were constructed. One series was constructed for each of the five sweeteners. Each series consisted of four citric acid/sweetener mixtures, a solution of unmixed sweetener, and water (six stimuli). The sixth series consisted of the four unmixed citric acid concentrations (0.00125, 0.0025, 0.005, and 0.010 M) and water (five stimuli). Each of the six series of experimental stimuli was compared with regard to sourness intensity with three citric acid solutions: 0.00 (water), 0.0025, and 0.010 M citric acid. In six experiments, the three comparison stimuli were presented as first stimuli; in six other experiments they served as second stimuli.

Procedure. The subjects were instructed to judge the magnitude of the difference in perceived sourness intensities between the first and second stimulus of each pair. The instructions emphasized that only the sourness intensity should be judged.

The judgments were expressed by a slash mark on a 250-mm visual analogue scale. The middle of the scale was defined thus: "The first and second stimulus are equal with respect to perceived sourness intensity" (see De Graaf et al., 1987; Figure 3). If the first stimulus was perceived as tasting more sour than the second stimulus, the subject placed a mark on the left side of the scale. The subject marked the right side of the scale when the second stimulus was perceived as being more sour. The distance between the slash mark and the middle of the scale indicated the size of the intensity difference beween the two samples of one pair. The left end and the right end of the scale were labeled "maximum difference." In the instructions, "maximum difference" was defined as the difference in sourness intensity between the stimuli of the reference pair (i.e., water as the first stimulus and 0.0125 M citric acid as the 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 millimeters 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 more sour than the first, and a value below 125 indicated that the first stimulus was perceived as being the most sour 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 in polystyrene medicine cups that 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 24th pair of each session. The time interval between and within pairs was 40 sec. Each of the 12 factorial judgment designs was presented to each subject twice. It took each subject 12 50-min sessions to complete the entire investigation.

Results

A procedure recently developed by De Graaf et al. (1987) and De Graaf and Frijters (1988) was applied to the present data. A brief outline of the psychometric properties of the response scale and an explanation of how scale values were derived is given in the next section.

Psychometric properties of response scale and derivation of scale values. The subjects were instructed to judge the difference between the perceived taste intensities within each pair of stimuli. Parallelism in a factorial judgment plot implies that the response function is linear with the perceived difference. Because individuals may vary in their judgment functions (linear or nonlinear), or in their comparative operations (which may or may not be subtractive), individual analyses were performed first. The measure of the degree of nonparallelism—that is, the row × column interaction—was tested for statistical significance in an analysis of variance, with the row × column × replication interaction as an error term. Out of 168 analyses, none showed a significant row × column (first stimulus × second stimulus) interaction ($p > .01$).

At group level, the row × column interaction was tested for significance against the row × column × subject interaction for each of the 12 factorial judgment designs. The interaction appeared to be significant in one case only ($p < .01$).

The number of significant interactions approximates the number that may be expected to reach significance given this number of analyses and the specified alpha level. Therefore, it can be concluded that the responses obtained are 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 an interval scale (Anderson, 1981).

If it is assumed that water has no taste, then scale values can be derived for each of the experimental stimuli by calculating the difference between the marginal mean for the experimental stimulus and the marginal mean for water in each of the 12 experiments. The final scale value for each stimulus was calculated by averaging the scale value for that stimulus tasted as first stimulus of each pair and the scale value when tasted as second stimulus of each pair. All data were averaged over subjects and replications.

Comparison of the sweeteners with regard to sourness suppression. Figure 1 shows the sourness of citric acid and the citric acid/sweetener mixtures as a function of the sourness of citric acid with a separate curve for each mixture type. Visual inspection shows that the sourness intensity of all citric acid/sweetener mixtures is lower than the sourness of the corresponding unmixed citric acid concentrations in all cases.

If an acid is mixed with a number of different concentrations of the same sweetener, a plot of diverging curves is observed (e.g., see Figure 4). The sourness of each acid/sweetener mixture depends on both the acid and the sweetener concentration. If the sourness of citric acid is differentially suppressed by each of the five equisweet sweeteners used in this study, a similar diverging pattern is to be expected. However, if the five sweeteners are equally effective in suppressing the sourness of citric acid, the five mixture curves should coincide. Figure 1 shows that the differences in the degrees of sourness suppression caused by the five equisweet sweeteners were not comparable to those caused by different concentrations of the same sweetener. In contrast, the five mixture functions are similarly shaped and differ only slightly. Analysis of variance of the five citric acid/sweetener mixtures shows significant effects for the citric acid concentration [$F(4,52) = 109.68$, $p < .001$] and the sweetener type [$F(4,52) = 2.66$, $p = .04$]. The sweetener × citric acid interaction is not significant [$F(16,208) = 0.69$, $p = .80$].

The significance of the sweetener type effect is largely due to the aspartame/citric acid mixtures that have consistently higher scale values than the other mixture types. If the aspartame data are excluded from the analysis, the observed sweetener effect is no longer significant [$F(3,39) = 0.88$, $p = .46$].

The higher sourness scale values for the aspartame mixtures may result from the sourness of the unmixed sweetener. The sourness scale value of 0.0030 M unmixed aspartame differs almost significantly from zero [one-tailed t test, $p = .07$]. Therefore, the aspartame curve may lie higher than the other curves, because the sourness intensity of the unmixed aspartame may have been added to the sourness of citric acid at each citric acid level. This could be a plausible explanation, since the significance of the sweetener effect disappears if the sourness scale value of each unmixed sweetener is subtracted from the scale value of each mixture of that sweetener with citric acid [$F(4,52) = 1.25$, $p = .30$].

It may seem as if the differences between sweeteners are consistent over concentrations because the aspartame mixtures have higher scale values (at four citric acid levels) and the sorbitol mixtures have lower scale values (at three citric acid levels) than the other mixtures. Such consistent differences can be the consequence of the calculation method employed. The scale value of each stimu-

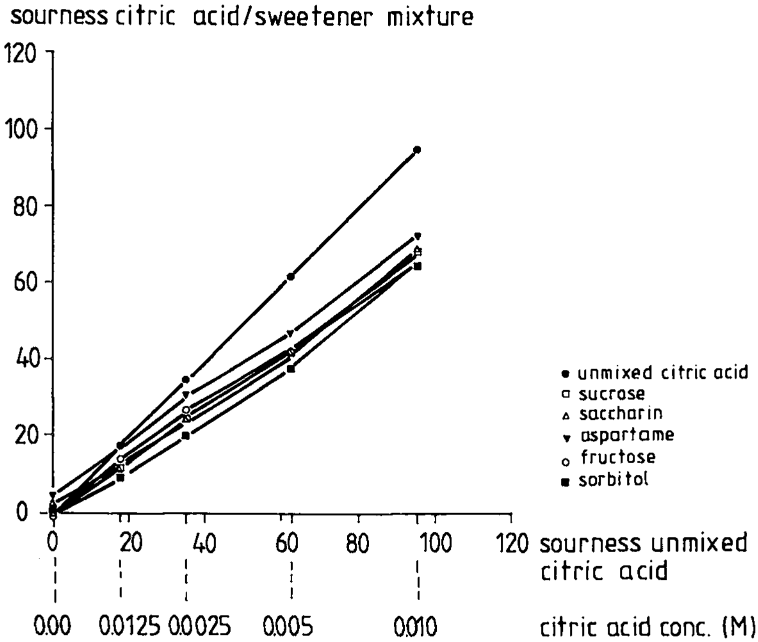

Figure 1. The perceived sourness intensity of citric acid/sweetener mixtures, plotted as a function of the sourness of unmixed citric acid with a separate curve for every sweetener.

lus is derived by calculating the difference between the marginal mean for that stimulus and the marginal mean for water, which is used as a rational zero point. Therefore, the marginal mean for water determines the position of the scale values on the ordinate. For each of the six factorial judgment designs, one marginal mean is calculated for water. This marginal mean is not the same for each sweetener, but rather is subject to some random variation (standard error of mean ≈ 4). Because the scale values for each sweetener are calculated from a different factorial judgment design, a set of slightly differing but parallel curves may appear instead of a set of coinciding curves.

In summary, it can be concluded that four of the five mixture functions in Figure 1 do not differ statistically. The deviance of the aspartame curve might be due to a sour side-taste of the unmixed aspartame at the concentration level used in this experiment and/or to an artifact of the calculation method employed.

EXPERIMENT 2

Method

Subjects. The subjects were 14 paid volunteers, 11 women and 3 men, whose ages ranged from 20 to 26 years. All subjects were undergraduate students at the Agricultural University. All subjects had had previous experience with psychophysical tasks, but were naive with respect to the substances used and the purpose of the study.

Stimuli. The stimuli were solutions of aspartame (Holland Sweetener Company), sucrose (Merck 7651), citric acid (Merck 244), and citric acid/sweetener mixtures in demineralized water.

In a preliminary experiment, sucrose was matched as regards perceived sweetness intensity with 0.0003, 0.0010, 0.0032, and 0.0102 M aspartame, using the method of constant stimuli (De Graaf & Frijters, 1986). In this experiment, all 14 subjects participated. The concentrations that were determined as being equisweet to the aspartame concentrations were 0.05, 0.14, 0.27, and 0.44 M sucrose. The citric acid concentrations were 0.00, 0.00125, 0.0025, 0.005, and 0.010 M citric acid.

Every sweetener concentration was mixed with every citric acid level in order to obtain eight different series. Within every series, the citric acid level varied while the sweetener concentration remained constant. Every mixture series consisted of four citric acid/sweetener mixtures, the unmixed sweetener, and water. In addition to the mixture series, a series of unmixed citric acid stimuli was used. The reference pair for the sourness investigation consisted of water and 0.0125 M citric acid.

In a separate investigation, the sweetness of the unmixed sweetener concentrations was assessed. In this investigation, the reference pair consisted of water as first stimulus and 1.25 M sucrose as second stimulus.

The solutions were prepared at least 24 h before tasting and were stored at 4° C for a period not longer than 1 week.

Design. The sourness investigation consisted of 18 experiments, each of which employed a factorial judgment design. There were 16 6×3 and 2 5×3 factorial judgment designs. In order to incorporate all the experimental stimuli in factorial judgment designs, nine series of stimuli were constructed: one series of unmixed citric acid solutions (five stimuli) and eight series of citric acid/sweetener mixtures (six stimuli). Water was included in each of these series as a meaningful zero point to be used in the calculations of scale values.

Each of the nine series of experimental stimuli was compared with regard to sourness intensity with three citric acid solutions: 0.00 (water), 0.0025, and 0.0100 M citric acid. These three solutions were presented as first stimuli in nine experiments and as second stimuli in nine other experiments.

To check the perceptual similarity of the unmixed aspartame and sucrose levels, the perceived sweetness intensities of the unmixed sweetener levels were determined in a separate investigation. This sweetness investigation consisted of four experiments, each of which employed a 5×3 factorial judgment design. There were two series of five experimental stimuli: one series of aspartame solutions and one series of sucrose solutions. Water was included in both series as a meaningful zero point.

The two series were compared with regard to perceived sweetness intensity with three sucrose solutions: 0.00 (water), 0.25, and 1.00 M sucrose. Each of these solutions was presented as the first stimulus in two experiments and as the second stimulus in the two other experiments.

Procedure. The procedure was identical to the procedure used in the first study. In the sweetness investigation, however, the magnitude of the difference in perceived sweetness intensities had to be judged.

The 22 experiments (18 sourness and 4 sweetness experiments) were presented to each subject twice. During each session, all pairs of two designs were judged. The order of presentation of the designs was random, with the restriction that two designs, which were to be presented simultaneously, had to be of the same type (sourness *or* sweetness experiment). It took each subject 22 50-min sessions to complete the entire investigation.

Results

Psychometric properties of the response scale and derivation of the scale values. In order to check the linearity of the response function, analyses of variance were carried out for each individual subject for each factorial judgment design (14×22 = 308 analyses). The row × column interaction was found to be significant in only four cases ($p < .01$). None of the subjects had more than one significant interaction ($p < .01$). On group level (22 analyses), the row × column interaction was not significant in any of the cases ($p > .01$).

Since the number of significant interactions approaches the number that may be expected to reach significance given this number of analyses, it can be concluded that the responses obtained are a linear function of the perceived taste intensity differences. Consequently, the marginal means of the row and column stimuli are validated estimates of the perceived taste intensity on an interval scale (Anderson, 1981). The procedure that was followed to calculate the scale values was identical to the one described in the first study.

Sweetness of the unmixed sweeteners. The psychophysical functions for aspartame and sucrose have been reproduced in Figure 2. The aspartame function accelerates negatively over the whole concentration range, while the sucrose function accelerates positively at low concentration levels and accelerates negatively at high concentration levels. The correspondence between the sweetness intensities at the four different concentration levels is almost perfect ($r = 1.00$). The concentrations of aspartame and sucrose obtained in the matching experiment appear to be equisweet (Figure 3). Analysis of variance of the sweetness data showed that sweetener type had no significant effect [$F(1,13) = 0.11$, $p = .75$].

Comparison of the sweeteners with regard to sourness suppression. Figure 4 (panels A and B) shows the sourness of citric acid and the sweetener/citric acid mixtures as a function of the sourness of citric acid, with a separate curve for each sweetener concentration. Visual inspection shows two highly similar plots of diverging functions, in which higher sweetener concentrations obviously produce a greater sourness-suppressing effect. In addition, the citric acid concentration influences the sourness intensity and the degree to which it is suppressed.

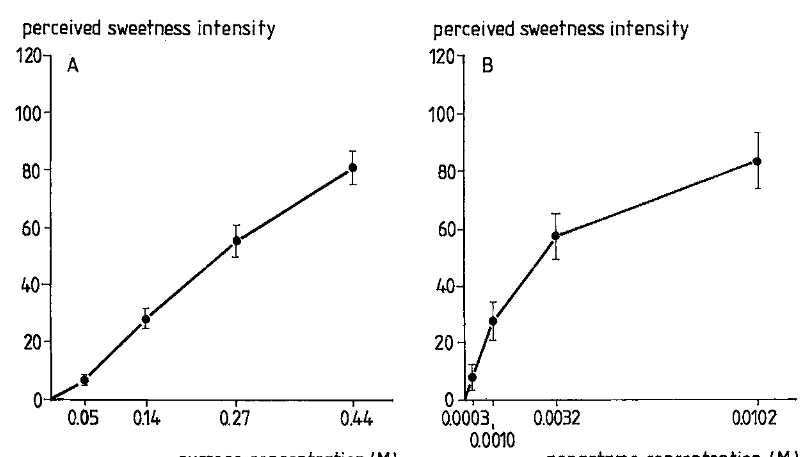

Figure 2. Psychophysical functions for the sweetness intensities of sucrose (panel A) and aspartame (panel B). The error bars around each point represent the 95% confidence interval for each scale value.

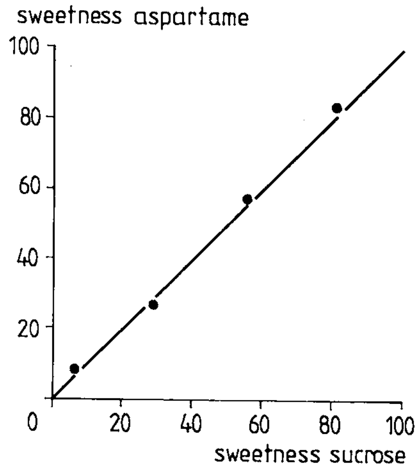

Figure 3. The relationship between the sweetness of aspartame and the sweetness of sucrose. Points are located on the diagonal if the aspartame and sucrose concentrations are equisweet.

Analysis of variance of the data of the aspartame mixtures showed significant effects for the citric acid concentration [$F(4,52) = 889.61, p < .001$], the aspartame concentration [$F(3,39) = 118.71, p < .001$], and the aspartame × citric acid interaction [$F(12,156) = 19.03, p < .001$]. Analysis of the data for the sucrose mixtures gave similar results. The citric acid concentration [$F(4,52) = 1{,}227.52, p < .001$] and the sucrose concentration [$F(3,39) = 85.17, p < .001$] showed significant effects, and the sucrose × citric acid interaction [$F(12,156) = 9.15, p < .001$] was also significant. These results indicate that the degree of sourness suppression depends on both the citric acid concentration and the sweetener level.

The type of sweetener has no effect on the sourness intensity or on the degree of sourness suppression, however. An analysis of variance of the entire data set reveals neither a significant effect of the type of sweetener [$F(1,13) = 0.00, p = .98$] nor a significant sweetener type × citric acid interaction [$F(4,52) = 1.83, p = .14$]. Figure 5 shows the relationship between the sourness of the aspartame/citric acid mixtures and the sourness of the sucrose/citric acid mixtures. These results clearly indicate that both sweeteners suppress the sourness of citric acid to the same degree ($r = .98$).

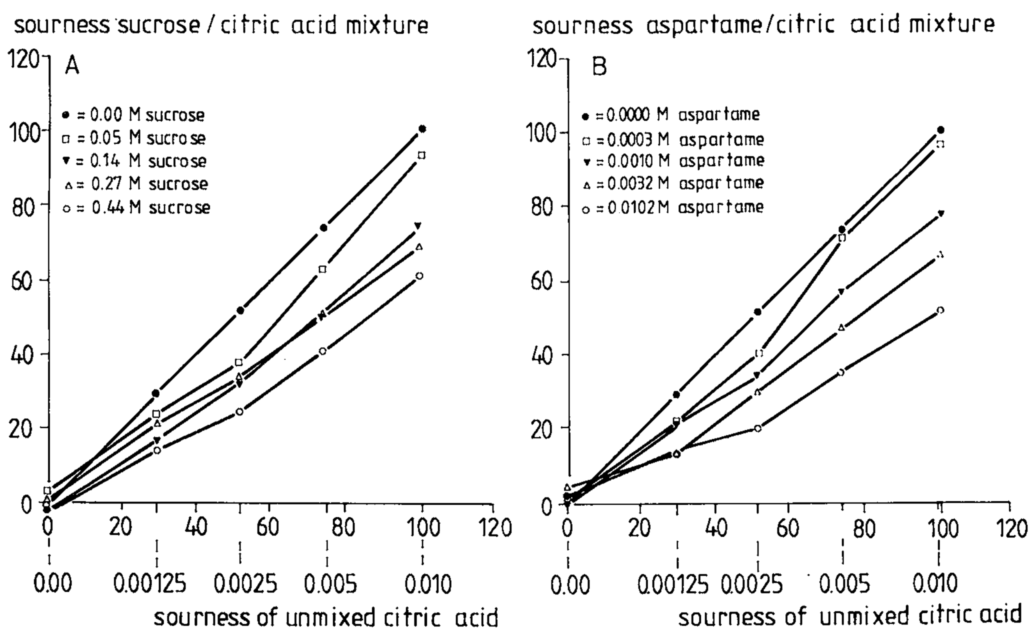

Figure 4. The sourness intensity of citric acid and the citric acid/sweetener mixtures as a function of the sourness of unmixed citric acid, with a separate curve for each sweetener concentration. Panel A shows the sourness of the sucrose/citric acid mixtures. Panel B shows the sourness of the aspartame/citric acid mixtures.

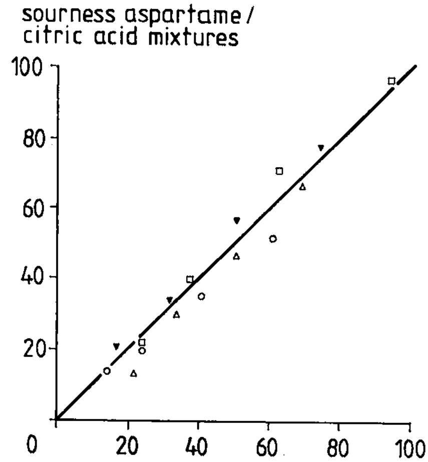

Figure 5. The relationship between the sourness of the citric acid/sucrose mixtures and the sourness of the citric acid/aspartame mixtures. Points are located on the diagonal if the sucrose mixtures and the aspartame mixtures are equisour. The citric acid concentrations were 0.00125, 0.0025, 0.005, and 0.010 M in all cases.

It should be noted that unmixed aspartame has a slight positive sourness value at each of the four concentration levels. The sourness value of 0.0032 M aspartame is significantly different from zero ($p < .05$). Unlike the results of the first study, however, the scale values of the 0.0032 M aspartame/citric acid mixtures are not consistently higher than those for the mixtures containing 0.27 M sucrose.

DISCUSSION

Side Tastes

Aspartame was found to elicit a slight sour side taste at 0.0030 M (first study) and 0.0032 M (second study). Schiffman, Reilly, and Clark (1979) reported that several subjects detected a bitter component in the aspartame taste, which developed with time. Some of the graphs and tables published by Larson-Powers and Pangborn (1978b) show that aspartame tastes slightly more bitter and sour than sucrose. Nevertheless, these authors agree with most of their colleagues that aspartame tastes much like sucrose (e.g., Larson-Powers & Pangborn, 1978a, 1978b; Schiffman, Crofton, & Beeker, 1985).

Saccharin is known to elicit a bitter side taste, especially at high concentration levels (e.g., Larson-Powers & Pangborn, 1978a, 1978b; Moskowitz, 1970; Moskowitz & Klarman, 1975; Schiffman et al., 1985; Schiffman et al., 1979), and sometimes it has been reported to have a sour side taste (e.g., Larson-Powers & Pangborn, 1978a, 1978b; Schiffman et al., 1985).

In the present instance, the sourness intensity of 0.0030 M aspartame seems to have influenced the results of the first study, because the scale values of the aspartame/citric acid mixtures were consistently higher than the scale values of the other mixtures. In the second study, however, citric acid/aspartame mixtures and citric acid/sucrose mixtures elicited the same sourness intensity. Saccharin, which is known to elicit more intense side tastes than aspartame (e.g., Larson-Powers & Pangborn, 1978b), did not deviate substantially from the other sweeteners in the first study. It seems therefore, reasonable to conclude that side tastes do not affect the degree to which sweeteners suppress the sourness intensity of citric acid.

Mixture suppression: Central or peripheral? According to Kroeze (1989), there is no simple answer to the question of whether mixture suppression is a peripheral or central phenomenon, since the afferent sensory system should be regarded as a continuous pathway between receptor sites and the locus of sensation. Furthermore, perception should be regarded as an active process in which feedback channels may play an important role by inducing peripheral sensory changes and causing subjects to display selective attention.

The objective in the present study was to investigate whether perceptually equal stimuli give rise to the same sensory interactions. The results demonstrated that equisweet solutions produce the same degree of sourness suppression when mixed with the same quantity of acid for the concentration ranges used in the two experiments. This outcome makes it very unlikely that mixture suppression can be accounted for by chemical or receptor events. This conclusion can be substantiated by the following example. Sucrose and aspartame are two, chemically entirely different, substances. They elicit the same sweetness intensities at completely different concentration levels. For instance, according to the results of the second study, 0.14 M sucrose is equisweet to 0.0010 M aspartame. If one tries to account for the sourness suppression in a citric acid/sweetener mixture by referring to the proton-accepting capacity of the sucrose molecule (Kuznicki & McCutcheon, 1979), it follows from the present results that one molecule of aspartame should accept about 140 times the number of protons a sucrose molecule attracts, which is very unlikely.

Sweet substances and the ways in which these substances are perceived can be very different. In the present study, several sweet substances were used, with different chemical structures, different concentration levels, and unequally shaped psychophysical functions for the ranges of concentration (Figure 2). Several authors have suggested that sweet substances might stimulate different types of receptor sites to some degree (e.g., De Graaf & Frijters, 1986; Lawless & Stevens, 1983; McBride, 1988). Perhaps two sweetness messages may be processed in a different manner in the peripheral neural system. The present study has demonstrated that, in spite of all these differences, two sweeteners that taste equally sweet will always give rise to the same degree of sourness suppression. Therefore, it seems plausible to conclude that, since perceptually equal stimuli give rise to the same degree of mixture suppression when mixed with the same amount of acid, sourness suppression in citric acid/sweetener mixtures must take place at the perceptual level and not in the solution or at the receptor.

In a recently published study, McBride and Finlay (1990) reported that sucrose suppresses the sourness intensity of citric acid more effectively than fructose does. It was not mentioned whether this difference was statistically significant. In our study, however, equisweet concentrations of fructose and sucrose were shown to be equally effective in suppressing the sourness intensity of citric acid, since their curves in Figure 1 coincide. It should be noted that McBride and Finlay (1990) used a much higher citric acid concentration in their experiment (0.050 M) than the highest concentration that was used in the present experiment (0.01 M). Such an increase in citric acid level and the corresponding increase in sourness intensity not only could affect the perceptual process but also might lead to chemical changes in the fructose or sucrose solutions because of the low pH value (Shallenberger & Birch, 1975).

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Chapter 3

INVESTIGATIONS ON SALTY-BITTER TASTING STIMULI

In this chapter, the taste sensations elicited by quinine hydrochloride/NaCl mixtures are investigated. The first study investigates the relationship between individual sensitivity differences for PROP and the perception of KCl, NaCl, quinine, and quinine/NaCl mixtures. The sensitivity to PROP is mainly determined by hereditary factors and, in previous studies, it has been related to the perception of many bitter and non-bitter substances. The effect of PROP-sensitivity on taste perception is studied in order to be able to decide whether this variable should be controlled in subsequent studies employing bitter tasting substances.

The second study investigates quinine/NaCl mixtures using two different experimental procedures.

The perception of the taste of KCl, NaCl and quinineHCl is not related to PROP-sensitivity.
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Two-stimulus versus one-stimulus procedure in the framework of functional measurement: a comparative investigation using quinineHCl/NaCl mixtures.
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The perception of the taste of KCl, NaCl and quinineHCl is not related to PROP-sensitivity

Hendrik N.J.Schifferstein and Jan E.R.Frijters

Wageningen Agricultural University, Department of Food Science, Bomenweg 2, 6703 HD Wageningen, The Netherlands

Abstract. Several investigators have studied the relationship between innate, individual, differences in sensitivity to PTC-type compounds and the perception of threshold and suprathreshold concentrations of a wide range of tastants. Some authors reported taste perception differed between 'tasters' and 'non-tasters'; others demonstrated no significant differences. The present study investigated whether an individual's PROP-sensitivity affects perception of KCl, NaCl and quinineHCl. The PROP-threshold concentrations for 60 subjects were determined using the method of limits. Two 20-subject contrast groups were selected to participate in the main experiment. Here, perceived bitterness, saltiness, and total taste intensity were assessed on 150 mm visual analogue scales. The two taster-groups did not differ in their perception of KCl, NaCl, or quinineHCl. It is hypothesized that the significant differences in the perception of PTC-unrelated compounds between 'tasters' and 'non-tasters' reported by other investigators may, in part, be the result of errors during the classification procedure and of inappropriate methods of statistical analysis.

Introduction

For most tastants the distribution of taste detection threshold concentrations in a group of individuals is Gaussian or monomodal (e.g. Blakeslee and Salmon, 1935). Fox (1932) has shown, however, that the threshold concentrations for phenylthiocarbamide (PTC)-type compounds are bimodally distributed. Individual differences in the ability to detect PTC are largely due to innate, hereditary differences (e.g. Blakeslee, 1932; Kalmus, 1971).

Subjects able to detect PTC-type compounds at low concentration levels are often referred to as 'tasters'; subjects relatively insensitive to PTC are called 'non-tasters'. This dichotomy is somewhat misleading since it suggests that the taster/non-taster classification represents two, well-defined groups. However, there is a continuous range of threshold concentrations between the thresholds of very sensitive and very insensitive subjects. Within one category subjects may differ considerably with regard to their individual PTC-thresholds. In addition, the term non-taster is misleading, because even 'non-tasters' can detect PTC at high concentrations. Nevertheless, the descriptors 'taster' and 'non-taster' will be used throughout this paper.

Several authors have noted that threshold concentrations for PTC correlate with the threshold concentrations of several substances chemically unrelated to PTC. Blakeslee and Salmon (1935) reported that subjects with low PTC-thresholds tended to have low thresholds for most of the other 16 substances they tested. We re-analyzed Blakeslee and Salmon's data and found that a subject's threshold concentration for PTC correlated positively with the threshold concentrations for quinine sulfate and optochin base, a substance chemically related to quinine (Spearman $r = 0.42$ and 0.34 respectively, $P < 0.05$). The threshold concentrations for quinine sulfate were correlated with six different substances, including optochin base, HCl, and NaCl ($P < 0.05$).

Subjects with high quinine detection thresholds and with low quinine thresholds are found in each of the two taster groups. However, subjects insensitive to 6-*n*-propylthiouracil (PROP), a PTC-type compound, have higher mean quinine thresholds than sensitive subjects. Within each of the two groups the mean PROP thresholds increase with increasing quinine thresholds. The antimode of the bimodal distribution for PROP detection threshold concentrations is found at lower PROP concentrations in subjects with low quinine thresholds than in subjects relatively insensitive to quinine (Kalmus, 1958; Leguèbe, 1960; Fischer and Griffin, 1963).

Hall *et al.* (1975) reported a bimodal distribution of caffeine-threshold concentrations in a population of twenty subjects (10 tasters and 10 non-tasters). The caffeine-threshold concentrations were correlated with the PTC-threshold concentrations. No relationship between PTC-taster status and the distributions of threshold concentrations for urea, quinine hydrochloride (QHCl) or NaCl was found.

Various attempts have been made to relate the differences in sensitivity to PTC and PROP to differences in perceived intensity of suprathreshold concentrations of substances not chemically related to PTC. Hall *et al.* (1975) reported differences between tasters and non-tasters for low caffeine levels (0.03 and 0.056 M) and for low urea levels (0.1 and 0.18 M). Leach and Noble (1986), using a time-intensity scaling procedure, found no significant difference for the perceived bitterness of caffeine. Mela (1989) did not find an association between PROP-sensitivity and bitterness intensity for caffeine nor for urea. Leach and Noble (1986) found a significant difference for the rated maximum intensity of the taste of quinine. Gent and Bartoshuk (1983) reported a similar result. Other investigators, however, did not find any association between PTC- or PROP-sensitivity and quinine bitterness (e.g. Hall *et al.*, 1975; Bartoshuk, 1979; Frank and Korchmar, 1985; Bartoshuk *et al.*, 1988; Mela, 1989). Mela (1989) found no significant differences between tasters and non-tasters for the perceived bitterness intensities of sucrose octa acetate and denatonium benzoate.

Bartoshuk (1979) reported that saccharin at low concentration levels (0.00032 M and 0.001 M) tasted significantly less bitter to PROP-non-tasters than to PROP-tasters. At higher concentration levels, no differences in bitterness intensity were reported. The sensitivity to saccharin seems to be unrelated to PROP-sensitivity (Blakeslee, 1932; Blakeslee and Salmon, 1935). Gent and Bartoshuk (1983) reported that saccharin was perceived as sweeter by PROP-tasters than by PROP-non-tasters. The perceived sweetness intensities of sucrose and neohesperidin dihydrochalcone have also been reported to be associated with PROP-sensitivity (Gent and Bartoshuk, 1983; Marks *et al.*, 1988). In 1979, Bartoshuk did not report whether the observed differences in sweetness scores for saccharin and sucrose were significant. Schiffman *et al.* (1985) found no differences between taster groups in their similarity scores of pairs of lemon-lime or cola beverages containing different types of sweeteners.

Bartoshuk *et al.* (1988) noted that subjects with high PROP-sensitivity rated NaCl, KCl, Na-benzoate and K-benzoate as being more bitter than subjects who had a low PROP-sensitivity. Neither NaCl saltiness nor HCl sourness seem to be associated with PROP-sensitivity (e.g. Bartoshuk, 1979; Frank and Korchmar, 1985; Mela, 1989).

Frank and Korchmar (1985) measured reaction times to PTC, sucrose, QHCl, NaCl and HCl. They concluded that the non-taster population was made up of two different groups. One group exhibited reaction times similar to those observed in the taster group for every substance tested. These 'sensitive' non-tasters seem to have a specific, PTC-sensitivity deficit that does not affect their perception of other substance tastes. The subjects in the 'insensitive' non-tasters group reacted slower to several classes of gustatory stimuli than did the tasters. The intensities rated for the stimuli were similar for 'sensitive' and 'insensitive' non-tasters.

In summary, it can be concluded that most studies mentioned above have produced conflicting results. All studies agree that the PTC-taster status affects the perception of PTC-related substances. The relationship between PTC-taster status and the perception of threshold or supra-threshold concentrations of substances chemically unrelated to PTC, however, remains to be established.

The present study is part of a larger investigation into taste interaction in bitter–salty tasting mixtures (Schifferstein and Frijters, 1991). Our objective was to determine the relationship between subjects' individual sensitivites for PROP and their perception of KCl, NaCl, QHCl and NaCl/QHCl mixtures. A preliminary experiment determined PROP-threshold concentration values of 60 subjects. In the main experiment, the saltiness, bitterness, and total taste intensity of KCl, NaCl, QHCl and NaCl/QHCl mixtures were assessed.

Preliminary experiment: methods and materials

Subjects

The subjects were 60 Caucasians, 13 men and 47 women, between 18 and 27 years of age. The subjects were paid for their participation. Most subjects were students of the Agricultural University and had little or no experience with psychophysical tasks. All subjects were naive as to the substances used and the purpose of the study.

Stimuli

The stimuli were solutions of 6-*n*-propylthiouracil (PROP) (Aldrich H3, 420–3) in demineralized water. The highest concentration, solution No. 14, contained 1.0212 g PROP/l. The other solutions were prepared by halving previous concentrations: thus, solution No. 13 contained 0.5106 g PROP/l, solution No. 12 contained 0.2553 g PROP/l, etc. (Fischer, 1971).

Solutions were prepared at least 24 h before tasting and were stored at 4°C for no longer than four days.

Procedure

There were two stages to each PROP detection threshold determination. During the first stage a rough estimate of the detection threshold was made using a modified 'up and down' method (e.g. Guilford, 1954; Cornsweet, 1962). During the second stage a more precise estimation of the threshold was made using the method of limits (e.g. Guilford, 1954; Corso, 1967; D'Amato, 1970).

The subject was first presented with solution No. 2, then No. 4, No. 6 etc. until the subject reported that a taste, clearly different from the taste of water, had been detected. When the subject reported that a taste was detected, the next lower concentrations were presented. For example, if the subject reported that a certain taste was perceived in solution No. 8, stimulus No. 7, 6, 5 etc. were presented. When the subject reported that no taste could be detected in a stimulus in this descending sequence, the subject was again presented with higher concentrations until a taste was perceived.

If the response reversals occurred at two, widely separated concentrations, the concentrations were lowered and heightened again until a reasonable estimate of the threshold had been achieved. The threshold concentration was estimated as equal to the mean of the two solution numbers (i.e. the geometric mean of the two concentrations) at which the two, last response reversals had occurred.

During the second part of the threshold determination the subject was presented with eight or ten alternating series containing either ascending or descending concentrations. Every examination started with an ascending series. The first part of threshold determination provided an initial approximation of the PROP-threshold concentration. This estimate was used to standardize the length of the eight or ten series (e.g. every determination started with solution number $y-5$, followed by a descending series that started with $y+3$, etc. where y stands for the estimate of the PROP-threshold based on preliminary determination). Where long series were needed, water or solution No. 14 could be presented several times at the beginning of an ascending or descending series. If the response changed from 'no taste' to 'taste' (ascending) or from 'taste' to 'no taste' (descending) the series was terminated.

The subjects were requested to rinse their mouths thoroughly with demineralized water after each stimulus. The stimuli were presented at room temperature (±20°C), and in polystyrene medicine cups. Each cup contained about 10 ml of solution. The time interval between two stimuli was a minimum of 30 s. If a subject needed more time to judge the stimuli, the time interval was extended.

Results

Each series yielded a threshold concentration. This value was taken as the mean of the solution number at which a series was terminated and the number of the stimulus immediately preceding it. The mean of these eight or ten threshold values was the estimated PROP detection threshold for each subject. Figure 1 shows the distribution of detection thresholds for the 60 subjects. The distribution is bimodal with the antimode at or near solution No. 8 (0.016 g = 9.4×10^{-5} M PROP).

Main experiment: methods and materials

Subjects

Two groups of 20 subjects were selected from the 60 subjects participating in the preliminary experiment. The tasters group, 4 male and 16 female subjects aged between 18 and 25 years, had the lowest PROP detection thresholds (mean threshold lower than, or equal to 6.5 = 3.3×10^{-5} M PROP). The non-tasters group, 5 male and 15 female subjects aged between 18 and 27 years, had thresholds higher than solution No. 9 (18.8×10^{-5} M PROP) (Figure 1). These subjects were selected because two-contrast groups were needed with regard to PROP detection thresholds.

All subjects were naive with respect to the substances used and the purpose of the study.

Stimuli

The stimuli were solutions of NaCl (Merck 6404), quinineHCl (Aldrich 14,592−0), KCl (Merck 4936), 6-*n*-propylthiouracil (PROP) (Aldrich H3,420−3), and mixtures of NaCl with QHCl in demineralized water.

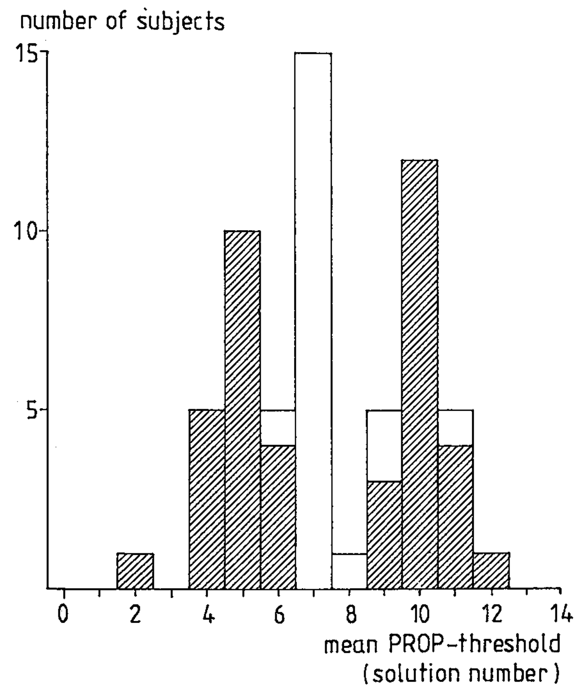

Fig. 1. Mean PROP detection threshold concentrations of 60 Dutch students. The values on the abscissa correspond to the solution numbers. A subject was classified in category x if the mean threshold value was greater than $x-0.5$ and smaller than or equal to $x+0.5$. The shaded area shows the threshold concentration distribution of the 40 subjects who participated in the main experiment.

Six levels of NaCl were combined factorially with six levels of QHCl, giving 36 stimuli. The concentrations of NaCl were 0.00, 0.03125, 0.0625, 0.125, 0.25, and 0.50 M NaCl. For QHCl these were 0.00, 1.5×10^{-5}, 3×10^{-5}, 6×10^{-5}, 12×10^{-5} and 24×10^{-5} M QHCl. The KCl concentrations were 0.0275, 0.055, 0.11 and 0.22 M KCl. In addition, 9.4×10^{-5} M PROP (solution No. 8 from the preliminary experiment) was presented twice to provide an internal check on the taster versus non-taster classification.

For reasons of standardization, reference stimuli were used. Minimum intensity on each of the three scales was defined as being equal to the perceived intensity of water. Maximum saltiness was defined as being equal to the saltiness of a reference containing 0.625 M NaCl. Maximum bitterness was defined as being equal to the bitterness of a reference containing 30×10^{-5} M QHCl. The second reference in the total taste intensity investigation was a mixture containing 0.75 M NaCl and 36×10^{-5} M QHCl. This reference defined the maximum total taste intensity.

Solutions were prepared at least 24 h before tasting and were stored at 4°C for no longer than four days.

Procedure

In the first investigation, the saltiness and bitterness of each of the experimental stimuli were assessed. Subjects' responses were recorded on sheets containing two, 150 mm graphic rating scales. One scale was used to assess the saltiness intensity of the stimulus and the other scale was used to assess the bitterness intensity of the same stimulus. The left and right ends of the saltiness scale were labelled 'not salty at all' and 'extremely salty'. Corresponding descriptors for the bitterness scale were 'not bitter at all' and 'extremely bitter'. The sequence of the two scales on the response sheet was randomized. During half the sessions subjects made their responses on sheets where the saltiness scale was printed above the bitterness scale. During the remaining sessions the position of the two scales was reversed. The subjects were instructed to judge the intensity of the perceived saltiness and the intensity of the perceived bitterness. They had to express their judgments by a slash mark on the corresponding scale. The instructions emphasized that only the saltiness and the bitterness intensity of a stimulus were to be judged and that the hedonic value and side tastes were to be disregarded.

In the total taste intensity investigation, the subjects judged the total taste intensity of each stimulus on one, 150 mm graphic rating scale. The left and right ends of the scale were labelled 'no taste at all' and 'extremely strong taste'. In the total taste intensity investigation, subjects were instructed to judge the total taste intensity, irrespective of quality, and to include every quality they perceived.

Subjects were requested to rinse their mouths thoroughly with demineralized water after each stimulus. The stimuli were presented at room temperature (±20°C), and in polystyrene medicine cups. Each cup contained about 10 ml of the solution. The time interval between stimuli was 60 s. In each session every subject judged 42 stimuli: the 36 stimuli resulting from the factorial mixing design, the four KCl concentrations, and the PROP concentration (which was presented twice each session). Each subject was given the stimuli in a random sequence and in a different order. The references (water, 0.625 M NaCl and 30×10^{-5} M QHCl for the saltiness–bitterness investigation; water and a mixture of 0.75 M NaCl and 36×10^{-5} M QHCl for the total taste intensity investigation) were presented at the beginning of each session and again after the 15th and 30th stimulus of each session. The saltiness–bitterness investigation was carried out before the total taste intensity investigation. Both investigations consisted of four, identical sessions. It took each subject eight one-hour sessions to complete the entire study.

Results

Responses to PROP

Each response was measured as the distance in mm from the left end of the scale to the slash mark given by the subject. The responses were classified into 151 categories corresponding to the distances measured (0, 1, 2 . . . 150 mm). The frequency of responses in each response category was determined. Finally, for each category the arithmetic mean of the responses in that category, and the responses in all lower categories was calculated. This arithmetic mean was called the 'cumulative mean' of the category.

Figure 2 shows the cumulative category means for the responses to 9.4×10^{-5} M PROP on the bitterness, saltiness, and total taste intensity scales for PROP-tasters and PROP-non-tasters. The threshold determination appears to have effectively separated the two groups. ANOVA revealed that the differences between the two taster-groups were significant for bitterness ($F(1,38) = 20.79$, $P < 0.001$) and total taste intensity

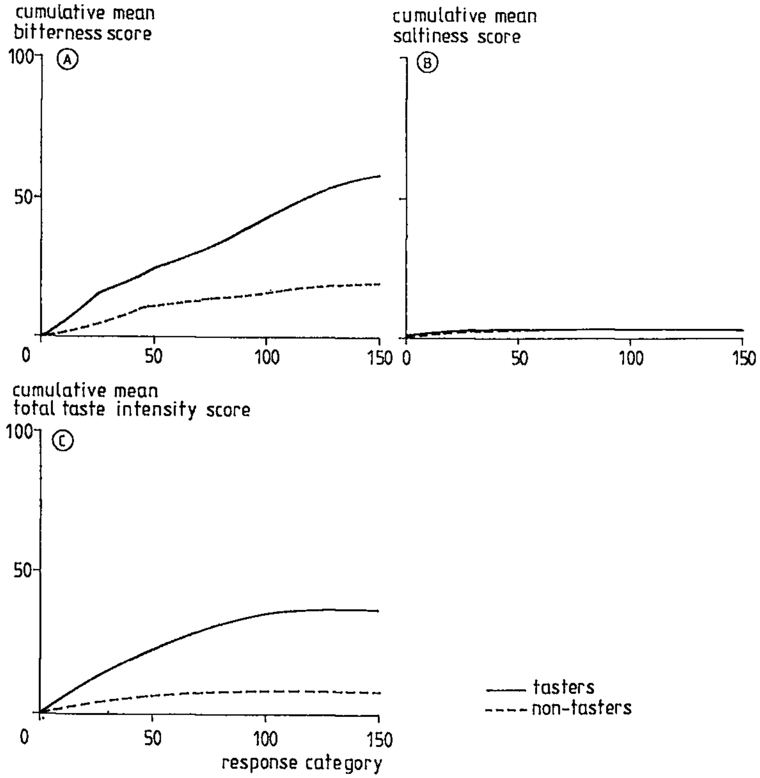

Fig. 2. The cumulative category means of 160 taster responses and 160 non-taster responses to 9.4×10^{-5} M PROP on the bitterness (A), saltiness (B), and total taste intensity (C) scale. The cumulative mean of the responses is given as a function of the distance (in mm) from the left of the scale. Each cumulative category mean is the arithmetic mean of the responses in that category and the responses in all lower categories.

($F(1,38) = 31.67$, $P < 0.001$) judgments, but not for saltiness estimates ($F(1,38) = 0.02$, $P = 0.88$).

The taste of KCl

ANOVA revealed that the KCl concentration had a significant effect on the bitterness, saltiness, and total taste intensity of KCl ($P < 0.001$). Figure 3 shows the relationship between KCl concentration and the mean responses on the three scales for PROP-tasters and PROP-non-tasters. Despite large differences in mean bitterness scores, ANOVA yielded no significant effects for taster status on any of the scales ($P > 0.20$). In addition, the apparent difference in bitterness scores between tasters and non-tasters is not in the expected direction. If PROP-taster status affects the perception of KCl, non-tasters are expected to be less sensitive to KCl, and, therefore, to give *lower* ratings on the bitterness scale. Figure 3A, however, shows that the non-taster group gives *higher* bitterness ratings than the taster group.

The taste of NaCl, quinineHCl and NaCl/quinineHCl mixtures

PROP taster status neither affects the perception of the bitterness of QHCl ($F(1,38) = 0.23$, $P = 0.63$) nor the perception of the saltiness of NaCl

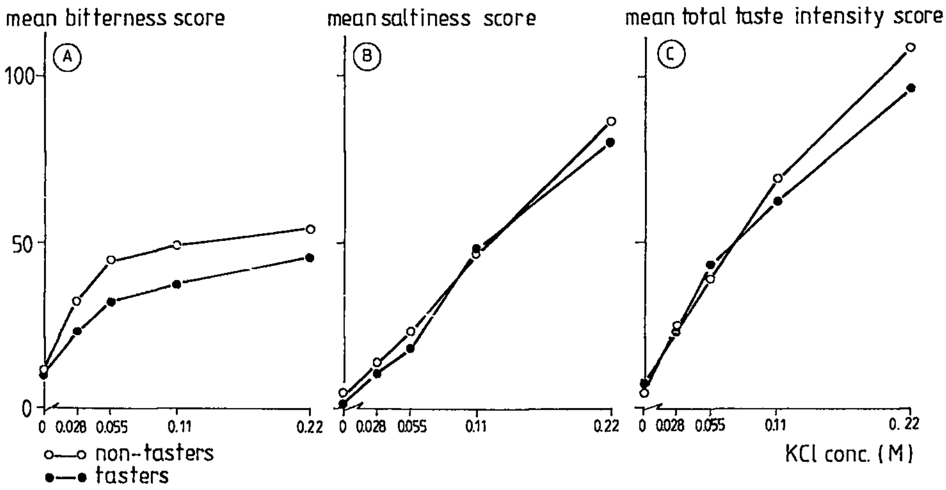

Fig. 3. Mean responses of tasters and non-tasters of PROP to KCl on the bitterness (A), saltiness (B), and total taste intensity (C) scale.

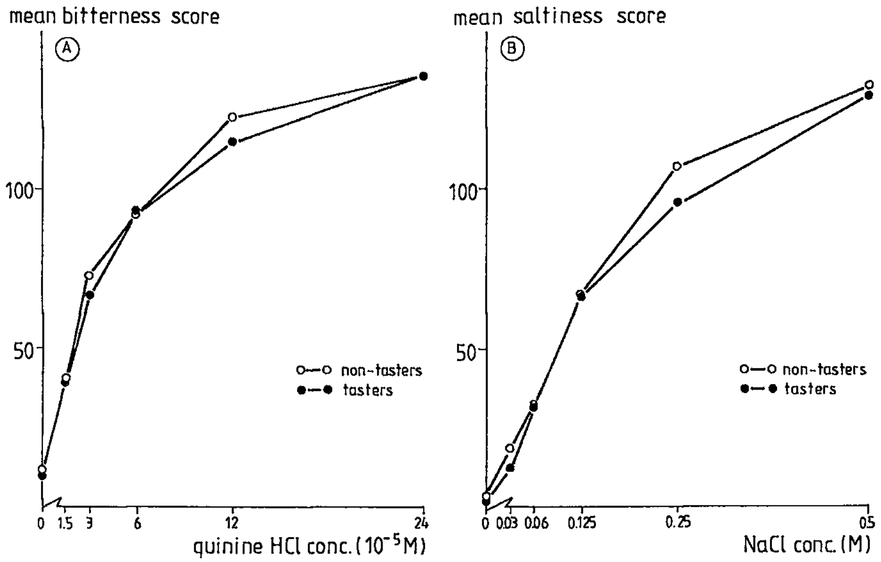

Fig. 4. Psychophysical functions for the bitterness of quinineHCl and the saltiness of NaCl with separate curves for PROP-tasters and PROP-non-tasters. The units on the bitterness scale and the saltiness scale are not necessarily equal.

($F(1,38) = 1.08$, $P = 0.31$) (Figure 4). Neither does PROP-sensitivity significantly affect the bitterness, saltiness, or total taste intensity of the 25 NaCl/QHCl mixtures ($P > 0.30$) (Figure 5).

It can be hypothesized that no effect of PROP taster status upon the taste intensity of QHCl, and NaCl was measured because the end points of the bitterness and saltiness scales were anchored by the use of references (water, 30×10^{-5} M QHCl, and 0.625 M NaCl). By anchoring the end points of a scale, the subjects judge every experimental stimulus relative to the two end-anchors. In this measurement technique

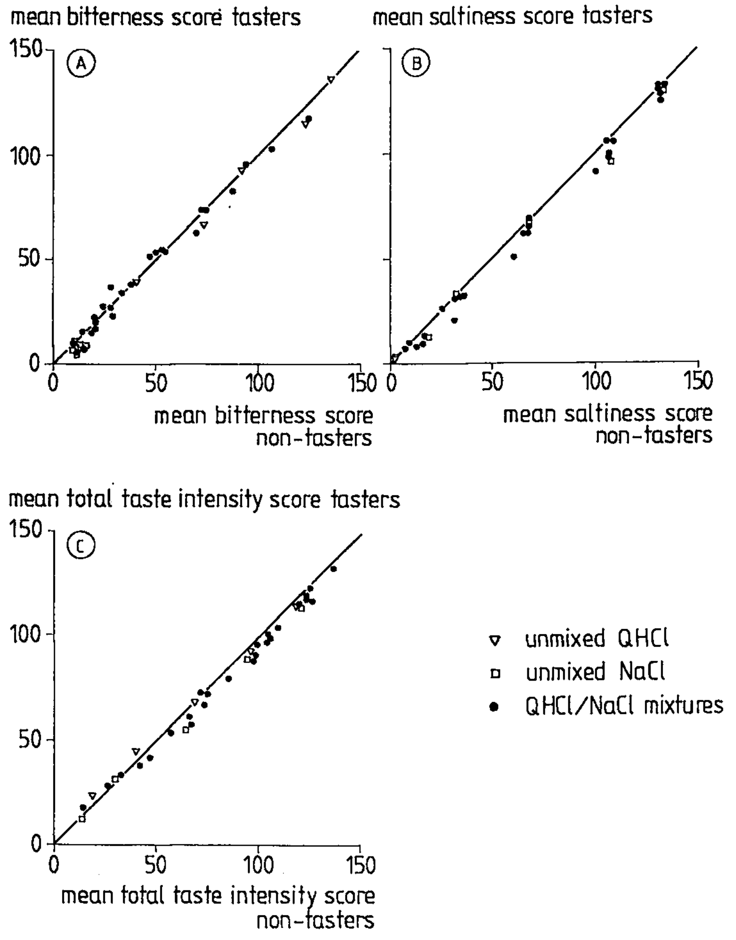

Fig. 5. The relationship between the mean responses of tasters and the mean responses of non-tasters of PROP to quinineHCl, NaCl, and quinineHCl/NaCl mixtures on the bitterness (A), saltiness (B), and total taste intensity (C) scale.

the means ratings derived are *relative*, not *absolute*. If, for example, the perceived bitterness intensity of a particular concentration of QHCl is higher for tasters than for non-tasters, the responses may be similar for the two groups because the tasters perceived the reference solutions as more bitter than the non-tasters.

On the total taste intensity scale the intensities of NaCl and QHCl were assessed on a scale with identical units. If the PROP-taster status affects the perception of QHCl but does not affect the perception of NaCl, the position of the tasters curve relative to the position of the non-tasters curve should be different for NaCl and QHCl. In fact, for QHCl the tasters' responses should be relatively high when compared to the responses of non-tasters. In the case of NaCl, the tasters' responses should be relatively low in comparsion with the responses of non-tasters. Figure 6 shows the psychophysical functions of QHCl and NaCl assessed on the total taste intensity scale. The above reasoning implies that the taster curve for QHCl would be relatively higher than the non-taster curve for QHCl (panel A) when compared to the position of the curves for

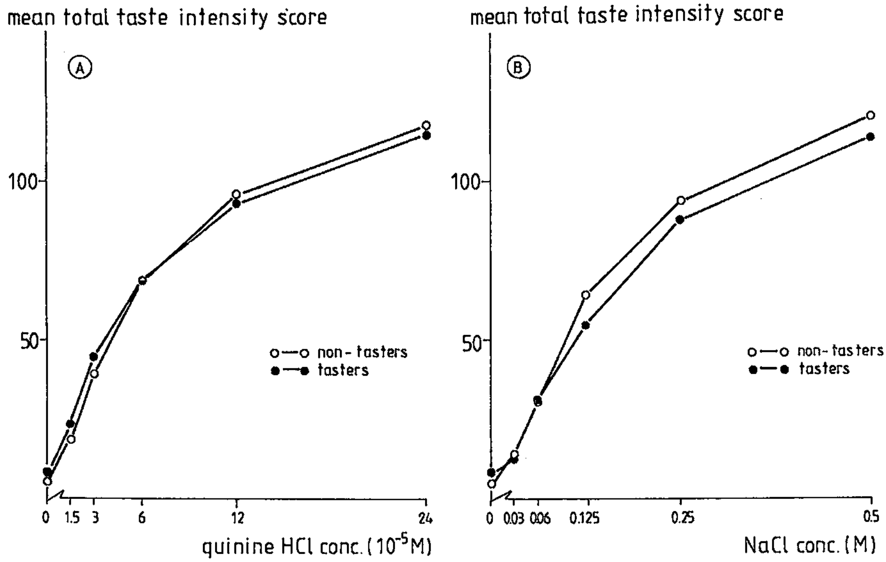

Fig. 6. Psychophysical functions for the total taste intensities of quinineHCl and NaCl with separate curves for PROP-tasters and PROP-non-tasters. The units on the two scales are equal.

NaCl (panel B). An ANOVA of the responses to the five concentrations of unmixed NaCl and the five concentrations of unmixed QHCl can test whether these differences are significant. The substance × taster-group interaction is tested against the substance × subject interaction as an error term. The substance × taster-group interaction was not significant ($F(1,38) = 0.51$, $P = 0.48$) and it can be concluded, therefore, that the PROP-taster status affects a subject's perception of the total taste intensities of NaCl and QHCl to the same degree. Since the taster-group effect is not significant for the NaCl ratings ($F(1,38) = 0.66$, $P = 0.42$) nor for the QHCl ratings ($F(1,38) = 0.05$, $P = 0.82$), it is unlikely that the perceived intensities of QHCl or NaCl are affected by a subject's PROP-sensitivity.

Discussion

Distribution of PROP detection threshold concentrations

The distribution of PTC- or PROP-threshold concentrations in a sample population is usually bimodal. The percentage of non-tasters depends upon the ethnic group sampled. The reported proportions of non-tasters in a Caucasian sample population range from 25 to 42%. In other ethnic groups this proportion is usually reported to be smaller and can be as small as 3% (e.g. Levine and Anderson, 1932; Cohen and Ogdon, 1949; Harris and Kalmus, 1949; Leguèbe, 1960; Sato and Sata, 1989). In the present study, 38% of the subjects had a mean PROP threshold greater than the antimode. This value is within the range of values reported above for a Caucasian population.

Lawless (1980) chose 56×10^{-5} M PROP (equivalent to a mean threshold of 10.4) as the antimode of the threshold concentration distribution. Fischer and Griffin (1963) reported that solutions 9 or 10 (18.8 or 37.5 $\times 10^{-5}$ M PROP) should be regarded the antimode. In the present study, the antimode was found to be equal to solution number

8 (9.4×10^{-5} M PROP). Lawless chose the antimode on the basis of the reported values in previously published papers, not on the basis of his own data. In addition, Lawless (1980) and Fischer and Griffin (1963) used a forced-choice procedure instead of the method of limits. During the forced-choice trials, subjects had to determine which four out of eight cups contained a tastant. Since this task differs substantially from the threshold determination employed in the present study, the antimodes found may not be directly comparable.

The relationship between PROP- or PTC-taster status and the perceived taste of KCl, QHCl and NaCl

Bartoshuk *et al.* (1988) studied the same substances as we examined in the present experiment. In contrast to the present results, however, they found several significant differences between PROP-tasters and PROP-non-tasters. First, their Figure 1 shows a significant effect of PROP-taster status on the perceived bitterness intensity of KCl, Na-benzoate, and K-benzoate. Interestingly, Bartoshuk *et al.* also reported that subjects highly sensitive to PROP estimated the bitterness of NaCl as higher than those subjects insensitive to PROP. NaCl, however, is not known to elicit a bitter taste quality (e.g. Bartoshuk, 1980). There is no straightforward explanation for the high bitterness estimates for unmixed NaCl among the PROP-tasters. It is possible that the subjects in the PROP-taster group tended to give higher magnitude estimates when judging bitterness than the subjects in the non-tasters group. The higher bitterness estimates for NaCl and KCl, Na-benzoate, and K-benzoate could then be the result of a *response* effect, and not of a *sensory* effect. This explanation can also account for the fact that the estimated magnitude for water was substantially (although not significantly) higher for tasters than for non-tasters.

A note on statistical analysis

In several studies investigating the relationship between PTC-taster status and the perception of PTC-unrelated compounds only t-tests (Hall *et al.*, 1975; Gent and Bartoshuk, 1983; Marks *et al.*, 1988) and/or non-parametric equivalents of the t-test (Bartoshuk, 1979) were used to test hypotheses. The use of the t-test is functionally equivalent to the use of an F-test with one degree of freedom (e.g. Winer, 1971, p. 36) in an analysis of variance with fixed factors (as probably used by Leach and Noble, 1986). A serious disadvantage of these tests is the fact that they all test the hypothesis that the mean response in the 'taster'-group differs from the mean response in the 'non-taster'-group. Whether the conclusion of the statistical test can be extrapolated to conclude that 'tasters' differ from 'non-tasters' depends upon the size of the variance between subjects. A discussion of ANOVA models can clarify this issue. An outline of the ANOVA for the responses to KCl using a factorial design with three fixed factors is given in Table I. Since every subject participates in only one of the two taster-groups the subjects effect is nested under the taster-group effect. In this type of ANOVA each of the main effects is tested for significance against the residual variance.

In most of the psychophysical experiments the subjects are regarded as representative of the population they were sampled from. In the present study, for example, the 'tasters'-group is supposed to represent Caucasians highly sensitive to PROP. Therefore, the subjects effect should not be regarded as a fixed effect but as a random effect (e.g.

Table I. Summary of analysis of variance for the responses to KCl. The subjects effect is nested under the taster-group effect. The third column gives the expected mean squares for a fixed effects model. The fourth column gives the expected mean squares for a mixed model in which the subjects-effect is random and the KCl-effect and the taster-group effect are fixed (adapted from Winer (1971), pp. 363 and 375)

Source of variation	df*	Expected mean squares	
		Fixed effects	Mixed model
Taster-group	p−1	$\sigma_\epsilon^2 + nkq\sigma_\tau^2$	$\sigma_\epsilon^2 + nq\sigma_\pi^2 + nkq\sigma_\tau^2$
Subjects-within-groups	p(k−1)	$\sigma_\epsilon^2 + nq\sigma_\pi^2$	$\sigma_\epsilon^2 + nq\sigma_\pi^2$
KCl	q−1	$\sigma_\epsilon^2 + npk\sigma_\alpha^2$	$\sigma_\epsilon^2 + n\sigma_{\pi\alpha}^2 + nkp\sigma_\alpha^2$
KCl × taster-group	(p−1) (q−1)	$\sigma_\epsilon^2 + nk\sigma_{\tau\alpha}^2$	$\sigma_\epsilon^2 + n\sigma_{\pi\alpha}^2 + nk\sigma_{\tau\alpha}^2$
KCl × subjects-within-groups	p(k−1) (q−1)	$\sigma_\epsilon^2 + n\sigma_{\pi\alpha}^2$	$\sigma_\epsilon^2 + n\sigma_{\pi\alpha}^2$
Error	pkq(n−1)	σ_ϵ^2	σ_ϵ^2

*p = number of groups.
k = number of subjects within each group.
q = number of concentration levels of KCl.
n = number of replications.
σ_ϵ^2 = random variance.
σ_τ^2 = variance between taster-groups.
σ_π^2 = variance between subjects.
σ_α^2 = variance due to differences in KCl concentrations.
$\sigma_{\tau\alpha}^2$ = variance due to interaction between KCl and taster-groups.
$\sigma_{\pi\alpha}^2$ = variance due to interaction between KCl and subjects.

O'Mahony, 1986; Lundahl and McDaniel, 1988). The expected mean squares for a mixed model ANOVA with a random subjects effect is shown in the 4th column of Table I. From this column, it can be concluded that the taster-group effect should be tested for significance using the subjects-within-groups effect as an error term. If tested against an error term containing only residual variance (σ_ϵ^2), a significant effect may be due to the influence of taster status (σ_τ^2) or to the variation between subjects within the same group (σ_π^2). Therefore, not using the subjects-within-groups effect but an other error term might lead to erroneous conclusions.

It is noteworthy that several authors who tested the taster-group effect against the subjects-within-groups effect (Frank and Korchmar, 1985; Mela, 1989) did not report any significant effect of taster status upon responses to PTC-unrelated compounds. Only Bartoshuk *et al.* (1988) reported significant differences between taster-groups for the perception of KCl, Na-benzoate, and K-benzoate.

It can be hypothesized, therefore, that reported, significant differences between tasters and non-tasters with regard to taste intensities elicited by substances chemically unrelated to PTC may, in part, have resulted from inappropriate methods of statistical analysis.

The effect of taster status upon the perception of near-threshold concentration levels

Several authors have reported significant differences between tasters and non-tasters with regard to the perceived intensities of low concentration levels of caffeine (Hall *et al.*, 1975), urea (Hall *et al.*, 1975), saccharin (Bartoshuk, 1979), sucrose (Marks *et al.*, 1988), and NaCl (Marks *et al.*, 1988), whilst the intensities of higher concentration levels were similar for both groups. The reported differences are not necessarily the result of PTC-taster status, but may have resulted from the classification procedure employed. As subjects are classified on the basis of their detection threshold concentration for PTC or PROP, the 'tasters' have low threshold concentrations and the 'non-tasters' have high threshold concentrations for PTC or PROP. However, since threshold concentrations for many sapid stimuli are positively correlated (e.g. Hopkins, 1946; Hinchcliffe, 1959; Fischer and Griffin, 1963), the subjects in the 'taster'-group may not only be more sensitive to PTC or PROP, but may also be more sensitive to many other substances than the subjects in the 'non-taster'-group. Therefore, differences in perceived intensities at near-threshold concentration levels may be due to an overall sensitivity difference between the subjects in the two taster-groups, and not to one particular difference in PTC-sensitivity.

In order to avoid this error during the classification procedure, Kalmus (1958) and Fischer and Griffin (1963) have argued that subjects should be classified according to their PTC- or PROP-threshold concentration *and* their threshold concentration for quinine. However, in none of the studies reporting differences between taster-groups at low concentration levels quinine thresholds were determined to improve the taster-group classification. Therefore, the reported differences may be an artefact of the classification procedure employed.

Two implicit assumptions have been made by authors investigating the association between PROP-sensitivity and the perception of bitterness or other taste qualities in suprathreshold concentrations of tastants. First, it is assumed that a subject's PTC detection threshold is related to the detection threshold for the substance under investigation. The threshold concentrations for this tastant have to be bimodally distributed, similar to the threshold concentrations for the PTC-type compounds. To our knowledge, such a biomodal threshold distribution has only been claimed to exist for caffeine (Hall *et al.*, 1975). A statistically significant positive correlation between the individual threshold concentrations for a certain tastant and those for PTC should not be regarded as solid evidence for the fact that the sensitivity for that tastant is related to PTC-sensitivity, since threshold concentrations for many sapid stimuli have been reported to correlate positively (e.g. Hopkins, 1946; Hinchcliffe, 1959; Fischer and Griffin, 1963).

Second, it is implicitly assumed that a direct correspondence exists between a subject's detection threshold and the intensity rating or magnitude estimate given to a suprathreshold concentration. An extrapolation from threshold determinations to suprathreshold intensity estimates is not legitimate, however (Harper, 1950). If detection thresholds are used as valid measures of perceived intensities, perceived intensities must grow with increasing stimulus concentrations at identical rates for all tastants investigated (e.g. Harper, 1972; Bartoshuk, 1978). Many substances, however, appear to have differently shaped psychophysical functions. Differential sensitivities (Weber fractions) and exponents of power functions vary within and between taste qualities (e.g. Schutz and Pilgrim, 1957; Moskowitz, 1971a,b). Moskowitz (1970a,b), for example, reported exponents of psychophysical power functions for the sweetness of fifteen sugars that ranged from 0.24 to 1.36 and for the sweetness of three artificial sweeteners that ranged from 0.3 to 1.0.

It can be concluded therefore, that previous studies have not convincingly demonstrated that tasters and non-tasters differ with regard to their perceived taste intensities of compounds unrelated to PTC. In the present study, such a difference was not demonstrated for any of the substances used. On the basis of the available data it can only be concluded that tasters and non-tasters of PTC or PROP differ substantively with regard to their perception of the bitterness of PTC-type compounds.

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Two-stimulus versus one-stimulus procedure in the framework of functional measurement: a comparative investigation using quinine HCl/NaCl mixtures

Hendrik N.J.Schifferstein and Jan E.R.Frijters

Department of Food Science, Agricultural University, Bomenweg 2, 6703 HD Wageningen, The Netherlands

Abstract. When subjects are requested to judge single stimuli the observable responses are the result of both sensory and judgmental processes. De Graaf *et al.* (1987) employed functional measurement in combination with a two-stimulus procedure in order to separate these two types of processes. This paper discusses the results of two experiments investigating taste interactions in quinine HCl/NaCl mixtures. The first experiment employed a one-stimulus procedure, the second experiment employed De Graaf *et al.*'s two-stimulus procedure. Comparing the two procedures, the main advantage of the one-stimulus procedure seems to lie in its simplicity. In addition, it enables the determination of a scale value for water. However, the obtained ratings are context-dependent and are affected by end effects of the response scale. The most important benefit of the two-stimulus procedure is that it allows for a post-experimental verification of the linearity of the response-output function. This check ensures that all scale values are assessed on an interval scale. If water can be assumed to be tasteless, ratio scale values can be obtained. It was shown that quinine bitterness is largely suppressed by NaCl, whilst the saltiness intensity elicited by NaCl remains virtually unaffected. In both experiments, the perceived total taste intensity of a mixture could be well predicted by the weighted sum of the saltiness and bitterness sensations within the mixture percept.

Introduction

A valid description of taste interaction phenomena requires that one scale value is derived for each sensation perceived. This value must represent a taste intensity on an interval or ratio scale. The stimulus-organism-response (S-O-R) paradigm of psychophysical judgment distinguishes between a psychophysical stage relating stimulus to sensation and a judgmental stage relating sensation to response. Whether or not the sensation scale derived from the responses has interval properties, depends on the linearity of the relationship between perceived intensities and overt responses. Since the judgmental operation is irrelevant to the peripheral psychophysical and central psychosensory interactions, a correct description of the sensory processes involved in the perception of taste mixtures can be achieved only by a measurement procedure that separates the sensory processes from the judgmental processes.

Figure 1 describes the relationship between stimulus and response according to an S-O-R point of view. The notation used in this paper is identical to that proposed by Frijters (1987). The physical concentration of an unmixed stimulus is denoted by ϕ and the physical concentration of a component in a mixture by Φ. The taste intensities of single substances outside the mixture are denoted by ψ and the taste intensities of the mixture or the compounds within the mixture are denoted by Ψ. Coded sensations are given by s (unmixed stimulus) and S (mixture). The Roman subscripts a and b refer to the chemicals used, whilst Greek subscripts refer to the sensations to be judged. The subscripts i and j represent particular concentrations of the substances a and b.

The relationship between the physical concentrations of a mixture and the response given by a subject can be conceived of as a sequence of three consecutive transformations.

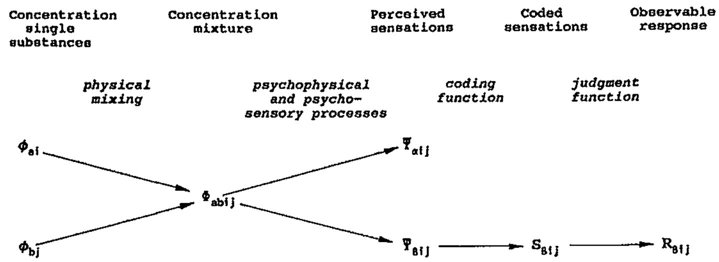

Fig. 1. Conceptual outline of a one-stimulus procedure from an S-O-R point of view. Each concentration i of substance a is mixed with each concentration j of substance b (factorial mixing design). The physical mixture evokes two sensations, α and β, that are elicited by substance a and b, respectively. The sensation to be judged (β) is encoded into a coded sensation. This coded sensation is transformed into an observable response. For an explanation of the symbols used, see text.

First, there is a psychophysical function relating the physical mixture to the perceived sensations elicited by that mixture. These sensations, temporarily stored in the sensory buffer, may be transformed into coded sensations and subsequently stored in the short-term memory. If longer retention is required, they may also be stored in the long-term memory. Strictly speaking, a coded sensation is not a sensation, but a cognitive entity (Frijters, 1992). Any sensory scale derived from rated intensities necessarily represents coded sensations. Marks (1979) and Algom and Katzir (1990) have suggested that subjects may use different sensation scales, implying different coding functions, under different response conditions. However, Birnbaum (1978) successfully demonstrated that the nature of the coding function is not affected by varying the set of instructions. De Graaf and Frijters (1988a) obtained results similar to Birnbaum's in an experiment employing taste stimuli. Therefore, the coding function is assumed to be an intermediate transformation from the sensory to the cognitive level of perception, which does not depend upon the response procedure used. This assumption is the basis of the *scale convergence criterion* in studies investigating cognitive algebraic models (e.g. Birnbaum and Veit, 1974; Birnbaum and Mellers, 1978). The third function describes the relationship between the coded sensation and the overt response. This function is often referred to as judgment function or response output function.

In order to construct mixtures in a systematic way, several authors have made use of a *factorial mixing design* (e.g. McBride, 1986; Frank and Archambo, 1986; De Graaf *et al.*, 1987). In such a design, each of a number of concentrations of one compound is mixed with each of a number of concentrations of the other compound. If subjects are requested to judge the intensity of the mixtures resulting from a factorial mixing design in a single stimulus procedure, the observable response is the result of both sensory and judgmental processes. Only when the factorial plot of the factorial mixing design exhibits a specific pattern (parallel lines, bilinear fan), can conclusions be drawn about the separate perceptual and judgmental processes. If a plot of parallel lines is obtained, it can be concluded that the two substances behave additively at the sensory and at the judgmental level, and also that the response output function must be linear. However, if the curves converge or diverge, it cannot be concluded logically whether this interaction has a psychophysical or a judgmental origin since both types of processes

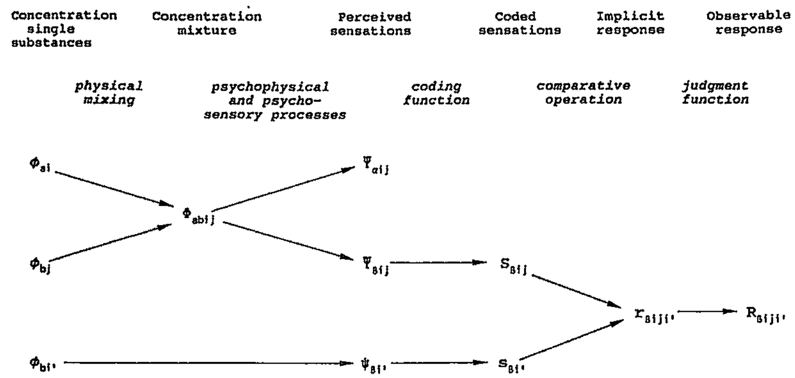

Fig. 2. Conceptual outline of the two-stimulus procedure as proposed by De Graaf *et al.* (1987). The subject compares the intensity of a sensation elicited by one stimulus (the experimental stimulus) to the intensity elicited by another stimulus (the comparison stimulus). If the comparative operation between the two coded intensities can be represented by an algebraic difference function, then the implicit response r must resemble the difference between $S_{\beta ij}$ and $s_{\beta i'}$.

can account for the observed interaction (Anderson, 1974, 1981; Klitzner, 1975; De Graaf *et al.*, 1987; Frijters, 1992).

De Graaf *et al.* (1987) have used a combination of a two-stimulus procedure with functional measurement (e.g. Anderson, 1974, 1981) in taste mixture research. Such a combination was first applied in taste research by Klitzner (1975) in a study of hedonic integration. This methodology permits a separation of the sensory from the judgmental processes. De Graaf *et al.* instructed subjects to judge the magnitude of the difference between the perceived taste intensity of each 'row' (first) stimulus and each 'column' (second) stimulus. The authors called this type of design a *factorial judgment design*. The pairs of stimuli consisted of one experimental stimulus, often a mixture, and one comparison stimulus (Figure 2). It has been shown that subjects perform a subtractive operation when they are instructed to judge a difference. The subtractive model predicts no interaction between row and column stimuli, assuming the response scale is linear (e.g. Birnbaum, 1978; Birnbaum and Mellers, 1978). Therefore, testing the row × column interaction for significance provides the basis for testing (a) whether the comparative operation is subtractive and (b) whether the function transforming the difference between the two sensations into a 'difference' response is linear. The shape of the response output function is independent of the kind of taste interaction that has occurred or the shape of the psychophysical functions. After the linearity of the response scale in a particular experiment has been checked and confirmed, scale values for the experimental stimuli can be calculated from the marginal means of the row and column stimuli. These calculated scale values are considered to be valid estimates of the perceived taste intensity on an interval scale (Anderson, 1981). Since the coding function is not affected by the judgmental task (e.g. Birnbaum, 1978), the encoding process is not likely to affect the obtained sensation scale. Therefore, the calculated scale values can be regarded as the output from psychophysical and psychosensory processes.

It should be noted that the term *factorial mixing design* refers to the physical composition of mixtures and should not be confused with the term *factorial judgment design* which refers to the presentation of pairs of (mixed and unmixed) stimuli to the subjects (De Graaf and Frijters, 1988b).

Taste interaction in mixtures of bitter and salty tastants

Few studies have been reported on bitter–salty taste interactions. Pangborn (1960) observed that a subthreshold concentration of caffeine reduced NaCl saltiness and that, inversely, a subthreshold concentration of NaCl reduced caffeine bitterness. Kamen *et al.* (1961) observed no effect of caffeine on NaCl saltiness or vice versa. Quinine bitterness is largely suppressed by NaCl. The taste of NaCl is also suppressed by quinine but to a much lesser degree (Indow, 1969; Bartoshuk, 1975, 1980; Kroeze, 1980).

In the present study, results obtained with a one-stimulus procedure will be compared to results obtained with a two-stimulus procedure within the framework of functional measurement. The results of two investigations researching taste interactions in mixtures of quinine hydrochloride (QHCl) and NaCl are reported. The comparison between the two procedures will focus upon the implications of using one of these procedures on the outcomes of a taste mixture experiment.

First study

In the first study a one-stimulus procedure was employed in combination with a factorial mixing design. This study was designed to resemble studies performed by e.g. Frank and Archambo (1986), McBride and Johnson (1987) and McBride (1989). In each of these studies, subjects were instructed to judge more than one attribute per stimulus presentation (specific taste sensations, total taste intensity and/or affective value) on 21-point category scales or graphic rating scales. In the present study, the assessment of total taste intensity was done separately from the assessments of the two specific taste intensities in order to avoid response dependencies between total taste intensity scores and specific taste intensity scores.

Materials and methods

Subjects

The subjects were 40 paid volunteers, 9 men and 31 women, ranging in age from 18 to 27 years. Most subjects were students of the Agricultural University and had little or no experience with psychophysical tasks. All subjects were naive with respect to the substances used and the purpose of the study.

Stimuli

The stimuli were solutions of NaCl (Merck 6406), quinine HCl (Aldrich 14, 592-0), KCl (Merck 4936), 6-*n*-propylthiouracil (PROP; Aldrich H3, 420-3) and mixtures of NaCl with QHCl in demineralized water.

Six levels of NaCl were combined factorially with six levels of QHCl, giving 36 stimuli. The concentrations of NaCl were 0.00, 0.03125, 0.0625, 0.125, 0.25 and 0.50 M. For QHCl these were 0.00, 1.5×10^{-5}, 3×10^{-5}, 6×10^{-5}, 12×10^{-5}

and 24 $\times$ 10^{-5} M. Four solutions of KCl and two of PROP were included in view of another study (Schifferstein and Frijters, 1991b).

For reasons of standardization, reference stimuli were used. Minimum intensity on each of the three scales was defined as being equal to the perceived intensity of water. Maximum saltiness was defined as being equal to the saltiness of a reference containing 0.625 M NaCl. Maximum bitterness was defined as being equal to the bitterness of a reference containing 30 $\times$ 10^{-5} M QHCl. The second reference stimulus in the total taste intensity investigation consisted of a mixture of 0.75 M NaCl and 36 $\times$ 10^{-5} M QHCl. This reference defined the maximum total taste intensity.

Solutions were prepared at least 24 h before tasting and were stored at 4 °C in a dark room for no longer than 4 days.

Procedure

In one investigation, the saltiness and bitterness of each of the experimental stimuli were assessed. Subjects' responses were recorded on sheets containing two 150 mm graphic rating scales. One scale was used to assess the saltiness intensity of the stimulus and the other scale was used to assess the bitterness intensity of the same stimulus. The left and right ends of the saltiness scale were labelled 'not salty at all' and 'extremely salty'. Corresponding descriptors for the bitterness scale were 'not bitter at all' and 'extremely bitter'. The sequence of the two scales on the response sheet was randomized. During half the sessions subjects made their responses on sheets where the saltiness scale was printed above the bitterness scale. During the remaining sessions the position of the two scales was reversed. The subjects were instructed to express their judgements by a slash mark on the corresponding scale. The instructions emphasized that only the saltiness and the bitterness intensity of a stimulus were to be judged, and that the hedonic value and side tastes were to be disregarded.

In the total taste intensity investigation, the subjects judged the total taste intensity of each stimulus on one 150 mm graphic rating scale. The left and right ends of the scale were labelled 'no taste at all' and 'extremely strong taste'. In the total taste intensity investigation, subjects were instructed to judge the total taste intensity, irrespective of quality, and to include every quality they perceived.

Subjects were requested to rinse their mouths thoroughly with demineralized water after each stimulus. The stimuli were presented at room temperature (~20°C) in polystyrene medicine cups. Each cup contained about 10 ml of solution. The time interval between stimuli was 60 s. In each session every subject judged 42 stimuli: the 36 stimuli resulting from the factorial mixing design, four KCl concentrations and two PROP solutions. Each subject was given the stimuli in a random sequence and in a different order. The references (water, 0.625 M NaCl and 30 $\times$ 10^{-5} M QHCl for the saltiness-bitterness investigation; water and a mixture of 0.75 M NaCl and 36 $\times$ 10^{-5} M QHCl for the total taste intensity investigation) were presented at the beginning of each session and again after the 15th and 30th stimulus of each session. The saltiness-bitterness investigation was carried out before the total taste intensity investigation. Both investigations consisted of four identical sessions. It took each subject eight 1-h sessions to complete the entire study.

Results

Saltiness, bitterness and total taste intensity of quinine HCl/NaCl mixtures

Figure 3 (panel A) shows the bitterness of QHCl, NaCl and their mixtures as a function of the bitterness of QHCl, with a separate function for each NaCl concentration. Visual inspection shows a diverging pattern of functions in which a higher concentration of NaCl produces a greater bitterness suppressing effect. In addition, the QHCl concentration influences the bitterness and the degree of suppression. ANOVA showed statistically significant effects for QHCl [$F(5,195) = 389.23$, $P < 0.001$], NaCl [$F(5,195) = 157.22$, $P < 0.001$] and the QHCl × NaCl interaction [$F(25,975) = 30.55$, $P < 0.001$].

Figure 3B shows the saltiness of NaCl, QHCl and QHCl/NaCl mixtures as a function of the saltiness of NaCl. Visual inspection shows that the saltiness intensities of the QHCl/NaCl mixtures almost equal those of the unmixed NaCl. Despite the minimal differences between the saltiness intensities of the mixtures, ANOVA showed significant effects for NaCl [$F(5,195) = 3372.85$, $P < 0.001$], QHCl [$F(5,195) = 11.60$, $P < 0.001$] and the QHCl × NaCl interaction [$F(25,975) = 1.97$, $P < 0.01$]. Only the saltiness ratings for the highest QHCl concentration mixed with 0.03125 or 0.125 M NaCl were significantly lower than the ratings of unmixed NaCl (one-tailed Dunnett *t*-test, $P < 0.05$).

Figure 4 shows the total taste intensity of the experimental stimuli as a function of the total taste intensity of unmixed QHCl, with a separate curve for each concentration of NaCl. The curves show a convergent pattern where, in several cases, the total taste intensity of a mixture is lower than the total taste intensity of unmixed QHCl. Obviously,

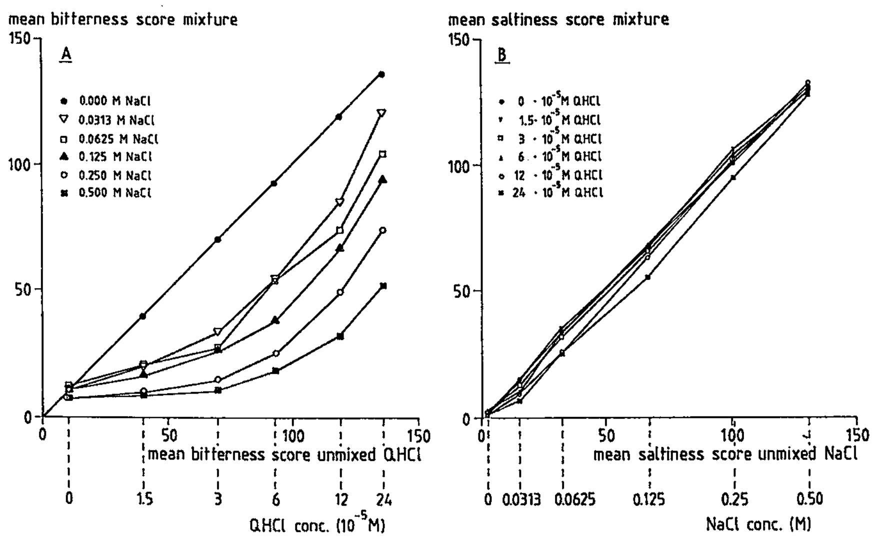

Fig. 3. Panel A shows the mean bitterness scores of QHCl, NaCl and the NaCl/QHCl mixtures as a function of the mean bitterness scores of unmixed QHCl with a separate curve for each NaCl concentration. Panel B shows the mean saltiness scores of NaCl, QHCl and the NaCl/QHCl mixtures as a function of the mean saltiness scores of NaCl with a separate curve for each QHCl concentration. The units of the 'bitterness' scale and the 'saltiness' scale are not equal.

QHCl bitterness is suppressed by NaCl. ANOVA showed significant effects for QHCl [$F(5,195) = 308.42$, $P < 0.001$], NaCl [$F(5,195) = 249.95$, $P < 0.001$] and the QHCl × NaCl interaction [$F(25,975) = 76.22$, $P < 0.001$].

Bitterness and total taste intensity of QHCl and saltiness and total taste intensity of NaCl

Figure 5A shows the relationship between the mean bitterness scores and the mean total taste intensity scores for QHCl. Figure 5B shows a similar plot for the mean saltiness scores and mean total taste intensity scores for NaCl. The lines were obtained through orthogonal linear regression through the origin (e.g. Hampton, 1983), yielding regression coefficients of 0.78 for the QHCl data ($R^2 = 0.986$) and 0.90 for the NaCl data ($R^2 = 1.000$).

The mean scores on the two scales for QHCl are clearly not linearly related. The difference between the mean scores on the bitterness scale and those on the total taste intensity scale may be hypothesized to have a sensory origin or may be attributed to a different response output function. The first explanation assumes that the total taste intensity is higher than the bitterness intensity of QHCl at high concentration levels. This explanation suggests the appearance of side tastes at high QHCl levels. However, QHCl is known to elicit a singular, purely bitter taste (e.g. O'Mahony *et al.*, 1983). In addition, the results of experiment 2 to be discussed below yielded a linear relationship between bitterness and total taste intensity scale values, which makes an explanation on the basis of sensory heterogeneity of the QHCl sensation unlikely.

The second explanation assumes that the non-linearity results from different response output functions in the two investigations. A possible explanation may lie in the unequal

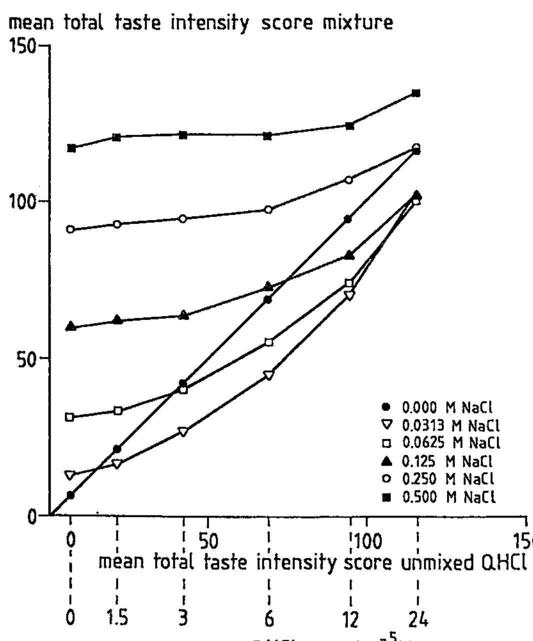

Fig. 4. The mean total taste intensity scores of QHCl, NaCl and the NaCl/QHCl mixtures as a function of the mean total taste intensity scores of unmixed QHCl, with a separate curve for each NaCl concentration.

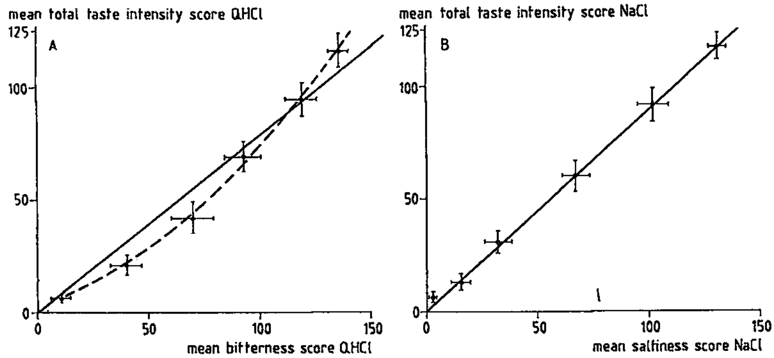

Fig. 5. Panel A shows the relationship between the mean bitterness scores and mean total taste intensity scores of QHCl. Panel B shows the relationship between the mean saltiness scores and mean total taste intensity scores of NaCl. In both graphs the point which is nearest to the origin shows the mean rating for demineralized water. The straight lines were obtained by linear orthogonal regression through the origin. The dotted line in panel A shows the least squares second order polynomial function obtained after correction for the mean water scores. The error bars parallel with the ordinate represent the 95% confidence intervals for the mean total taste intensity scores. The error bars parallel with the abscissa represent the 95% confidence intervals for the mean bitterness and mean saltiness scores, respectively.

distribution of the perceived bitterness intensities over the psychological continuum (Parducci, 1974; Riskey *et al.*, 1979; Mellers and Birnbaum, 1982). Due to the large degree of bitterness suppression by NaCl, only 10% of the stimuli obtained a mean rating higher than 100 on the bitterness scale, compared to 64% with a rating lower than 50. The saltiness intensities of the stimuli seem to be more equally distributed on the psychological continuum, since 29% of the stimuli obtained a rating higher than 100, and 55% a rating lower than 50. On the total taste intensity scale, 33% of the stimuli were rated lower than 50, and 31% higher than 100.

Figure 5B shows a nearly perfect linear relationship between saltiness and total taste intensity scores for NaCl, implying absence of side tastes for NaCl and equal response output functions in both intensity determinations.

Bitterness intensity and saltiness intensity of QHCl, NaCl and NaCl/QHCl mixtures in relation to their total taste intensity

The coefficients resulting from the regression lines in Figure 5 can be used to calibrate the total taste intensity scale with the specific taste intensity scales. By multiplying the scale values on the 'bitterness' scale with 0.78 and multiplying the scale values on the 'saltiness' scale with 0.90, equivalent units of bitterness, saltiness and total taste intensity can be approximated. After the units on all sensation scales have been equalized, the process that integrates bitterness and saltiness into total taste intensity can be studied.

Figure 6A shows the relationship between the sum of bitterness and saltiness (after scale calibration), and the total taste intensity for the 25 mixtures. The sum of bitterness and saltiness clearly overestimates the total taste intensity since almost every data point lies below the diagonal. There may be several reasons for this deviation.

(1) The mean score for water is not equal to zero. The value for the sum contains two times the scale value of water, whilst the value for total taste intensity contains it only once, which may produce a systematic increase in the value of the sum.

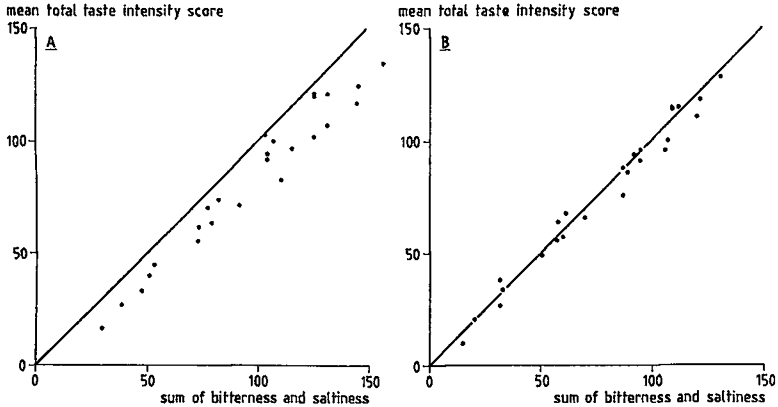

Fig. 6. The relationship between mean total taste intensity score and the sum of the mean bitterness and the mean saltiness scores for each of the 25 QHCl/NaCl mixtures. Panel A shows the results after calibration of the bitterness and saltiness scores using a multiplication factor. Panel B shows the results after correction for the scale value of demineralized water and a calibration of saltiness ratings using a multiplication constant and a calibration of bitterness ratings using a non-linear transformation.

(2) The relationship between bitterness scores and total taste intensity scores is non-linear. Therefore, the calibration overestimates the bitterness scores at low QHCl concentrations.
(3) The sum of bitterness and saltiness may produce scores larger than 150. For the mixture of 0.5 M NaCl and 24 × 10^{-5} M QHCl, the estimated total intensity is 0.78*52 + 0.90*128 = 156, whilst such a score cannot be obtained on the total taste intensity scale. All three rating scales may suffer from so-called 'end-effects' (see Discussion), but since an approximate maximum total taste intensity score is not necessarily the result of a nearly maximum saltiness and/or a nearly maximum bitterness, the sum of specific sensations may suffer less from end-effects than the total taste intensity score.
(4) The total taste intensity scores do not represent total taste intensities on a ratio scale and, therefore, it is not allowed to add the calibrated bitterness scores to the saltiness scores.

In a re-analysis, the first two factors mentioned above were taken into account in order to calibrate the bitterness and saltiness scores.

(1) Each scale value was calculated as the difference between the mean score for the experimental stimulus and the mean score for water.
(2) The bitterness scale values were calibrated using a second order polynomial instead of a linear transformation function.

The transformation function was obtained by estimating a least squares polynomial regression equation through the origin (i.e. the mean scores given to water). The polynomial function (R^2 = 0.999) is depicted as the dotted line in Figure 5A. The effects of this re-analysis for the relationship between total taste intensity and the sum of bitterness and saltiness are shown in Figure 6B. Figure 6B shows that the sum of saltiness and bitterness gives a good approximation of the total taste intensity of a stimulus after correction for the scale value of water and the non-linearity of the bitterness response-output function. Apparently, the total taste intensity scale has approximate ratio scale properties, since bitterness and saltiness, expressed in total taste intensity units, can be added in order to estimate the total intensity of a mixture. The difference in susceptibility to end effects between the mean total taste intensity score and the sum of bitterness and saltiness is minimal: only a small deviation from the diagonal can be noted at high total intensities.

Multiple linear regression through the origin, with the mean bitterness scores (S_α) and mean saltiness scores (S_β), corrected for the scale value for water and non-linearity in the response output function, as independent variables, yielded the regression equation:

$$S_{\tau ij} = 0.98 * S_{\alpha ij} + 0.98 * S_{\beta ij} \tag{1}$$

having an R^2 of 0.996. The standard errors of the regression weights were 0.03 and 0.02, respectively. This equation implies that bitterness and saltiness have equal weights, near to unity, in contributing to the total taste intensity.

Second study

In the second study, the two-stimulus procedure as employed by De Graaf *et al.* (1987) is used. The study consists of three similarly designed investigations. In the first one bitterness is assessed, whilst the second and the third investigation assessed saltiness and total taste intensity, respectively (De Graaf and Frijters, 1989).

Materials and methods

Subjects

Thirteen paid volunteers, seven women and six men, ranging in age from 19 to 31 years, served as subjects. All the subjects were students of the Agricultural University, Wageningen. All subjects had previous experience with psychophysical scaling experiments.

Stimuli

The stimuli were QHCl (Aldrich 14, 592-0), NaCl (Merck 6404) and mixtures of these substances in demineralized water. The upper panel of Figure 7 shows the concentrations and composition of the experimental stimuli. The concentrations of the unmixed QHCl solutions were equal to the ones used in the first study. For NaCl, 0.00, 0.03125, 0.125 and 0.50 M were used. The mixtures were constructed on the basis of a factorial mixing design. Each of the QHCl concentrations were mixed with each of the NaCl concentrations. The references were identical to the ones used in the first study.

Design

The bitterness investigation and the total taste intensity investigation consisted of eight experiments each. The saltiness investigation consisted of 12 experiments. Every experiment was based on one factorial judgment design. Using a factorial judgment design implies that subjects are presented with pairs of stimuli. In each investigation

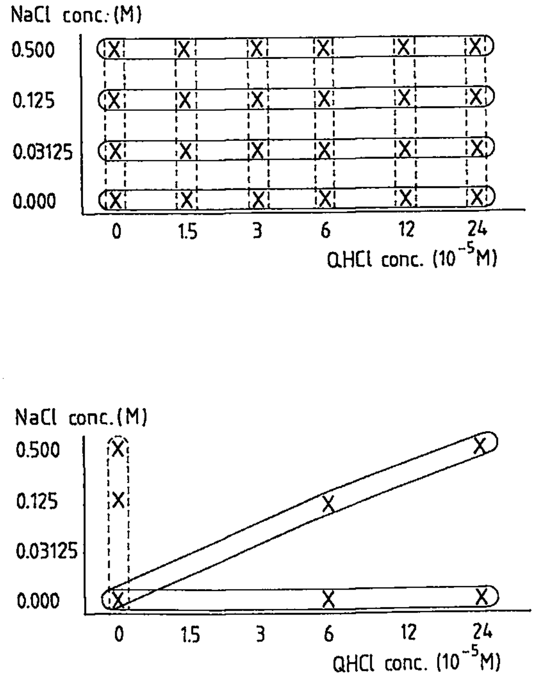

Fig. 7. The upper panel shows the composition of the series of experimental stimuli. The series equal in NaCl concentration (unmixed QHCl and three mixture series) are surrounded by solid lines. The series equal in QHCl concentration (unmixed NaCl and five mixture series) are surrounded by dotted lines. Water was included in each of the series. This is shown only for the series of unmixed QHCl and unmixed NaCl. The lower panel shows the concentrations and compositions of the three series of stimuli to which each of the series of stimuli in the upper panel were compared. In the bitterness investigation, the horizontal series in the upper panel were compared to the series of QHCl stimuli in the lower panel. In the saltiness investigation, the vertical series in the upper panel were compared to the series of unmixed NaCl stimuli in the lower panel. In the total taste intensity investigation, each horizontal series in the upper panel was compared to the series of QHCl/NaCl mixtures in the lower panel.

an $m \times n$ design is employed, where m and n denote the number of concentrations of the first (row) and second (column) stimulus. In order to incorporate all the experimental stimuli into factorial judgment designs, series of stimuli have to be constructed. One possible way to construct ordered series of mixtures is to mix one concentration of one substance with all the concentrations of the other substance. In this manner, four series equal in NaCl concentration or six series equal in QHCl concentration can be constructed for the present study. In the bitterness investigation and the total taste intensity investigation, the four series equal in NaCl concentration were used (horizontal series in the upper panel of Figure 7). In the saltiness investigation, the six series equal in QHCl concentration were used (vertical series in the upper panel of Figure 7). Water was included in each of the mixture series as a rational zero point to be used in the calculation of scale values.

The use of a factorial judgment design implies that the subjects are presented with pairs of stimuli that originate from combining all stimuli from a series of first stimuli with all stimuli from a series of second stimuli. In the 'bitterness' investigation each stimulus of each of the four series of experimental stimuli was compared with 0.0, 6×10^{-5} and 24×10^{-5} M QHCl. Similarly, in the 'saltiness' investigation each stimulus of each of the six series was compared with three NaCl solutions: 0.00, 0.125 and 0.5 M, and in the 'total taste intensity' investigation each stimulus of each series was compared to water, a mixture of 6×10^{-5} M QHCl and 0.125 M NaCl, and a mixture of 24×10^{-5} M QHCl and 0.5 M NaCl (lower panel of Figure 7). In half of the experiments the three comparison stimuli were presented as first stimuli, in the other half of the experiments they served as second stimuli.

In summary, the total study consisted of 28 experiments (eight bitter, 12 salty and eight total intensity). In every experiment each stimulus of one of the series of stimuli from the upper panel of Figure 7 was compared to each stimulus of one of the three series of comparison stimuli from the lower panel of Figure 7.

Procedure

Except for the instructions and response scale, the experimental procedure in each of the three investigations was identical. Only the experimental procedure for the 'bitterness' investigation is described and specific differences with the designs of the other investigations will be mentioned.

The subjects were instructed to judge the magnitude of the difference in perceived bitterness intensities (saltiness, total taste intensities) between the first and the second stimulus of each pair. The instructions emphasized that only the bitterness (saltiness) intensity was to be judged, and that the hedonic value and side tastes were to be disregarded. In the 'total taste intensity' investigation, subjects were instructed to judge the total taste intensity, irrespective of quality, and to include every quality they perceived.

The judgements 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 bitterness intensity' (saltiness, total taste intensity) (see De Graaf *et al.*, 1987, their Figure 3). If the first stimulus was perceived as tasting more bitter (saltier, more intense) than the second stimulus, the subject placed a mark on the left side of the scale depending on the magnitude of the difference. The subject marked the right side of the scale when the second stimulus was perceived as being more bitter (saltier, more intense). The left end and the right end of the scale were labelled 'maximum difference'. In the instructions 'maximum difference' was defined as the difference in bitterness intensity (saltiness, total taste intensity) between the stimuli of the reference pair, i.e. water as first stimulus and 30×10^{-5} M QHCl (0.625 M NaCl, a mixture of 36×10^{-5} M QHCl and 0.75 M NaCl) 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 more bitter (saltier, having a higher total taste intensity) than the first one, and a value below 125 indicated that the first stimulus was perceived as the most bitter (the saltiest, 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°C) in polystyrene medicine cups. Each cup contained about 10 ml of solution. The pairs 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, 24th and 36th pair of each session. The time interval between and within pairs was50 s. Each of the factorial judgement designs of every investigation were presented to each subject twice in a random order. It took each subject eight 80-min sessions to complete each investigation so that 24 sessions were needed to complete the entire study.

Results

Psychometric properties of response scale and derivation of scale values

Because individuals may vary in their judgement functions (linear or non-linear), or in their comparative operations (which may or may not be subtractive), first individual analyses were performed (28 experiments $\times$ 13 subjects = 364 analyses). The measure of the degree of non-parallelism, that is the row $\times$ column (first stimulus $\times$ second stimulus) interaction, was tested in an analysis of variance for statistical significance with the row $\times$ column $\times$ replication interaction as an error term. Depending on the specified alpha level, 3 ($P < 0.01$), 15 ($P < 0.05$) or 33 ($P < 0.10$) row $\times$ column interactions were found to be significant. None of the subjects had more than one significant interaction at the $P < 0.01$ level.

On group level, the row $\times$ column interaction was tested for significance against the row $\times$ column $\times$ subject interaction for each of the 28 factorial judgement designs. The interaction appeared to be significant in 2 ($P < 0.01$), 5 ($P < 0.05$) or 7 ($P < 0.10$) cases. These numbers of significant interactions deviate from the number that can be expected to occur by chance. Therefore, the question now arises as to whether these deviations invalidate the assumed psychological model. As the objective of the present investigation is to determine scale values for solutions of NaCl, QHCl and NaCl/QHCl mixtures, whether the deviations have a substantive effect upon the obtained scale values should be investigated. The relative magnitude of experimental effects was estimated by calculating the value of ω^2 for a three-way mixed model design (Vaughan and Corballis, 1969). Table I shows the relative contributions of the first stimulus, the second stimulus, and the first stimulus $\times$ second stimulus interaction for each of the factorial judgement designs. As the size of the experimental effect of the interactions is small (<1% in all cases) compared to the effects of the first and the second stimuli, the effect of the deviations from linearity on the scale values to be obtained is negligible. It is concluded, therefore, that the assumptions concerning the subtractive comparative operation and the linear judgement function were met. Consequently, the marginal means of the row and column stimuli are valid estimates of the perceived taste intensity on an interval scale (Anderson, 1981).

Assuming water elicits no taste, scale values were derived for each of the experimental stimuli by calculating the difference between the marginal mean for the experimental stimulus and the marginal mean for water in each of the 28 experiments. The final scale value for each stimulus was calculated by averaging the scale value for that stimulus tasted as the first stimulus of each pair and the scale value when tasted as the second stimulus of each pair. All data were averaged over subjects and replications.

Table I. The relative magnitude of experimental effects (ω^2) for each factorial judgment design

Type of design	Number of stimuli	Position comparison stimulus	ω^2 (in %)			
			left	right	sum (L + R)	L × R interaction
Bitterness investigation						
0.000 M NaCl	3 × 6	left	44.7	37.1	81.8	0.06
0.000 M NaCl	6 × 3	right	31.6	47.7	79.3	0.04
0.03125 M NaCl	3 × 7	left	53.2	20.2	73.4	0.39
0.03125 M NaCl	7 × 3	right	18.8	57.3	76.1	−0.01
0.125 M NaCl	3 × 7	left	63.4	8.1	71.5	0.81
0.125 M NaCl	7 × 3	right	9.7	63.9	73.6	−0.03
0.500 M NaCl	3 × 7	left	57.5	7.5	65.0	−0.20
0.500 M NaCl	7 × 3	right	7.4	59.1	66.5	−0.15
Saltiness investigation						
0×10^{-5} M QHCl	3 × 4	left	44.3	42.9	87.2	−0.01
0×10^{-5} M QHCl	4 × 3	right	39.8	49.0	88.8	0.10
1.5×10^{-5} M QHCl	3 × 5	left	42.1	45.2	87.3	−0.06
1.5×10^{-5} M QHCl	5 × 3	right	37.4	50.0	87.4	0.22
3×10^{-5} M QHCl	3 × 5	left	42.0	45.9	87.9	−0.05
3×10^{-5} M QHCl	5 × 3	right	40.2	48.0	88.2	0.32
6×10^{-5} M QHCl	3 × 5	left	43.7	46.0	89.7	0.09
6×10^{-5} M QHCl	5 × 3	right	36.9	48.7	85.6	0.07
12×10^{-5} M QHCl	3 × 5	left	43.9	42.8	86.7	−0.01
12×10^{-5} M QHCl	5 × 3	right	35.6	50.2	85.8	0.13
24×10^{-5} M QHCl	3 × 5	left	45.3	37.5	82.8	−0.22
24×10^{-5} M QHCl	5 × 3	right	37.9	48.5	86.4	0.20
Total taste intensity investigation						
0.000 M NaCl	3 × 6	left	48.8	24.8	73.6	0.03
0.000 M NaCl	6 × 3	right	26.6	46.2	72.8	0.39
0.03125 M NaCl	3 × 7	left	59.9	19.7	79.6	0.05
0.03125 M NaCl	7 × 3	right	15.7	60.5	76.2	−0.11
0.125 M NaCl	3 × 7	left	56.0	14.5	70.5	−0.02
0.125 M NaCl	7 × 3	right	10.9	65.1	76.0	0.19
0.500 M NaCl	3 × 7	left	44.9	29.9	74.8	−0.12
0.500 M NaCl	7 × 3	right	20.8	52.5	73.3	0.05

Bitterness, saltiness and total taste intensity of quinine HCl/NaCl mixtures

Figure 8, panel A, shows the bitterness of QHCl, NaCl and the mixtures as a function of the bitterness of QHCl, with a separate function for each NaCl concentration. Visual inspection shows that the bitterness intensity of QHCl is to a large extent suppressed by NaCl. ANOVA of the results showed significant effects for QHCl [$F(5,60) = 101.10$, $P < 0.001$], NaCl [$F(3,36) = 16.72$, $P < 0.001$] and the QHCl × NaCl interaction [$F(15,180) = 18.83$, $P < 0.001$]. If the responses to the stimuli containing 0.0 and 0.03125 M NaCl are omitted, the NaCl main effect and the QHCl × NaCl interaction are no longer significant[$F(1,12) = 0.04$, $P = 0.85$ and $F(5,60) = 1.26$, $P = 0.30$].

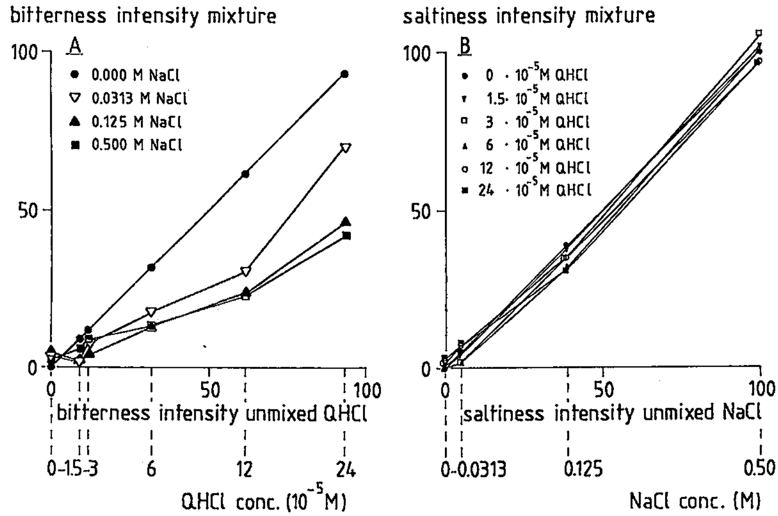

Fig. 8. Panel A shows the bitterness intensity of QHCl, NaCl and the NaCl/QHCl mixtures as a function of the bitterness of unmixed QHCl with a separate curve for each NaCl concentration. Panel B shows the saltiness of NaCl, QHCl and the NaCl/QHCl mixtures as a function of the saltiness of NaCl with a separate curve for each QHCl concentration. The units of the 'bitterness' scale and the 'saltiness' scale are not equal.

This implies that increasing the NaCl concentration from 0.125 to 0.5 M does not affect the degree of bitterness suppression in the QHCl/NaCl mixtures.

Figure 8B shows the saltiness of NaCl, QHCl and NaCl/QHCl mixtures as a function of the saltiness of NaCl. Visual inspection shows that the saltiness scale values of the NaCl/QHCl mixtures do not differ from the saltiness values for the unmixed NaCl. Apparently, QHCl does not affect the perception of the salty taste of NaCl. ANOVA showed statistically significant effects for NaCl [$F(3,36) = 538.45$, $P < 0.001$] and the QHCl × NaCl interaction [$F(15,180) = 3.49$, $P < 0.001$]. However, the QHCl main effect was not significant [$F(5,60) = 0.68$, $P = 0.68$].

Figure 9 shows the total taste intensity of the experimental stimuli as a function of the total taste intensity of unmixed QHCl, with a separate curve for each concentration of NaCl. The curves show a convergent pattern. For some mixtures containing high QHCl levels, the total taste intensity of the mixture is lower than the total taste intensity of unmixed QHCl. The bitterness of QHCl is obviously suppressed by NaCl. ANOVA showed significant effects for QHCl [$F(5,60) = 134.24$, $P < 0.001$], NaCl [$F(3,36) = 51.59$, $P < 0.001$] and the QHCl × NaCl interaction [$F(15,180) = 20.21$, $P < 0.001$].

Bitterness and total taste intensity of QHCl and saltiness and total taste intensity of NaCl

Figure 10A shows the relationship between the scale values of QHCl on the 'bitterness' scale and the scale values of QHCl on the 'total taste intensity' scale. The scale values on these two scales differ by a multiplicative constant only. Orthogonal linear regression through the origin yielded a value of 0.81 ($R^2 = 0.990$) for the slope. It appears that the total taste intensity of QHCl does not differ from its bitterness intensity.

Figure 10B 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. In this case,

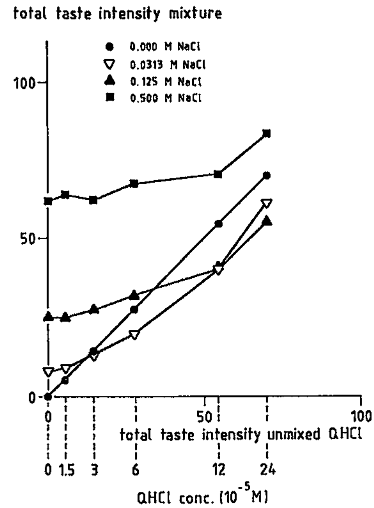

Fig. 9. The total taste intensity of QHCl, NaCl and the NaCl/QHCl mixtures as a function of the total taste intensity of unmixed QHCl, with a separate curve for each NaCl concentration.

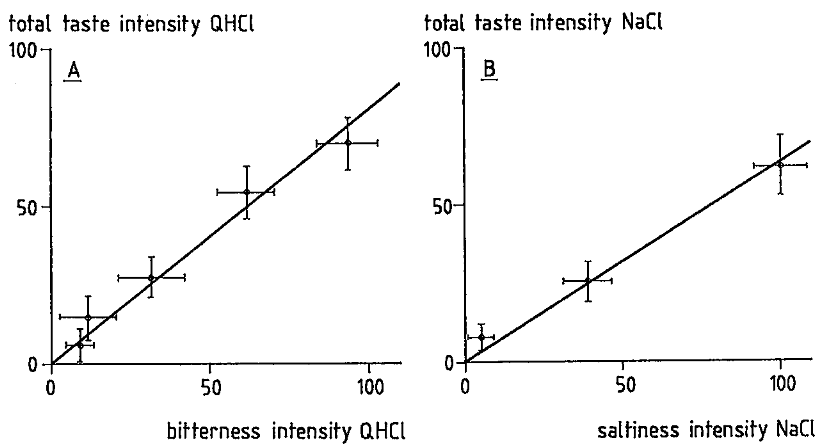

Fig. 10. Panel A shows the relationship between the bitterness scale values and the total taste intensity scale values of unmixed QHCl. Panel B shows the relationship between the saltiness scale values and the total taste intensity scale values of NaCl. The straight lines were obtained by linear orthogonal regression through the origin. The error bars parallel with the ordinate represent the 95% confidence intervals for the scale values of the total taste intensity. The error bars parallel with the abscissa represent the 95% confidence intervals for the scale values of bitterness and saltiness, respectively.

orthogonal linear regression yielded a multiplicative constant of 0.63 (R^2 = 0.994). However, as can be seen in Figure 9B, the scale values on the 'saltiness' scale deviate systematically from the values on the 'total taste intensity' scale at 0.03125 M NaCl. This deviation is probably caused by a sweet side taste of NaCl at low concentration levels (e.g. Kroeze, 1982a). It has been reported that this side taste is also detectable at higher concentration levels (e.g. De Graaf and Frijters, 1989).

Table II. Bitterness, saltiness, the sum of bitterness and saltiness, and total taste intensity of QHCl, NaCl and QHCl/NaCl mixtures (two-stimulus procedure)

QHCl concentration (10^{-5} M)	NaCl concentration (M)	Bitterness intensity S_α	Saltiness intensity S_β	Sum of bitterness and saltiness $S_\alpha + S_\beta$	Total taste intensity S_τ
0.0	0.00000	0.0	0.0	0.0	0.0
0.0	0.03125	2.6	3.0	5.6	8.0
0.0	0.12500	4.1	24.3	28.4	25.3
0.0	0.50000	2.4	63.0	65.3	62.2
1.5	0.00000	7.3	0.6	7.9	5.9
1.5	0.03125	1.5	2.6	4.1	9.2
1.5	0.12500	1.6	23.7	25.3	24.9
1.5	0.50000	5.1	64.1	69.2	63.9
3.0	0.00000	9.3	1.0	10.3	14.7
3.0	0.03125	6.2	1.3	7.4	13.6
3.0	0.12500	3.5	21.9	25.4	27.6
3.0	0.50000	7.3	66.2	73.4	62.5
6.0	0.00000	25.5	0.0	25.5	27.7
6.0	0.03125	14.1	1.2	15.3	19.9
6.0	0.12500	10.6	20.0	30.7	32.2
6.0	0.50000	11.0	63.1	74.2	67.5
12.0	0.00000	49.5	1.1	50.5	54.6
12.0	0.03125	24.5	4.6	29.1	39.8
12.0	0.12500	19.1	22.1	41.2	39.8
12.0	0.50000	18.9	60.3	79.2	70.5
24.0	0.00000	75.2	1.7	76.9	70.1
24.0	0.03125	56.4	4.8	61.2	61.1
24.0	0.12500	37.0	19.7	56.7	55.1
24.0	0.50000	34.0	60.8	94.8	83.5

Bitterness intensity and saltiness intensity of QHCl, NaCl and NaCl/QHCl mixtures in relation to their total taste intensity

By multiplying the scale values on the 'bitterness' scale with 0.81 and multiplying the scale values on the 'saltiness' scale with 0.63, equivalent units of bitterness, saltiness and total taste intensity can be approximated. Table II shows the bitterness intensity, saltiness intensity (both after scale calibration), the sum of these two, and the total taste intensity of the experimental stimuli. The same data are depicted in Figure 11. Multiple linear regression through the origin, with the bitterness (S_α) and saltiness (S_β) as independent variables, yields the regression equation:

$$S_{\tau ij} = 1.01 * S_{\alpha ij} + 0.89 * S_{\beta ij} \qquad (2)$$

having an R^2 of 0.992. The standard errors of the regression weights are 0.04 and 0.03, respectively. This equation implies that bitterness and saltiness have approximately equal weights in determining total taste intensity.

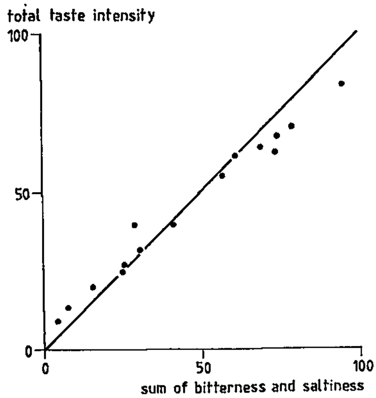

Fig. 11. The relationship between total taste intensity scale values and the sum of the bitterness and the saltiness scale values after scale calibration using a multiplication factor.

Although the sum of bitterness and saltiness appears to be a good approximation of the total taste intensity, slight deviations from the diagonal are found to occur. These deviations may reflect departures from the simple summation rule (see Schifferstein and Frijters, 1992). The deviations at low intensity levels could also be due to the sweet side taste of NaCl.

A comparison of the first and the second study

Figure 12 shows the relationship between the mean ratings, corrected for the mean rating for water, obtained with the one-stimulus procedure and the scale values obtained with the two-stimulus procedure. The relationship between the intensity estimates in the two experiments is concave downward for each attribute. At high intensity levels, the scale values from the one-stimulus procedure are somewhat lower than the values obtained with the two-stimulus procedure. In addition, the bitterness values differ considerably between the two experiments.

Discussion

A comparison of the two experimental procedures

Figure 12A shows a non-linear relationship between the bitterness values for unmixed QHCl obtained in the two experiments. The present results deviate from those obtained by De Graaf *et al.* (1990), who obtained a linear relationship between the bitterness scale values for quinine sulphate/caffeine mixtures by a single stimulus procedure and by a two-stimulus procedure. The non-linearity in Figure 12A bears some resemblance to the non-linearity in Figure 5A, where bitterness scores were compared to total taste intensity scores. As discussed earlier, the non-linearity may have resulted from a context-induced non-linear response output function in the bitterness investigation of the first experiment. In addition, it should be noted that the bitterness values for the QHCl/NaCl mixtures in Figure 12A are not located on the same curve as the bitterness values for the unmixed QHCl solutions. Differences in the degree of mixture suppression between the two experiments may be due to the large difference in the relative number of unmixed QHCl stimuli that were presented to the subjects (Kroeze, 1982b).

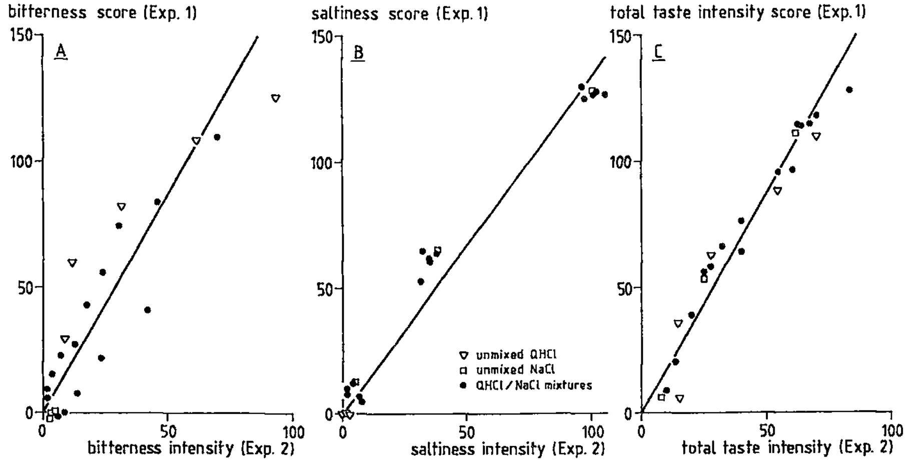

Fig. 12. The relationship between mean scores, after correction for the mean rating for water, obtained with the one-stimulus procedure (Exp. 1) and the scale values obtained with the two-stimulus procedure (Exp. 2). The drawn lines are regression lines obtained by orthogonal linear regression through the origin. Panels A, B and C show the results for the bitterness, saltiness and total taste intensity investigations, respectively.

There are two reasons why the context effects that affected the bitterness scores in the first experiment are expected to be smaller or even absent in the second investigation. First, the bitterness intensities of the stimuli in the second study were more uniformly distributed over the sensory continuum than in the first study. In the first experiment, only a few bitter stimuli were presented to the subjects since the bitterness of QHCl was largely suppressed by NaCl. In the bitterness investigation of the second study, however, every experimental stimulus was compared to water, 6×10^{-5} and 24×10^{-5} M QHCl. In this investigation, therefore, many more bitter stimuli were presented. Second, it is unlikely that the scale values obtained by the two-stimulus procedure were affected by experimental context, since Mellers and Birnbaum (1982) found no difference between the scale values obtained in a positively skewed context and those in a negatively skewed context in an experiment where intensity differences between two stimuli were judged.

In addition to the effect of experimental context, the bitterness scores in the first experiment may have been affected by the saltiness scores that were given simultaneously. Simultaneous and separate rating procedures have been found to yield different reported specific taste intensities (e.g. Ganzevles and Kroeze, 1987; Frank *et al.*, 1990).

In the following sections the advantages of the one-stimulus procedure and those of the two-stimulus procedure are discussed.

One-stimulus procedure. The first advantage of the one-stimulus procedure over the two-stimulus procedure is that it gives information about the taste elicited by water. In De Graaf *et al.*'s (1987) two-stimulus procedure it is assumed that water elicits no taste and water is taken as a rational zero point to be used in the calculation of scale values. This assumption cannot be verified because no information is obtained on single stimuli. Several investigators, however, have noted a slight, bitter taste for demineralized water (e.g. Peryam, 1960; Bartoshuk *et al.*, 1964; Bartoshuk, 1968; McBurney and Pfaffmann, 1963). Therefore, the assumption that water is tasteless may lead to biased scale values in a bitterness investigation using the two-stimulus procedure.

A related problem in the two-stimulus procedure is the fact that every series of experimental stimuli has to contain one sample of water in order to anchor the sensation scale. The marginal mean for water is used later in calculating the scale values. Consequently, the final numerical scale values obtained in each series depend upon the scale value obtained for water in that series. The between series variation in the water scale value may, therefore, introduce systematic bias in the scale values for the experimental stimuli (Schifferstein and Frijters, 1991a).

The second advantage is the simplicity of the experimental design for the one-stimulus procedure. Many more different stimuli can be presented to the subject during a session than when using the two-stimulus procedure. For each experimental stimulus, three pairs (six stimuli) have to be presented in the two-stimulus procedure if three comparison stimuli are used. Since not all the stimuli can be presented during one session when employing the two-stimulus procedure, between-session variation increases the amount of within-subjects variation. In addition, between-session variation can become a systematic source of variation if series of experimental stimuli are constructed on the basis of a factorial mixing design. Because mixture series are often evaluated in different sessions, systematic between-session differences may lead to apparent between-series differences.

Two-stimulus procedure. The two-stimulus procedure allows for a post-experimental check on the form of the response output function, independent of the mixture interactions or psychophysical functions. This is the main merit of this procedure. In taste mixtures, most tastants interact in a non-additive fashion at the psychophysical level. This non-additivity produces a convergent pattern of curves in the factorial plot at the sensation level. If a single stimulus procedure is used and the response output function is linear, the factorial plot at response level will also exhibit convergence. Therefore, the assumptions of Anderson's (1981) parallelism theorem are not met and, consequently, the sensation scale cannot be validated. The two-stimulus procedure is, therefore, at present the only procedure that allows for a check on the linearity of the response output function in taste mixture research.

The second advantage of the two-stimulus procedure is the fact that the scale values are likely to be less affected by end effects of the rating scale than the values obtained with a one-stimulus procedure. The occurrence of end effects distorts the equal-interval properties of the response scale. This distortion affects the arithmetic mean and the standard deviation, which limits their use in hypothesis testing (e.g. Garner, 1952, 1953; Guilford and Dingman, 1955; Eriksen and Hake, 1957; Parducci *et al.*, 1966).

In the one-stimulus procedure, a high intensity stimulus suffers from the end-effect every time it is judged, since its intensity approaches maximum intensity. In the two-stimulus procedure, however, the scale value for stimulus X is calculated from the difference judgments of six different pairs, that is X-water, X-C1, X-C2, water-X, C1-X and C2-X (where C1 and C2 are two comparison stimuli eliciting medium and high intensity, respectively). Only the judgments of two pairs, water-X and X-water, may suffer from end-effects since these are the only two pairs that can give rise to a maximum difference in intensity. Therefore, only 33% of the judgments in which X

is involved suffer from end-effects, compared to 100% in the one-stimulus procedure. All three panels of Figure 12 show that the scale values from the one-stimulus procedure are lower than the values from the two-stimulus procedure at high intensity levels. The hypothesis that scale values obtained by a one-stimulus procedure are more affected by end effects than values obtained by a two-stimulus procedure could account for this finding.

As discussed before, presenting comparison stimuli is not only expected to reduce end effects, but also to diminish context effects. In addition, the two-stimulus procedure seems to be insensitive to contextual manipulations, since scale values obtained using an intramodal difference judgment task are not affected by changes in experimental context (Mellers and Birnbaum, 1982).

In conclusion, it can be stated that the two-stimulus procedure benefits from an independent post-experimental check on the form of the response output function. However, if the assumption that water is tasteless is not met, the obtained scale values deviate systematically from sensations measured on a ratio scale. The responses obtained with a one-stimulus procedure are subject to systematic biases (end effects and/or context effects resulting in a non-linear judgment function), which are smaller or absent during a two-stimulus procedure. In addition, no experimental check on those deviations is provided in the single stimulus procedure. Therefore, the application of the two-stimulus procedure is to be preferred over the one-stimulus procedure.

Taste interaction between NaCl and QHCl

Asymmetrical mixture suppression is a common finding in mixtures containing two differently tasting substances (e.g. Kamen *et al.*, 1961; Frank and Archambo, 1986; McBride, 1989; De Graaf and Frijters, 1989; Schifferstein and Frijters, 1990). The asymmetry in the degree to which NaCl and QHCl suppress each other's taste intensity is striking, however. The bitterness elicited by quinine is suppressed to a large degree when NaCl is added to QHCl, whilst the saltiness elicited by NaCl remains virtually unaffected. In the first experiment, the highest QHCl concentration significantly suppressed NaCl saltiness at two NaCl concentrations only (Figure 3), whilst in the second experiment no effect was demonstrated (Figure 8).

Experimental evidence suggests that the suppression of the bitterness of QHCl by NaCl mixtures is largely peripheral and not central in origin. For many heterogeneous mixtures, mixture suppression takes place at a level located centrally to the locus of the adaptation mechanism. For QHCl/NaCl mixtures, however, the bitterness of QHCl appears to be largely suppressed before adaptation can take place. Since adaptation affects the periphery of the perceptual system (Borg *et al.*, 1967), the activity of QHCl must already be suppressed to a large extent in the periphery of the sensory system, before the locus of adaptation is reached. Three observations will be mentioned to make it plausible that bitterness suppression in QHCl/NaCl mixtures is largely peripheral in origin.

A first indication is the finding that adaptation to a QHCl/NaCl mixture does not lead to cross-adaptation of the bitterness of unmixed QHCl (mentioned in Bartoshuk and Gent, 1985). Following the line of reasoning set out by Kroeze (1978, 1979), this finding implies that the activity of QHCl in the mixture must already have been suppressed before it could become effective as an adaptor.

A second finding is reported in Bartoshuk (1980). She reported that, in general, after adaptation to one of the components of a heterogeneous mixture, the taste of the other component was released from suppression. In these mixtures, the intensity of the sensation elicited by a suppressor is apparently decreased by adaptation and can no longer suppress the intensity of the other component. Therefore, the adaptation must have taken place before the mixture suppression can exert its influence. The QHCl/NaCl mixture, however, deviated from this rule since the bitterness intensity of the QHCl/NaCl mixture was not released from suppression after adaptation to NaCl. Therefore, in the QHCl/NaCl mixture the bitterness suppression must occur before a bitterness message can be formed in the afferent system.

Kroeze and Bartoshuk (1985) found a 23% decrease in bitterness intensity in a QHCl/NaCl mixture when QHCl and NaCl were applied separately to the two tongue halves, compared to 69% when both substances were applied to the same tongue half. Since there are no structural elements of the neural part of the taste system connecting the two sides of the tongue before the thalamic level (Norgren and Leonard, 1973), these investigators concluded that the observed decrease in bitterness intensity in QHCl/NaCl mixtures resulted to a large degree from peripheral suppression.

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Chapter 4

APPLICATION OF THE HABITUATION PARADIGM IN SIP-AND-SPIT EXPERIMENTS

Habituation is central rather than peripheral in origin. Therefore, central mixture suppression mechanisms can be studied if it is possible to habituate subjects to one of the mixture's components. In the two studies reported in this chapter, a habituation paradigm was used in combination with a sip-and-spit procedure.

No release from bitterness suppression after repetitive stimulations with NaCl

Sweetness does not habituate during a sip-and-spit experiment
Physiology & Behavior, 51, 331-336, 1992

NO RELEASE FROM BITTERNESS SUPPRESSION AFTER REPETITIVE STIMULATIONS WITH NACL

Introduction

Several authors observed that after elimination or reduction of the taste intensity of one component, the taste sensation of the other component in a binary, heterogeneous mixture percept is, to some degree, released from suppression. This suppression release has been demonstrated following blocking of sweetness perception using *Gymnema sylvestre* (e.g. Kuznicki and McCutcheon, 1979; Lawless, 1979), and after adaptation (e.g. Bartoshuk, 1980; Gillan, 1982; Kuznicki and McCutcheon, 1979; Lawless, 1979) or habituation (Kroeze, 1982a, 1982b, 1983) to one of the mixture components.

Since habituation removes the suppressor's effect at the central level, release of one mixture sensation from suppression after habituation to the other sensation provides evidence for a central locus of the mixture suppression mechanism (Kroeze, 1989). A second central process that might explain a rise in mixture ratings after habituation to one of the two taste sensations, is successive contrast (Kroeze, 1983). According to the successive contrast hypothesis, the saltiness of a NaCl/sucrose mixture may be overestimated after repetitious stimulations with sucrose stimuli, because the salty taste stands out against the previously perceived sweet tastes. The increment in the saltiness score is then not accounted for by a decrease in the degree of saltiness suppression as a consequence of the habituation to the sweetness of sucrose, but by an overestimation of the saltiness intensity. Kroeze (1983) obtained two different functions for the mixture suppression condition and for the contrast condition. After correcting the data for the contrast-effect, a negatively accelerating relationship remained between the saltiness estimates and the number of preceding sucrose stimulations. He concluded, therefore, that successive contrast cannot fully account for the observed increment in response to a mixture after habituation to one of its components.

In the present experiment, the release from bitterness suppression is studied using quinineHCl/NaCl mixtures and equi-intense KCl solutions. Subjects are presented with a number of NaCl solutions in order to become habituated to the salty taste before the test stimulus is judged. To correct for the rise in response due to successive contrast, unmixed QHCl solutions, equibitter to the QHCl/NaCl mixtures are used as test stimuli in one condition.

If a significant degree of suppression release is observed for quinine/NaCl mixtures after habituation to NaCl, this would imply that the bitterness suppression has a central origin. Similarly, if the bitterness of KCl is released from suppression, the two taste sensations that are elicited by KCl should also suppress each other centrally.

Methods and Materials

Subjects

The subjects were 28 paid volunteers, 7 men and 21 women, ranging in age from 18 to 27 years. Most subjects were students of the Agricultural University and all had participated in psychophysical scaling experiments before. All subjects were naive with respect to the substances used and the purpose of the study.

Stimuli

The stimuli were solutions of quinineHCl (Aldrich 14,592-0), KCl (Merck 4936) and a mixture of quinineHCl with NaCl (Merck 6404) in demineralized water. The concentrations of the unmixed quinineHCl (QHCl) were 30 µM (Q) and 10 µM (⅓Q). The KCl concentration was 0.11 M (K). The QHCl/NaCl mixture (QN) contained 30 µM QHCl and 0.076 M NaCl.

These concentrations were found to be approximately equibitter (QN, ⅓Q, and K) and equisalty (QN and K) in a preliminary experiment. In this experiment, the 28 subjects rated the bitterness and saltiness of nine QHCl/NaCl mixtures, 0.11 M KCl, and three unmixed QHCl solutions on 150 mm line scales.

Solutions were prepared at least 24 hours before tasting and were stored in a dark, refrigerated room at 4 °C for no longer than four days.

Table I. Overview of the three experimental conditions. Every series contains one solution of unmixed QHCl (Q), none or a certain number of habituating unmixed NaCl solutions (N), and a test stimulus that differs between the three conditions: a QHCl/NaCl mixture (QN), an unmixed KCl solution (K), or an unmixed QHCl solution (⅓Q)).

	Mixture condition	KCl condition	Contrast condition
1	Q QN	Q K	Q ⅓Q
2	Q N QN	Q N K	Q N ⅓Q
3	Q N N QN	Q N N K	Q N N ⅓Q
4	Q N N N N QN	Q N N N N K	Q N N N N ⅓Q
5	Q N N N N N QN	Q N N N N N K	Q N N N N N ⅓Q

Design

There were three conditions, each consisting of five different series (Table I). In the first condition, a QHCl/NaCl mixture (QN) was preceded by none or a certain number (1, 2, 4 or 5) of presentations of NaCl (N). The threefold repetitions were omitted for reasons of economy. Since the rated degree of mixture suppression in a heterogeneous taste mixture increases if the relative number of unmixed taste stimuli is increased (Kroeze, 1982c), each series started with an unmixed QHCl stimulus (Q). In this way, the number of experimental unmixed QHCl stimuli equalled the number of QHCl/NaCl mixtures. In the second condition the mixture stimuli were replaced by KCl solutions (K). In the third condition (the contrast condition) 10 µM QHCl (⅓Q) served as test stimulus.

Procedure

The subjects were instructed to judge the intensity of the perceived bitterness. The instructions emphasized that only the bitterness intensity was to be judged. The hedonic value and side tastes of the stimuli were to be disregarded. Subjects made their responses on sheets containing one 150 mm graphic rating scale. The left and right ends of the scale were labelled 'not bitter at all' and 'extremely bitter'.

The subjects were requested to rinse their mouths thoroughly with demineralized water after each stimulus. The stimuli were presented at room temperature (~ 20 °C) in polystyrene medicine cups. Each cup contained about 10 ml of solution. The time interval between stimuli was 60 s.

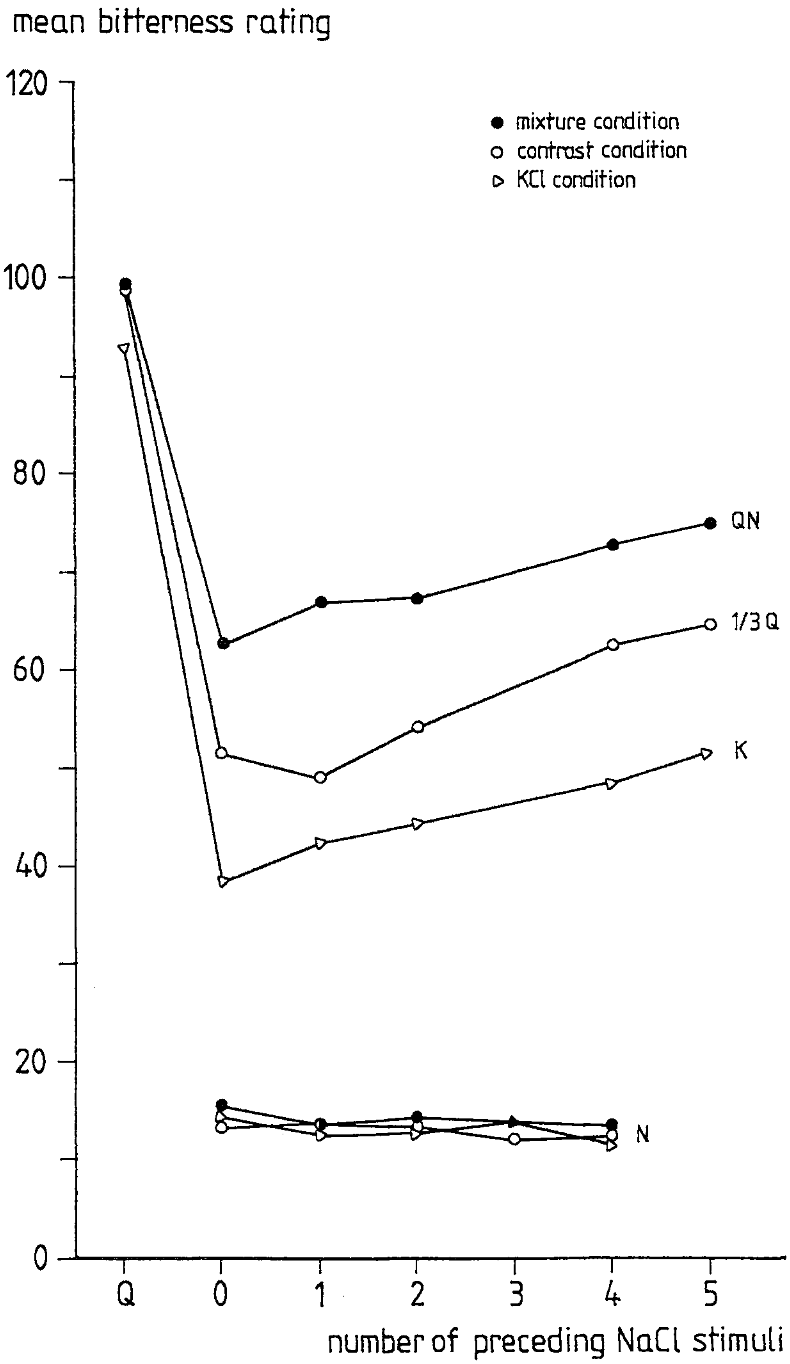

Fig. 1. Mean bitterness responses for Q, N, QN, ⅓Q, and K as a function of the number of preceding NaCl stimuli (N). One curve is drawn for each experimental condition.

The five series of each experimental condition were presented in a random sequence and in a different order for each subject. The order in which the three conditions were presented to the subjects was also randomized. During every session the subjects judged all 66 stimuli. The three conditions were replicated 5 times per subject. Therefore, every subject had to participate in five 70 min sessions to complete the entire investigation.

Results

Figure 1 shows the mean bitterness scores for unmixed QHCl (Q), the habituating NaCl solutions (N), and the mean bitterness scores of the test stimuli after repeated stimulation with a certain number of habituating stimuli. Figure 1 shows that the matching experiment did not succeed in equating the bitterness intensities of the three test stimuli (QN, K, and Q) since the mean bitterness scores for the three solutions tasted immediately after solution Q differ considerably. In addition, the three functions relating the bitterness ratings to the degree of pre- exposure to NaCl solutions are approximately linear. The differences in explained variance between linear regression equations and second order polynomials are not significant for all three conditions [F-test, $p>0.50$]. An analysis of variance of the bitterness ratings for the test stimuli reveals that the main effect of Pre-exposure [$F(4,108)=14.13$, $p<0.001$] and the main effect of experimental Condition [$F(2,54)=6.51$, $p<0.005$] are significant. The Condition × Pre-exposure interaction was not significant [$F(8,216)=0.67$, $p=0.72$], implying parallelism between the three curves in Figure 1. If the QHCl/NaCl mixture or KCl exhibited suppression release, the curves in Figure 1 for these conditions should have been steeper than the curve for the contrast condition. Therefore, the present results show no sign of suppression release for QHCl/NaCl mixture nor for KCl after repetitive stimulations with NaCl.

An effect of the number of preceding NaCl stimuli upon the bitterness responses for the habituating NaCl stimuli is absent in all three conditions [$F(4,108)<1.6$, $p>0.15$].

Discussion

The present results show that no release from bitterness suppression is found for KCl nor for QHCl/NaCl. These results deviate from the results reported by Kroeze (1983), who found suppression release for the saltiness and the sweetness of sucrose/NaCl mixtures.

The present results leave open two possible explanations for the discrepancy found. First, the suppression of bitterness may not be the result of a central mechanism but of a peripheral mechanism. This explanation would imply that there is no central bitterness suppression mechanism involved (or no suppression mechanism at all) in the perception of KCl and the QHCl/NaCl mixture. The second explanation implies that the experimental procedure employed in the present study does not result in habituation. In his habituation experiments, Kroeze (1982a, 1982b, 1983) delivered the stimuli by means of a gravitational flow system. The present experiment used a sip-and-spit procedure.

In order to investigate the second possibility, Kroeze's (1983) experiment on the release of saltiness suppression in sucrose/NaCl mixtures was replicated using a sip-and-spit procedure.

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Sweetness Does Not Habituate During a Sip-and-Spit Experiment

HENDRIK N. J. SCHIFFERSTEIN[1] AND JAN E. R. FRIJTERS

Wageningen Agricultural University, The Netherlands

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SCHIFFERSTEIN, H. N. J. AND J. E. R. FRIJTERS. *Sweetness does not habituate during a sip-and-spit experiment*. PHYSIOL BEHAV **51**(2) 331–336, 1992.—In gravitational flow studies, the estimated saltiness of a NaCl/sucrose mixture increases after repetitive stimulations with sucrose. This increment is hypothesized to be the consequence of successive contrast and suppression release. According to the successive contrast hypothesis, the saltiness of the mixture percept is overestimated because its salty taste stands out against the preceding sweet tastes. The release of saltiness from suppression is supposed to originate from habituation to sweet stimuli. In the present study, the saltiness of a NaCl/sucrose mixture was judged after repetitive stimulations with sucrose using a sip-and-spit procedure. The increment in saltiness estimates after repeated stimulations with sucrose could be fully accounted for by successive contrast. No suppression release was observed. Differences in experimental procedure (the degree of experimental control, the subjects' arousal level, the variation in the proximal stimuli, the area of the tongue stimulated, and the subjective intensities of the habituating stimuli) that may affect the rate of habituation, are suggested as potential sources of the differences between the gravitational flow studies and the present one.

Habituation Suppression release Successive contrast NaCl Sucrose Mixture suppression
Sip-and-spit Saltiness Sweet-salty mixtures

THE specific taste sensations elicited by each of the components within a mixture are often less intense than their specific taste sensations outside the mixture [e.g., (34)]. This phenomenon is called mixture suppression. Several authors observed that after elimination or reduction of the taste intensity of one component, the taste sensation of the other component in a binary, heterogeneous mixture percept is, to some degree, released from suppression. Several studies used a self- or cross-adaptation paradigm to demonstrate this phenomenon [e.g., (3, 9, 29, 30)]. In other studies, the perception of sweetness was blocked using *Gymnema sylvestre* [e.g., (29,30)].

Adaptation, cross-adaptation, and treatment with *Gymnema sylvestre* lead to the disappearance or reduction of the intensity of one of the two taste sensations by interference in the periphery of the neural system [e.g., (4)]. Kroeze (23, 24, 26) has tried to remove the suppressor's effect centrally instead of peripherally by habituating subjects to the suppressive component without adapting them. Fisher and Fisher (8) have shown that, on the average, 5 to 6 stimulations with sucrose solutions lead to habituation of the Galvanic Skin Response; interestingly, most subjects reported that the stimulus intensity remained fairly constant during the trials. This implies that repeated presentations of sucrose stimuli can lead to habituation to sweetness, without causing a decrease in the intensity of sucrose stimuli. The fact that the subjective intensity of the suppressor remains unaffected by stimulus repetition constitutes the important difference between the effects of adaptation and those of habituation. Adaptation leads to a decrement in the suppressor's intensity, which remains unaffected during habituation. Therefore, the suppression release observed during a habituation experiment does not result from a decrease in intensity of one of the components of the mixture percept, but from a central inhibitory mechanism (27).

Kroeze (24) repeatedly presented subjects with equisweet solutions of sucrose or glucose and subsequently presented a NaCl/sucrose mixture. He then demonstrated that the saltiness response to a NaCl/sucrose mixture approximated the saltiness response to unmixed NaCl. Apparently, habituation to the sweetness of the foregoing stimuli released the saltiness of NaCl from suppression. In a similar way, he demonstrated that the sweetness of the sucrose/NaCl mixture was released from suppression after repetitive stimulations with unmixed NaCl (26). Since habituation is a central event, the mixture suppression found is also taken to be of a central origin.

Another central process that might explain a rise in the saltiness rating of a NaCl/sucrose mixture after repetitious stimulations with sucrose, is successive contrast (26). According to the successive contrast hypothesis, the saltiness of the mixture percept is overestimated because the salty taste stands out against the previously perceived sweet tastes. The increment in the saltiness response is then not accounted for by a decrease in the degree of saltiness suppression as a consequence of the habituation to the sweetness of sucrose, but by an overestimation of the saltiness intensity. The successive contrast hypothesis can be tested using unmixed NaCl stimuli, that are equal in saltiness to the NaCl/sucrose mixtures, as experimental stimuli.

[1]Requests for reprints should be addressed to Hendrik N. J. Schifferstein, Department of Food Science, Agricultural University, Bomenweg 2, 6703 HD Wageningen, The Netherlands.

TABLE 1

THE TWO CONDITIONS USED IN BOTH EXPERIMENTS

			Mixture Condition				
1						N	SN
2					N	S	SN
3			N	S	S	S	SN
4	N	S	S	S	S	S	SN
			Contrast Condition				
5						N	½N
6					N	S	½N
7			N	S	S	S	½N
8	N	S	S	S	S	S	½N

Every series contains one solution of unmixed NaCl (N), none or a certain number of habituating unmixed sucrose solutions (S), and a test stimulus that differs between the two conditions [an NaCl/sucrose mixture (SN), or an unmixed NaCl solution (½N)].

Kroeze (26) obtained two different functions for the mixture suppression condition and for the contrast condition (see his Fig. 3). The magnitude of the estimated saltiness increased linearly with the number of preceding presentations of sucrose in the contrast condition. After correcting the data for the contrast-effect, a negatively accelerating relationship remained between the saltiness estimates and the number of preceding sucrose stimulations. He concluded, therefore, that successive contrast cannot fully account for the observed increment in response to a mixture after habituation to one of its components.

In his habituation experiments, Kroeze (23, 24, 26) delivered the stimuli by means of a gravitational flow system. The present experiments are similar to one of the experiments described by Kroeze (26), with the exception that the stimuli were presented using a sip-and-spit procedure instead of gravitational flow.

EXPERIMENT 1

METHOD

Subjects

The subjects were 24 unpaid volunteers, 11 men and 13 women, ranging in age from 19 to 30 years. Most subjects were students of the Agricultural University and had no experience in psychophysical scaling experiments. All subjects were naive with respect to the substances used and the purpose of the study.

Stimuli

The stimuli were solutions of NaCl (Merck 6406) and sucrose (Merck 7651) and a mixture of NaCl with sucrose in demineralized water (conductivity ~1 μS/cm). The concentrations of the unmixed NaCl were 0.32 M (N) and 0.16 M (½N). The sucrose concentration was 0.32 M (S). The NaCl/sucrose mixture (SN) contained 0.32 M NaCl and 0.32 M sucrose.

For reasons of standardization, subjects were presented with one reference pair at the beginning of the session. The first stimulus of the reference pair was water, the second stimulus was a solution of 0.40 M NaCl.

Solutions were prepared at least 24 hours before tasting and were stored in a dark, refrigerated room at 4°C for no longer than six days.

Design

There were two conditions, each consisting of four different stimulus series (Table 1). In the first condition (the mixture condition), a NaCl/sucrose mixture (SN) was preceded by 0, 1, 3, or 5 presentations of sucrose (S). Since the rated degree of mixture suppression in a heterogeneous taste mixture increases if the relative number of unmixed taste stimuli is increased (25), each series started with an unmixed NaCl stimulus (N). In this way, the number of experimental unmixed NaCl stimuli equalled the number of NaCl/sucrose mixtures.

In the second condition (the contrast condition) 0.16 M NaCl (½N) served as test stimulus. According to Kroeze (26), 0.16 M NaCl equals the NaCl/sucrose mixture with regard to perceived saltiness intensity. Apart from these test stimuli, the series were identical to the series in the mixture condition.

Procedure

The subjects were instructed to judge the intensity of the perceived saltiness. The instructions emphasized that only the saltiness intensity was to be judged. The hedonic value and side tastes of the stimuli were to be disregarded. Subjects made their responses on sheets containing one 150 mm graphic rating scale. The left and right ends of the scale were labelled "not salty at all" and "extremely salty." In the instructions the minimum saltiness and the maximum saltiness were defined as equal to the saltiness intensities of the two stimuli of the reference pair (i.e., water and 0.40 M NaCl respectively). The references were tasted at the beginning of the session.

The subjects were requested to rinse their mouths thoroughly with demineralized water after each stimulus. The stimuli were presented at room temperature (~20°C) in polystyrene medicine cups. Each cup contained about 10 ml of solution. The time interval between stimuli was 60 seconds.

Every subject participated in one 70 minute session. During this session each series was judged twice ($2 \times 34 = 68$ stimuli). The four series of each experimental condition were presented in a random sequence and in a different order for each subject. The order in which the two replications of the two conditions were presented to the subjects was also randomized. The subjects were unaware of the fact that the stimuli were presented in series, since the four series of one condition were handed to the subject simultaneously in one numbered tray.

RESULTS

Figure 1 shows the curves for the responses to the NaCl/sucrose mixture (SN) and the equisalty unmixed NaCl solutions (½N) as a function of the number of preceding stimulations with sucrose (S). In both experimental conditions, the mean responses for the test stimuli increase significantly with the number of sucrose stimulations [$F(3,69) > 14.0$, $p < 0.001$ for both conditions]. The differences between the mixture condition and the contrast condition are not significant [$F(1,23) = 0.00$, $p = 0.97$ for the main effect Condition; $F(3,69) = 2.24$, $p = 0.09$ for the Condition × Series interaction].

The shapes of the functions relating saltiness rating to the degree of preexposure are approximately linear. The differences in explained variance between linear regression equations and second order polynomials are not significant for both conditions (F-test, $p > 0.10$).

An inspection of the mean saltiness scores for the unmixed sucrose stimuli shows that the mean score tends to increase with the number of preceding sucrose solutions. This trend is significant for the habituating stimuli in the mixture condition, $F(4,92) =$

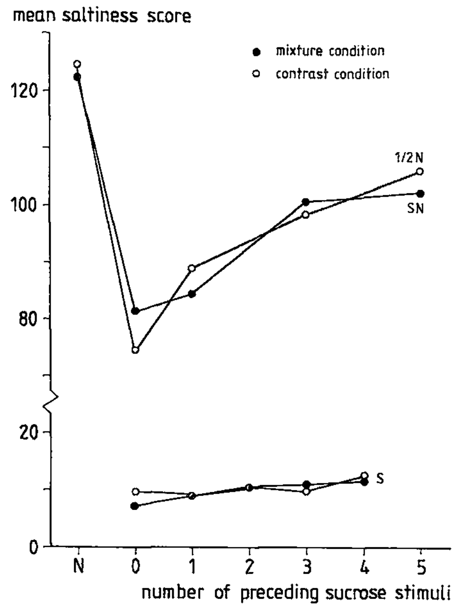

FIG. 1. Mean saltiness responses obtained in the first experiment for N, S, SN, and ½N as a function of the number of preceding sucrose stimuli (S). One curve is drawn for each of the experimental conditions.

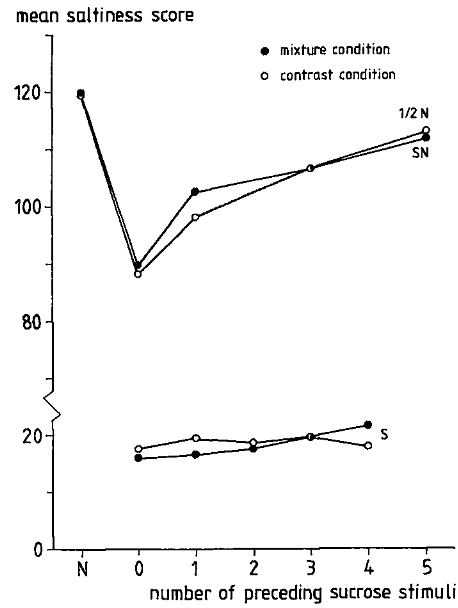

FIG. 2. Mean saltiness responses obtained in the second experiment for N, S, SN, and ½N as a function of the number of preceding sucrose stimuli (S). One curve is drawn for each of the experimental conditions.

2.55, $p<0.05$, but not in the contrast condition, $F(4,92)=0.86$, $p=0.49$.

According to the habituation paradigm, the degree of saltiness suppression in the mixture percept should be reduced because of habituation to sucrose sweetness, whilst the saltiness of the unmixed NaCl should remain unaffected. Therefore, saltiness responses to the mixture (SN) are expected to be higher than saltiness responses to the unmixed NaCl (½N) after stimulation with sucrose. The curves are highly similar, however, and not significantly different. These findings are in contradiction with the results obtained by Kroeze (26), who found higher saltiness responses for the NaCl/sucrose mixtures than for the contrast condition.

In order to reconcile the results of the present study and those reported by Kroeze (26), a second experiment was conducted. In this experiment, the experimental procedure was modified to resemble more closely the original procedure used by Kroeze: 1) in order to reduce carry-over effects from one series to another, the subjects were informed when each series began and when it ended and 2) no references were presented at the beginning of the session.

EXPERIMENT 2

METHOD

Subjects

The subjects were 13 paid volunteers, 1 man and 12 women, ranging in age from 18 to 22 years. Most subjects were students of the Agricultural University and had no experience with psychophysical scaling experiments. All subjects were naive with respect to the substances used and the purpose of the study.

Stimuli and Design

The stimuli were identical to the ones used in the first experiment, with the exception that no reference solutions were prepared. The experimental design was identical to the one described above.

Procedure

The instructions were similar to the instructions given in the first experiment, except that no reference solutions were given to the subjects. One stimulus was handed over to the subject every minute. In addition, the subjects were aware of the fact that the stimuli were presented in series. After each series, the subject received a written note saying the preceding series was finished. The time interval between the last stimulus of a series and the first stimulus of the following series was two minutes instead of one. The eight series (4 series × 2 conditions) were presented in a random sequence and in a different order for each subject.

During every session, the subjects judged all 34 experimental stimuli once. Every subject participated in two identical 45 minute sessions to complete the investigation.

RESULTS

Figure 2 shows the mean saltiness scores for unmixed NaCl (N) and for the test stimuli after repeated stimulations with a certain number of sucrose stimuli. The curve for the NaCl/sucrose mixture is almost identical to the curve for the contrast condition (½N). In both conditions, the mean saltiness score for the test stimuli increases with the number of preceding sucrose stimuli [F(3,36)>4.5, $p<0.01$ for both conditions], but the two experimental conditions do not lead to significant differences in mean responses [F(1,12)=0.03, $p=0.87$ for the main effect Condition; F(3,36)=0.16, $p=0.93$ for the Condition × Series interaction]. The number of preceding sucrose stimuli do not affect the saltiness judgments for unmixed sucrose stimuli in the mixture condition, F(4,48)=1.30, $p=0.28$, nor in the contrast condition, F(4,48)=0.20, $p=0.93$.

Similar to the first experiment, the functions relating saltiness rating to the degree of preexposure are approximately linear. The differences in explained variance between linear regression equations and second order polynomials are not significant for both conditions (F-test, $p>0.10$).

These results imply that successive contrast can account for the total increment in saltiness estimates after repeated stimulations with sucrose. Similar to the results of Experiment 1, no suppression release was observed for the NaCl/sucrose mixture.

GENERAL DISCUSSION

SUCCESSIVE CONTRAST

In the two experiments of the present study, the saltiness responses for the test stimuli increased to the same degree for both conditions. In previous research, the relationship between the intensities of preceding stimuli and the current responses has mostly shown contrast. For example, Riskey et al. (35) noted that solutions preceded by a higher sucrose concentration were judged significantly less sweet than the same samples preceded by a lower concentration. Similarly, Schifferstein and Frijters (36) reported that sucrose solutions obtained higher mean scores after tasting a low sucrose level than after a high level. The amount of contrast between stimuli and the dependency between successive responses varies with the discriminability of the stimuli (33,41) and task instructions (7).

The observed successive contrast cannot be accounted for by a peripheral contrast phenomenon like the appearance of the "water taste" after adaptation to sucrose (2,31). Since subjects were requested to rinse with demineralized water between samples, and since the time interval between stimuli (60 seconds) is long enough to recover completely from adaptation [e.g., (14)], it is unlikely that a water taste has appeared during the experiment. In addition, water tastes bitter after adaptation to sucrose, and not salty (2), and therefore cannot have affected the saltiness intensities of the test stimuli. The observed contrast is more likely to result from processes affecting the internal representations of stimuli and references or the response selection process [e.g., (7, 15, 41)].

SUPPRESSION RELEASE

Kroeze (26) reported significant differences between the mixture condition and the contrast condition for sucrose/NaCl mixtures after habituation to sucrose or to NaCl. According to Kroeze, one of the two sensations in the mixture percept was released from mixture suppression because the subjects were habituated to the other sensation. In the present study, the two conditions yielded similar results, implying no suppression release and no habituation. Since the design of Kroeze's study was similar to the one used for the present study, differences in the degree of habituation between the two studies must be explained from differences in experimental procedures.

As two different stimulus presentation procedures may differentially affect the subjects' sensory or receptor mechanisms, the degree of adaptation may have differed between the two studies. In Kroeze's (26) experiment, 1.3 to 1.5 cm^2 area of the left anterior tongue half was stimulated with 1.6 ml of solution. In the present study, subjects sipped about 10 ml of solution on each trial. Since the stimulus volume was larger in the present study, adaptation would have been more likely to have occurred during the present study than during Kroeze's experiment. If adaptation had occurred in the present study, this adaptation would have led to suppression release in the mixture condition of the present experiment [cf. (30)]. Since no suppression release was found in the present study, the differences between the results of the two studies under discussion cannot be explained on the basis of a differential effect of adaptation.

Since adaptation cannot account for the difference between Kroeze's findings and the present ones, the difference must be due to differences in habituation rates evoked by the two experimental procedures. Habituation of subjects to stimuli may be difficult to achieve since many experimental variables affect the rate of habituation [e.g., (1, 6, 10, 12, 18, 19)]. The experimental procedure employed by Kroeze differs from the procedure presently employed in at least five aspects: the degree of experimental control, the role of the subject in stimulus sampling, the degree of variation in the proximal stimuli, the area of the tongue stimulated, and possible differences in perceived subjective intensities.

Fisher and Fisher (8) took many precautions to isolate subjects from nongustatory stimulation. The subjects were seated comfortably, in a darkened room, with "Noisefoes" over their ears. In Kroeze's experiment, individual sessions were held, but no extra precautions against external cues were reported. During the present study, the subjects performed the experimental task in groups of 3 to 6 persons, each of them seated in an individual, separate test compartment. The individual test compartments did not only separate the subjects from other subjects and from several possible sources of nongustatory cues, but they also separated the subjects from the experimenter. Therefore, the subjects in the present experiments were not under experimental control to the same extent as in the studies performed by Kroeze, who stimulated each subject individually. The lower degree of experimental control in the present study may have allowed the subjects to pay attention to nontask events that may have produced dishabituation [e.g., (39)].

The second difference in the two experimental procedures is the role of the subject in stimulus administration. When a gravitational flow system is used, the subject is passively waiting for the next stimulus to be delivered. During the sip-and-spit procedure, however, the subject is presented with a new stimulus cup and/or receives a signal (human voice) requesting the subject to taste a new stimulus. Therefore, in the sip-and-spit procedure, the signal that a new sample should be evaluated leads to arousal of the subject, who must become active in order to perform all the movements necessary to taste the solution and to rinse with water. Therefore, the subject in the sip-and-spit procedure is likely to have a higher arousal level than the subjects stimulated by a gravitational flow procedure. Consequently, the subjects in the present study may have habituated more slowly than the subjects in Kroeze's experiment (10,40).

The third difference between the two studies under discussion concerns the variation in the proximal stimuli, i.e., the stimuli as they come into contact with the subject's receptors. Although the distal stimuli, i.e., the stimuli as they are prepared (concentrations, volume, temperature) were approximately constant in both studies, the degree of variation in the proximal stimuli may have differed between the two studies. During Kroeze's gravitational flow presentation, exactly the same restricted tongue area was always stimulated. During the sip-and-spit experiments, however, the subject was free to move the tongue and the part of the tongue stimulated may have differed per sample. As the proximal stimuli were not constant in the present study, the habituation rate depends upon whether stimulus generalization occurs or not [e.g., (17)]. If stimulus generalization does not occur during the sip-and-spit procedure, this can explain the absence of suppression release in the present data. An argument against this explanation may be derived from the results of Fisher and Fisher (8). These investigators stimulated the anterior dorsal tongue without restricting the stimulated area and still reported habituation of the GSR response, implying stimulus generalization.

It may be argued that the habituation rate during a sip-and-spit experiment may differ from the habituation rate during a gravitational flow experiment because more afferent nerves are stimulated during sip-and-spit tasting. The taste buds in the anterior two-thirds of the tongue are innervated by afferent fibres of the chorda tympani, a branch of the facial nerve (VII). The taste buds in the posterior third of the tongue are innervated by the lingual branch of the glossopharyngeal nerve (IX). Taste buds on the palate are innervated by the greater superficial petrosal branch of the facial nerve (VII), and the buds on the epiglottis and oesophagus by a branch of the vagus nerve (X) [e.g., (5)]. The trigeminal nerve (V) provides sensory innervation to the anterior two-thirds of the tongue, but not to the posterior third [e.g., (22)]. A special reason to note these differences in innervation of the areas stimulated by the two experimental procedures used, originates from the fact that the posterior part of the tongue is involved in the swallowing reflex. The afferent side of this reflex is formed by the glossopharyngeal nerve; the vagus nerve innervates palatal and pharyngeal muscles [e.g., (16)]. The swallowing reflex is one of the so-called "adaptation reflexes," that Sokolov (38) typifies as specialized reflexes that react to a limited type of stimuli only. These types of reflexes are known to resist habituation during the stimulation period. As the sensory neurons that lead to the swallowing reflex are also stimulated during sip-and-spit tasting, habituation to the gustatory stimuli may be impaired.

The fifth factor that may have contributed to the difference between the present results and those obtained by Kroeze (26) is the subjective intensity of the habituating stimuli. Kroeze stimulated only 1.3 to 1.5 cm^2 of the tongue's surface with a flow rate of 0.8 ml/s during 2 seconds (total stimulus volume: 1.6 ml). In the present study, the subjects tasted about 10 ml of solution, during which the whole mouth was stimulated. In addition, the subject was free to keep the solution in his mouth as long as desired. The average stimulus duration in a sip-and-spit experiment probably exceeds the 2 seconds used by Kroeze. This can be inferred from observations of subjects during experiments in which two or three sucrose solutions had to be discriminated (13). The average duration of stimulation was found to be 3.6 seconds per sample (individual values ranging from 2.4 to 5.4 seconds). Therefore, in the present study, a larger stimulus volume was used, a larger area of the tongue was stimulated, and the total stimulation time was longer than in Kroeze's experiment. Each of these three factors can contribute to an increase of the intensity of the sensation perceived [e.g., (11, 20, 21, 28, 32, 37)]. Since high-intensity stimuli habituate more slowly than low-intensity stimuli [e.g., (39)], subjects may habituate more slowly in a sip-and-spit experiment than in a gravitational flow experiment. However, the importance of subjective intensity in determining the rate of habituation is not to be overestimated, since Fisher and Fisher (8) reported that sucrose concentration (ranging from 0.03 M to 1.0 M), a major determinant of subjective intensity, did not affect the mean number of trials to GSR habituation.

In summary, the successive contrast phenomenon as demonstrated by Kroeze (26) and as observed in the present study originates from central sensory or judgmental processes. In an attempt to explain the absence of suppression release during the sip-and-spit experiments, five factors were suggested that may be responsible for the low habituation rate in the sip-and-spit experiments: the low degree of experimental control; the subject's relatively high level of arousal; the variation in the proximal stimulus; the tongue area stimulated; and the possibly higher subjective intensities of the stimuli. Adaptation is unlikely to have affected the results of the two studies under discussion.

Since habituation did not occur during the sip-and-spit experiments, habituation is also very unlikely to occur during eating and drinking. Therefore, the ecological meaning of habituation in food intake is minimal.

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Concluding remarks

The findings of the two experiments on sucrose/NaCl mixtures show that the absence of suppression release in the first experiment (QHCl/NaCl mixtures and KCl solutions) does not necessarily imply that the bitterness suppression mechanism is peripheral in origin, but could also be explained by the absence of habituation during a sip-and-spit experiment.

Chapter 5

PERCEPTUAL INTEGRATION IN HETEROGENEOUS TASTE PERCEPTS

In this chapter, the central integration processes are discussed, relating the total intensity of a mixture to its component intensities.

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Introduction

In studying the processes involved in the perception of mixtures of dissimilar tasting substances, two approaches have dominated mixture interaction research. One focuses upon the specific taste intensities (sweetness, sourness, saltiness, bitterness) of a mixture. In the other approach, the total taste intensity of the mixture is of central interest. The total taste intensity of a particular stimulus is usually defined as the strength of the overall impression, irrespective of the taste qualities perceived. In general, when a mixture of two substances eliciting different taste qualities is tasted, the specific taste sensations elicited by the mixture are less intense than the specific taste sensations elicited by the unmixed components outside the mixture. This phenomenon is called mixture suppression (e.g. Pangborn, 1960). With regard to total taste intensity ratings, it has been noted that the total taste intensity of a mixture is usually lower than the sum of the total taste intensities elicited by the unmixed components (Pfaffmann *et al.*, 1971).

Most taste research has focused upon the assessment of specific taste intensities rather than on the determination of total intensity. One could argue that this preoccupation with specific taste sensations has its roots in everyday life. Spontaneous reports on the quality of a meal will usually focus upon specific aspects of the food stuffs consumed (e.g. "too sweet", "too spicy"). Overall intensity judgments will occur only in those cases where our descriptive system is inadequate. For example, the taste of an alcoholic drink may be called "too strong", because an appropriate descriptor for the taste of alcohol is not available. In other senses, non-qualitative intensity judgments seem more familiar to our daily experiences. Music, for example, may be "too loud" or "too soft", and after stepping out of a dark room, a light may seem "very bright".

The significance of the concept of total taste intensity is evident for psychophysical research if we try to relate the sense of taste to the other senses. Even if subjective experiences may be qualitatively different, the amount of sensation is a universal characteristic of experience (Külpe, 1893; Marks, 1978a). The total taste intensity of a complex mixture of tastants for the sense of taste is comparable to the loudness intensity of a complex tone for audition, and the brightness of a complex visual field for vision. This intermodal correspondence between the senses forms the basis of cross-modality matching (Stevens, 1959).

Next to intermodal comparisons, total intensity has also been used in interqualitative comparisons within one sense modality. In taste mixture research, for example, Bartoshuk (1975) has focused on total intensity judgments to study the relationship between the form of the psychophysical functions of the unmixed components and the degree of mixture interaction. Total taste intensity seems to be the most logical and most convenient stimulus attribute to investigate if the taste elicited by a single substance does not correspond to one of the 'primary' tastes (see Schiffman & Erickson, 1971) or if the taste quality changes with concentration, as is the case for many salts (e.g. Dzendolet & Meiselman, 1967; Cardello & Murphy, 1977).

Since both specific and total intensity have been studied extensively in taste mixture research, the relationship between these variables provides insight into the perceptual and cognitive processes involved in mixture perception. De Graaf and Frijters (1989) developed a conceptual framework describing the interrelationships among the physical and psychological variables that play a role in the perception of mixtures of dissimilar tasting substances (Figure 1). Their notation is identical to that proposed by Frijters (1987), and will be used throughout this paper. The physical concentration of an *unmixed* stimulus is denoted by ϕ and the physical concentration of a component in a *mixture* by Φ. The taste intensities of *single* substances outside the mixture are denoted by ψ and the taste intensities of the *mixture* or its components within the mixture are denoted by Ψ. The Roman subscripts a and b refer to two dissimilar tasting chemicals, while the Greek subscripts α and β refer to the qualities of the specific taste sensations elicited by substance a and b, respectively. The Greek subscript τ refers to the total taste intensity elicited by a solution. The subscripts i and j represent particular concentrations of the chemicals a and b in moles/l.

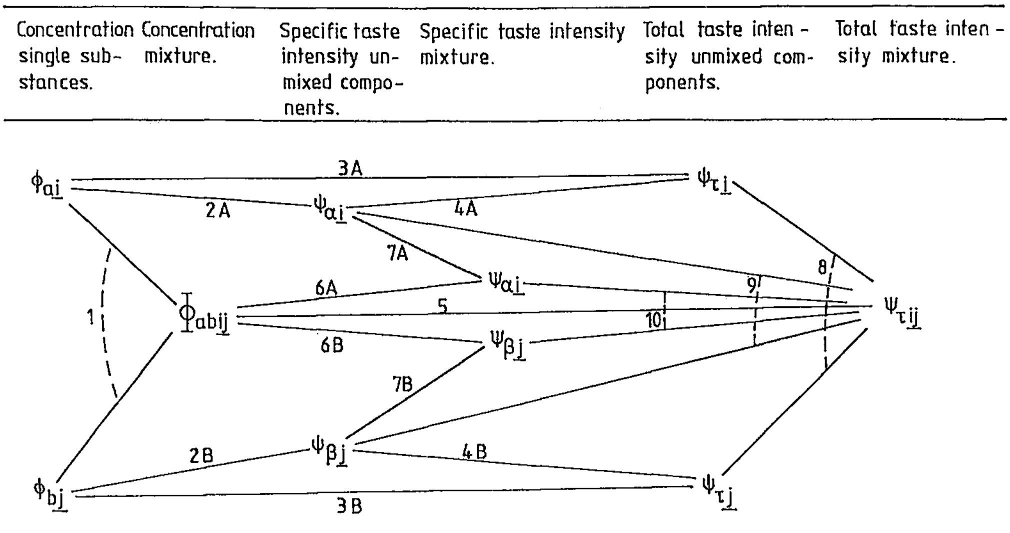

Fig. 1. Outline of interrelationships among perceived specific and total taste intensities when two qualitatively dissimilar taste substances are mixed (From De Graaf and Frijters, 1989).

Throughout this paper, the words sensation and percept will be used to address subjective experiences, elicited by tasting a stimulus. These terms refer to unobservable psychological events that are to be distinguished from the physically accessible stimuli and responses. In our terminology, the term percept refers to the total, complex experience, while a sensation is regarded as a part of the overall percept. If several taste sensations can be distinguished within a percept, this percept is said to be heterogeneous. If only one taste sensation is present, the percept is called homogeneous.

Psychophysical models, relating physical variables (concentrations) to perceived sensations (Figure 1: 5) will not be treated here (for a review, see Frijters, 1987). Most of these models are based on competition for receptor sites (e.g. the Substitution model (Moskowitz, 1974), the Beidler equation (see De Graaf & Frijters, 1986), and the Equiratio Mixture model (Frijters & Oude Ophuis, 1983)). These models are not designed to account for interactions in mixtures of dissimilar tasting substances, since dissimilar tasting substances usually compete for different receptor sites, as can be concluded from cross-adaptation studies (McBurney & Bartoshuk, 1973). In addition, the interactions between different tasting components have often been found to occur central to the reception mechanism (e.g. Kroeze, 1978, 1979; Lawless, 1979; Kroeze & Bartoshuk, 1985).

The present paper deals with *perceptual* models, identifying relationships among psychological constructs (sensations, percepts). In our discussion, no distinction is made between models relating the total taste intensity of a mixture to the total taste intensity of its unmixed components (Figure 1: 8) and those relating it to the specific taste intensities of its unmixed components (Figure 1: 9).

Models predicting total taste intensity

Figure 2 shows how the perceptual integration models applied in taste research can be ordered systematically. First, models relating total taste intensity of the mixture percept to the intensities of the *unmixed components* (Figure 1: 8 and 9) are to be distinguished from models relating total taste intensity of the mixture percept to the specific taste sensations *within the mixture percept* (Figure 1: 10). The first type of models can be applied in investigating either heterogeneous or homogeneous mixture percepts. The second type of models can only be applied in the investigation of heterogeneous percepts, since no specific taste sensations can be distinguished within a homogeneous percept.

Second, the models are to be distinguished according to the type of mathematical combination rule they employ in estimating the total taste intensity. Basically, a distinction can be made between four comparison rules: the unweighted and the weighted (scalar) summation rules, the vector summation rule, and the dominant component rule.

In the next paragraphs, the origin and use of the different combination rules will first be discussed for the models relating the mixture's total taste intensity to the intensities of the unmixed components (Type 1 models). Subsequently, the models relating total taste intensity to the specific taste sensations within the mixture percept will be treated (Type 2 models).

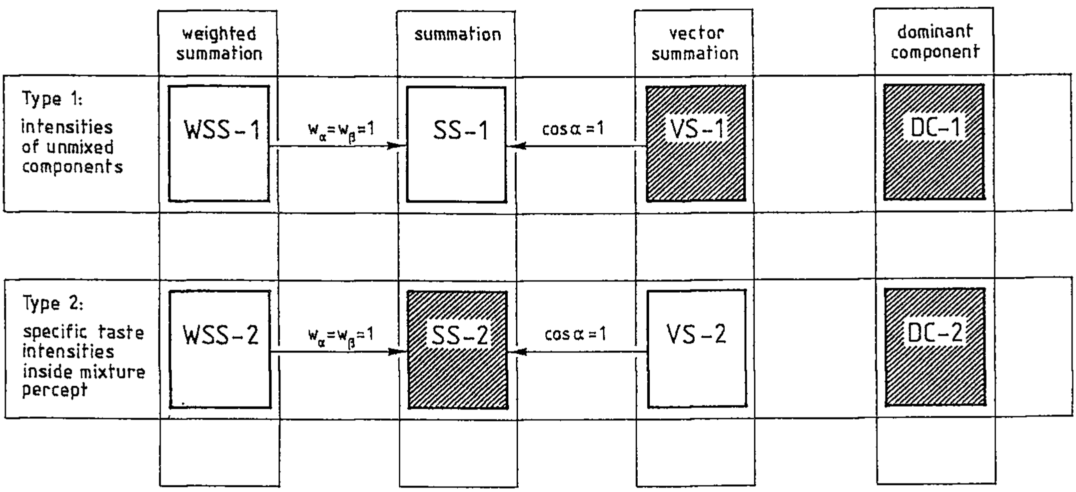

Fig. 2. Overview of perceptual models relating the total taste intensity of the mixture percept to the taste intensities of the unmixed components or to the specific taste intensities of the sensations within the mixture percept. The four models compared in this paper are shown in the shaded boxes.

By far the most simple combination rule is the simple addition of the intensities of the unmixed components. This *Sum of Sensations (SS-1)* can then be compared to the total taste intensity of the mixture percept. The additive rule forms the basis of Moskowitz's (1973) Addition Model and the Summated Response Comparison rule used in the assessment of taste interactions (e.g. Stone & Oliver, 1969; Bartoshuk, 1975; De Graaf & Frijters, 1988).

The *Vector Summation (VS-1)* model (Berglund, Berglund, Lindvall, & Svensson, 1973) can be conceived of as an application in olfactory research of Ekman's (1963) vector model for multidimensional ratio estimation. It predicts the intensity of a homogeneous odour mixture percept *AB* on the basis of the intensities of its unmixed components *A* and *B* if the degree of dissimilarity between the qualities of the two sensations elicited by *A* and *B* is known. The intensities of the sensations elicited by the mixture and its unmixed components are represented by the lengths of three vectors in a psychological space. The angle α between the sensations elicited by *A* and *B*, reflects the difference in quality between the two sensations. According to the model, the mixture percept equals the resultant of the two vectors representing the sensations for the unmixed components. The angle α is supposed to be constant for each pair of substances mixed. The angles between the component sensations and the resultant depend upon the ratio between the perceived intensities of *A* and *B*. Mathematically, the model is written:

$$\Psi_{\tau ij} = (\psi_{\tau i}^2 + \psi_{\tau j}^2 + 2\psi_{\tau i}\psi_{\tau j}\cos\alpha)^{0.5} \qquad \text{(I)}$$

The VS-1 model can, in principle, also be applied in taste mixture research (Bartoshuk, 1975). The angle α can be estimated by orthogonal linear regression (e.g. Hampton, 1983; Williams, 1986), using the formula (Schifferstein & Frijters, 1990):

$$(\Psi_{\tau ij}^2 - \psi_{\tau i}^2 - \psi_{\tau j}^2) = \cos\alpha\ (2\psi_{\tau i}\psi_{\tau j}) \qquad \text{(II)}$$

McBride's (1989) *Dominant Component (DC-1)* model is based on the assumption that *'the (subjectively) dominant component determines the total intensity of the mixture'*. When a mixture of dissimilar tasting compounds is presented to the taste receptors, each of the mixture components is independently processed as if the tastants were unmixed, according to the DC-1 model. Furthermore, the model states that the subject experiences the total intensity of a mixture as being equal to the intensity of the unmixed component eliciting the highest taste intensity. The model is represented by Equation III:

$$\Psi_{\tau ij} = \text{MAX}\ (\psi_{\tau i}, \psi_{\tau j}) \qquad \text{(III)}$$

De Graaf & Frijters (1989) suggested that the total taste intensity of a mixture percept follows from a *Weighted Sum of the specific taste Sensations (WSS-2)* elicited by that mixture. For a two-component mixture percept, this model is written:

$$\Psi_{\tau ij} = w_\alpha{*}\Psi_{\alpha i} + w_\beta{*}\Psi_{\beta j} \qquad \text{(IV)}$$

Estimates of the weights in Equation IV for group data have ranged from 0.92 to 1.07 (De Graaf & Frijters, 1989; Schifferstein & Frijters, 1990, 1992), indicating that such weights are near to unity. Since the weights in the WSS-2 model were found to approximate unity, the WSS-2 model can be simplified to the (unweighted) *Sum of Sensations (SS-2)* model:

$$\Psi_{\tau ij} = \Psi_{\alpha i} + \Psi_{\beta j} \qquad (V).$$

If $\Psi_{\alpha i}=0$ or $\Psi_{\beta j}=0$, Equation IV yields $\Psi_{\tau ij}=w_\beta{*}\Psi_{\beta j}$ or $\Psi_{\tau ij}=w_\alpha{*}\Psi_{\alpha i}$, respectively. Since the total intensity should equal one of the specific taste intensities if the other sensation is absent, it is not surprising to find that $w_\alpha \approx w_\beta \approx 1$.

The SS-2 model is equivalent to the analytical addition principle used in loudness research (e.g., Marks, 1978b, p.20) which was first applied in the taste realm by Marks & Bartoshuk (1979). In addition, the SS-2 model is used implicitly in taste mixture research if subjects are instructed to rate total intensity and break this numerical response up into ratings for a number of specific taste categories (Smith & McBurney, 1969).

The SS-2 model is not only a special case of the WSS-2 model; it can also be regarded as a special case of a *Vector Summation (VS-2)* model in which the total intensity of a mixture percept results from the combination of the specific taste sensations, represented by vectors in a psychological space (Schifferstein & Frijters, 1990). The angle between the specific taste sensations reflects the difference in importance of the specific taste sensations in determining the total intensity of the mixture percept. The VS-2 model is written mathematically:

$$\Psi_{\tau ij} = (\Psi_{\alpha i}^2 + \Psi_{\beta j}^2 + 2\Psi_{\alpha i}\Psi_{\beta j}\cos\alpha)^{0.5}. \qquad (VI)$$

According to the SS-2 model:

$$\Psi_{\tau ij}^2 = (\Psi_{\alpha i} + \Psi_{\beta j})^2 = \Psi_{\alpha i}^2 + \Psi_{\beta j}^2 + 2\Psi_{\alpha i}\Psi_{\beta j}.$$

The SS-2 model is, therefore, a special case of the VS-2 model with $\cos\alpha=1$, implying $\alpha=0°$.

Ganzevles & Kroeze (1987) noted that *'the estimated 'total' intensity is equal to the dominant taste in the [taste] profile'*. According to these authors, the total taste intensity of a mixture equals the specific taste intensity of the dominant sensation within the mixture percept (and not outside as in the DC-1 model). This *Dominant Component (DC-2)* model can be described as follows:

$$\Psi_{\tau ij} = \mathrm{MAX}\,(\Psi_{\alpha i}, \Psi_{\beta j}) \qquad (VII)$$

It can be concluded that most of the models appearing in Figure 2 have already been applied by one or more investigators in taste mixture research. The only model that has not been used, as far as we know, is the WSS-1 model. In the following sections, four of the eight models will be discussed in detail. These models are marked in Figure 2. Both Dominant Component models will be discussed since these models have recently gained interest (McBride, 1989; Ganzevles & Kroeze, 1987). From the other Type 1 models, only the VS-1 model will be discussed. The VS-1 is the most interesting Type 1 model since taste mixture studies in which the VS-1 model was used have yielded α values ranging from 87° to 115° (Frank & Archambo, 1986; De Graaf & Frijters, 1989; Schifferstein & Frijters, 1990). The predictions of the VS-1 model are, therefore, likely to be better than the ones of the SS-1 model, which assumes $\alpha=0°$. In addition, the SS-1 model has been shown to be invalid since the degree of additivity of the mixture components depends upon the form of the psychophysical functions for the unmixed substances (Bartoshuk, 1975). From the Type 2 models, only the SS-2 model will be discussed since the weights of the WSS-2 model and the estimate of cosα in the VS-2 model have been found to approximate 1, which supports the SS-2 model (Schifferstein & Frijters, 1990).

Evaluation of four models

Psychometrical prerequisites

Every model mentioned in Figure 2 implicitly assumes that all variables are assessed on scales with equal units. For the models that predict the total taste intensity elicited by a mixture on the basis of the total taste intensities of its unmixed components (Type 1 models), this assumption does not pose problems, since only one (total taste intensity) scale is used. For the Type 2 models, however, the specific taste intensities and the total taste intensity must all be assessed on scales with identical units. Calibrating the scales is necessary since subjects may have used different psychological units for each attribute judged. Response behaviour is considered to be independent of the perceptual processes that lead to the formation of a mixture percept.

De Graaf and Frijters (1989) calculated multiplicative constants between the units of different sensation scales in order to calibrate the specific taste sensation scales with the total taste intensity scale. Their scale calibration procedure is based on the testable assumption that the psychophysical function relating concentration to total taste intensity and the function relating concentration to the chemical's specific taste intensity are identical for each of the substances used in mixture construction (i.e. the substances under investigation elicit no side tastes). After checking this assumption, plotting the relationship between the scale values on the total taste intensity scale and the scale values on the specific taste intensity scales for the unmixed substances results in the value of the calibration constant.

For example, the sweetness intensities elicited by three sucrose concentrations are 10, 17, and 30 on the sweetness scale. The total taste intensities of the same solutions are judged to equal 7, 12, and 21. The value of the calibration constant, used to calibrate the sweetness scale and the total taste intensity scale, will then equal 0.7 since 0.7*10=7, 0.7*17=11.9, and 0.7*30=21. De Graaf and Frijters (1989) and Schifferstein and Frijters (1990, 1992) have reported calibration factors ranging from 0.56 to 0.90.

A second psychometrical aspect of the models that deserves attention is the measurement level on which the variables in the model are assessed. According to the Dominant Component models, the subject selects the largest of two values. Since this implies a judgment of which of the two values is larger than the other one, only the ordinal measurement level is required. In the VS and the (W)SS models, however, variables are added and/or multiplied. Both of these arithmetic operations require data assessed on ratio level.

In the following sections, the predictions and properties of four models (VS-1, DC-1, DC-2, and SS-2) will be discussed using data on sucrose/NaCl mixtures (De Graaf & Frijters, 1989), on sucrose/citric acid mixtures (Schifferstein & Frijters, 1990), and on quinine hydrochloride (QHCl)/NaCl mixtures (Schifferstein & Frijters, 1992). Each of these studies employed an experimental procedure, based on functional measurement in combination with a two-stimulus procedure (Klitzner, 1975; Anderson, 1981; De Graaf, Frijters, & van Trijp, 1987). This methodology permits a separation of the sensory from the

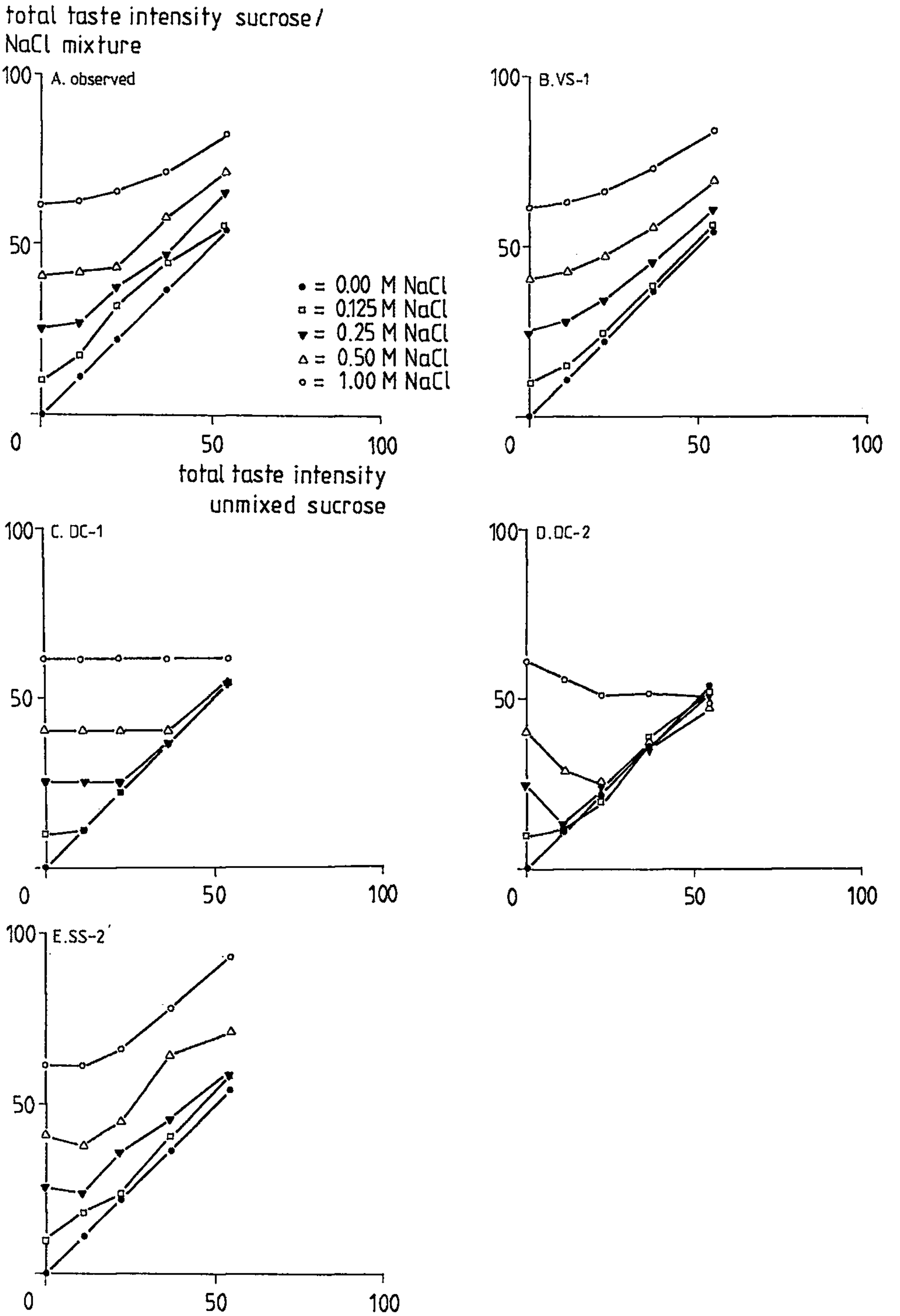

Fig. 3. The total taste intensity of sucrose, NaCl, and sucrose/NaCl mixtures as a function of the total taste intensity of sucrose, with a separate curve for each NaCl level (Data from De Graaf and Frijters, 1989). Panel A shows the results obtained experimentally. Panels B to E show the predictions of the VS-1, the DC-1, the DC-2, and the SS-2 models, respectively.

judgmental processes. The procedure, thereby, allows a post-experimental check of the response scale.

In this procedure, subjects are instructed to judge the magnitude of the difference between the perceived taste intensity of each 'row' (first) stimulus and each 'column' (second) stimulus. This type of design is called a factorial judgment design. It has been shown that subjects perform a subtractive operation when they are instructed to judge a difference. The subtractive model predicts no interaction between row and column stimuli, assuming the response scale is linear (e.g. Birnbaum, 1978; Birnbaum & Mellers, 1978). Therefore, testing the row × column interaction for significance provides the basis for testing (a) whether the comparative operation is subtractive and (b) whether the function transforming the difference between the two sensations into a 'difference' response is linear. The shape of the response output function is independent of the kind of taste interaction that has occurred or the shape of the psychophysical functions. After the linearity of the response scale has been confirmed, scale values for the experimental stimuli can be calculated. These scale values are considered to be valid estimates of perceived taste intensity on an interval scale (Anderson, 1981). By calculating the difference between the scale value for an experimental solution and the scale value for water (assuming the taste intensity for water to be a rational zero point on a taste intensity scale), the intensity scale derived has ratio scale properties.

Predictive abilities

Figures 3-5 show the results and the predictions made by the four models for the three studies mentioned above. In each figure, panel A shows the data obtained experimentally. Panels B to E show the predictions of the VS-1, the DC-1, the DC-2, and the SS-2 models, respectively. Each panel shows the total taste intensity of the experimental stimuli as a function of the total taste intensity of one of the unmixed components (sucrose or QHCl), with a separate curve for each concentration of the other substance (NaCl or citric acid).

The description of the taste interactions between sucrose and NaCl, and between sucrose and citric acid by the Vector Summation (VS-1) model is almost perfect. However, for the QHCl/NaCl mixtures, the model overestimates the total taste intensity of mixtures below the diagonal.

According to McBride's DC-1 model, the total taste intensity of a mixture is determined by the subjectively dominant component (outside the mixture). Therefore, the predicted total taste intensity equals the total intensity of NaCl or citric acid at low concentrations of sucrose or QHCl (horizontal lines). As the concentration of sucrose or QHCl increases, and the intensity exceeds the intensity of NaCl or citric acid, the total taste intensity curve will coincide with the diagonal for increasing concentrations of sucrose or QHCl.

Experimental results (panels A), however, do not follow this pattern. For example, the sucrose/NaCl data show that the total taste intensity of a 1 M NaCl solution increases monotonically with increasing sucrose concentrations. In QHCl/NaCl mixtures, the bitterness intensity of QHCl is suppressed to a large degree by NaCl, even at low NaCl concentrations. In some cases, the magnitude of the observed suppression causes the total taste intensity to be lower than the bitterness of unmixed QHCl. The DC-1 model, however, does not allow the intensity of a mixture to be lower or higher than the intensity of the most intense tasting unmixed component. The DC-1 model is, therefore, unable to account for the data.

According to the DC-2 model, the total intensity equals the maximum of one of the specific taste sensations within the percept. Deviations from the DC-2 model occur

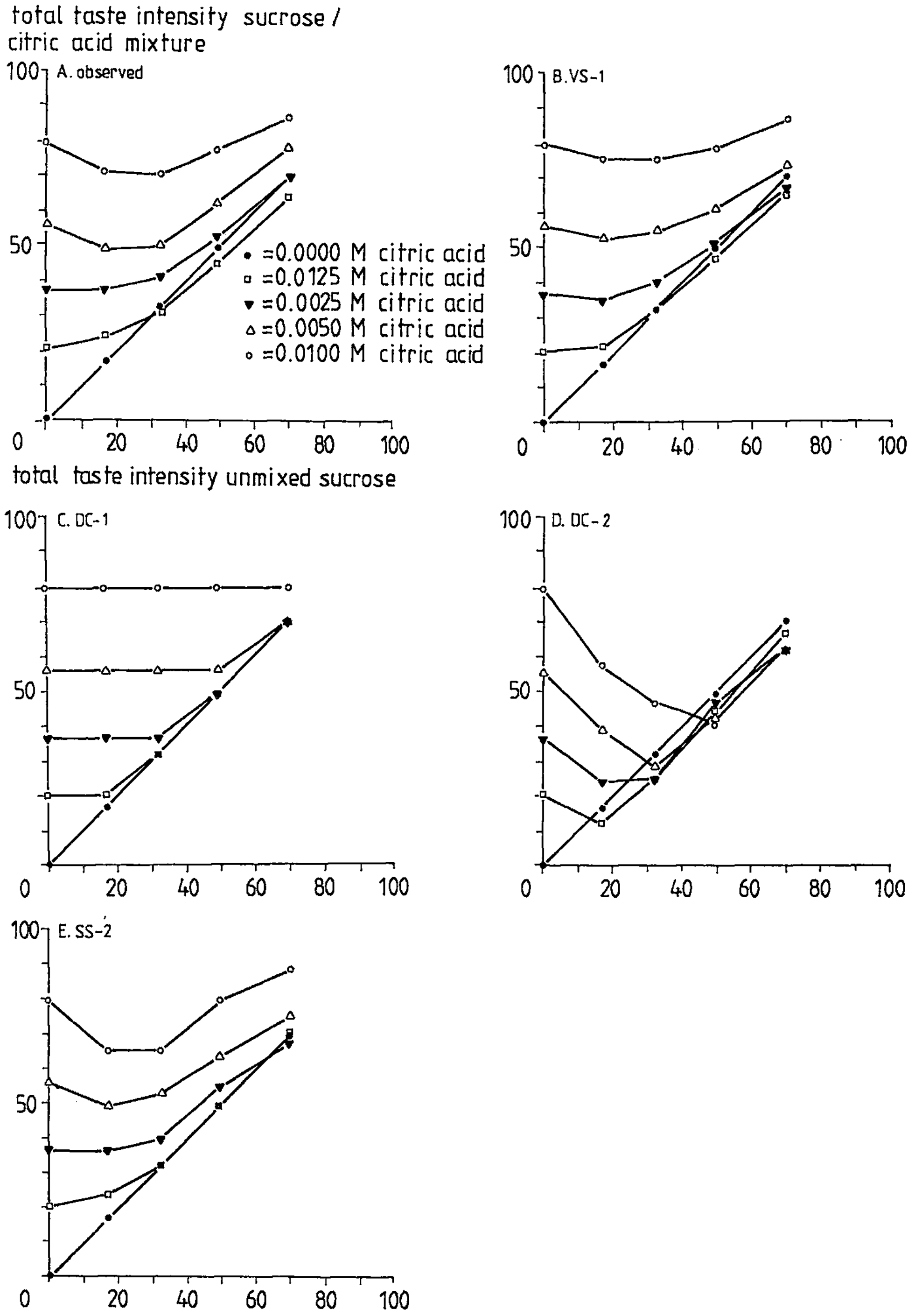

Fig. 4. The total taste intensity of sucrose, citric acid, and sucrose/citric acid mixtures as a function of the total taste intensity of sucrose, with a separate curve for each citric acid level (Data from Schifferstein and Frijters, 1990). Panel A shows the results obtained experimentally. Panels B to E show the predictions of the VS-1, the DC-1, the DC-2, and the SS-2 models, respectively.

frequently in the experimental data depicted in Figures 3-5. A notable feature of the DC-2 model is the fact that all mixture curves end below the diagonal. Especially for the sucrose/NaCl mixtures and the sucrose/citric acid mixtures, where many experimental curves do not cross the diagonal, the predictions of the DC-2 model systematically underestimate total taste intensity. If no taste enhancement occurs between two components, the model cannot account for the phenomenon that a mixture may be more intense than the two components tasted separately.

The SS-2 model performs well for the results of each of the three experiments. The SS-2 model can describe all the phenomena encountered, and does not have any obvious deficits. Perhaps the fit may be improved by using weight parameters different from 1 (see below). The estimates of the total taste intensity according to the DC-2 model will, in all cases, be lower than the estimates obtained by the SS-2 model, since only one of the specific taste sensations contributes to the DC-2 estimator, whilst both are added in the SS-2 model.

The goodness of fit of each model was evaluated using the proportion of explained variance U (Eisler & Roskam, 1977) rather than the Pearson coefficient of correlation r. Using r would be similar to determining the degree of fit of an unrestricted least squares regression line relating predicted to observed total taste intensities. Testing the goodness of fit of a model, however, demands that the relationship between predicted and observed scale values is given by a straight line through the origin with a slope of 1. Pearson coefficients of correlation give a too favourable impression of models that yield predictions that deviate systematically from the main diagonal (e.g. Alf & Abrahams, 1974).

Table I gives the proportions of explained variance (U) accounted for by the total intensities as predicted by the VS-1, DC-1, DC-2, and SS-2 models. These calculations were performed on the data of the three studies cited above (De Graaf & Frijters, 1989; Schifferstein & Frijters, 1990, 1992). These U-values show that the predictions from the VS-1 and SS-2 models are better than the predictions from the two Dominant Component models. The DC-2 model is clearly inferior to the other models since it produces U-values<0.2 in two out of three cases. The U-value for the DC-1 model is not higher than 0.66 for the sucrose/NaCl data.

Table I. The proportion of explained variance (U) accounted for by the Vector Summation model (VS-1: Berglund *et al.*, 1973), the Dominant Component Models (DC-1: McBride, 1989; DC-2: Ganzevles and Kroeze, 1987), and by the Sum of Sensations Model (SS-2: De Graaf and Frijters, 1989). U is calculated by the formula $U = 1 - \Sigma(x-\hat{x})^2/(x-\bar{x})^2$, where x are observed total taste intensities, $\hat{x}$ are estimated values, and $\bar{x}$ is the mean observed total taste intensity (Eisler and Roskam, 1977).

Experiment	Qualities	n*	VS-1	DC-1	DC-2	SS-2
De Graaf & Frijters, 1989	salty-sweet	16	0.968	0.659	0.176	0.919
Schifferstein & Frijters, 1990	sweet-sour	16	0.976	0.906	0.102	0.966
Schifferstein & Frijters, 1992, Exp. 2	salty-bitter	15	0.909	0.851	0.751	0.919

*n=number of mixtures

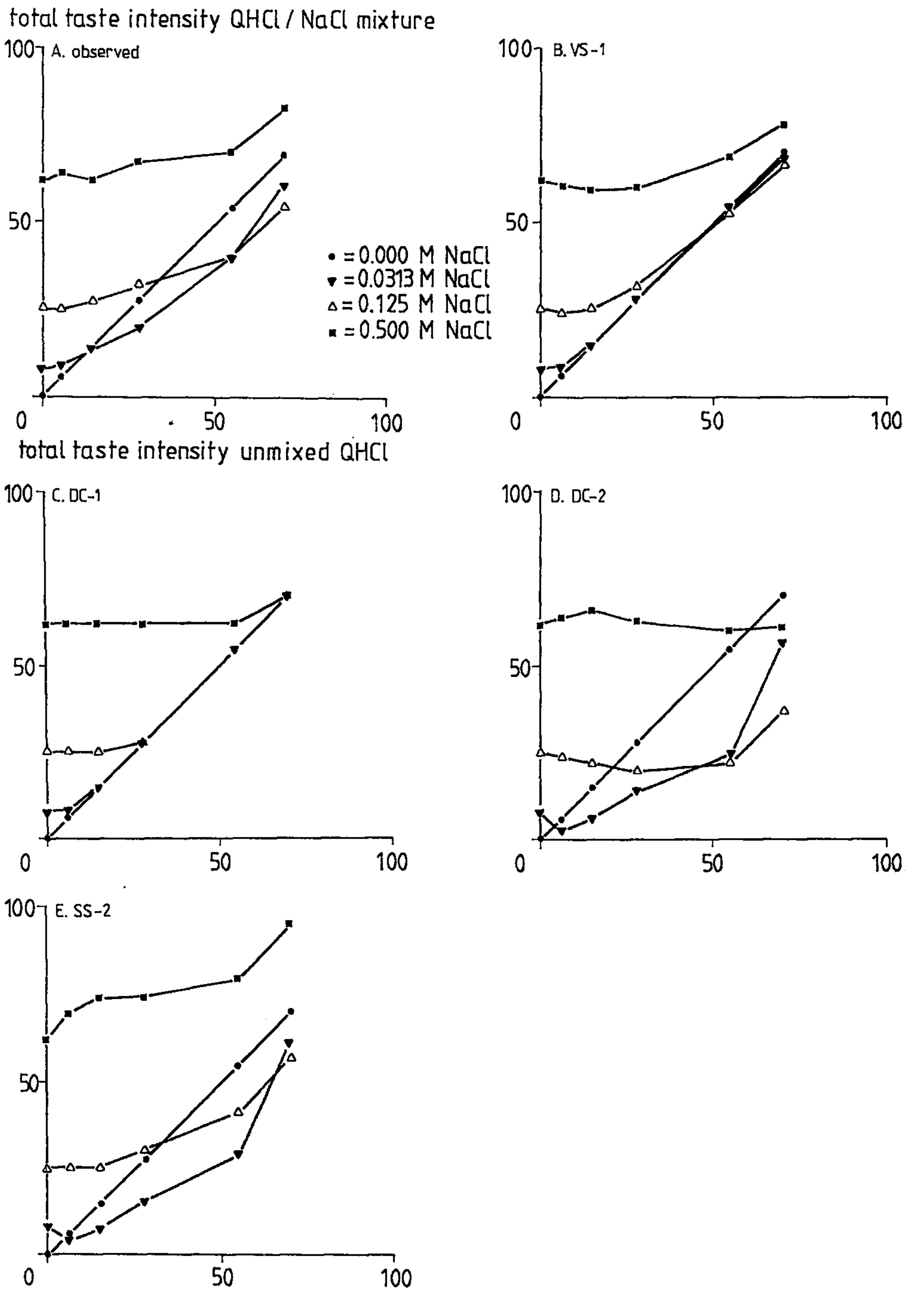

Fig. 5. The total taste intensity of QHCl, NaCl, and QHCl/NaCl mixtures as a function of the total taste intensity of QHCl, with a separate curve for each NaCl level (Data from Schifferstein and Frijters, 1992: Experiment 2). Panel A shows the results obtained experimentally. Panels B to E show the predictions of the VS-1, the DC-1, the DC-2, and the SS-2 models, respectively.

In order to test whether the four models differ with regard to the quality of their predictions, the deviation of the predicted total intensity from the observed intensity was calculated for each mixture (16+16+15=47 mixtures). In six paired comparisons, the difference in predictive validity between two models was tested for statistical significance using the Wilcoxon signed rank test (Steel & Torrie, 1981). The best model was the one producing the smallest deviations from the observed total intensities. The only two models that did not differ with regard to the quality of their predictions were the VS-1 model and the SS-2 model [two-tailed test, $p>0.20$]. All other paired comparisons showed significant differences between models [$p<0.001$]. On the basis of these tests, it can be concluded that the Vector Summation model is the best Type 1 model; the Sum of Sensations model is the best Type 2 model.

It should be noted that the proportions of explained variance for the VS-1 model in Table I are flattered. This is due to the nature of the model. The predictions of the VS-1 model cannot be calculated without the value of $\cos\alpha$. In order to obtain a value for $\cos\alpha$, this parameter is estimated on the basis of the same data (or parts thereof) that are used to calculate the predictions. In determining $\cos\alpha$, the estimate obtained minimizes the amount of residual variance. Therefore, the optimization process used to estimate $\cos\alpha$ is likely to decrease the amount of unexplained variance as shown in Table I. The three other models make no use of estimated parameters and are, therefore, more parsimonious.

Validity as psychological processing models

In evaluating psychological models, one should not only adhere to statistical criteria in deciding whether a model is correct. Of course, the correct model necessarily must provide a good fit to the data. However, the correct model does not necessarily provide the *best* fit to the data (e.g. Birnbaum, 1973, 1974). Therefore, in selecting a model from a set of models that all produce high values for the goodness of fit indices, the selection should be based on the correctness of the principles of the model and not on the qualities of its predictions. A correct model should be able to describe all empirical phenomena observed, without its basic principles being violated.

The first set of phenomena the models have to deal with is those resulting from mixture interaction. From studying the specific taste sensations elicited by mixtures it is evident that the two components of a mixture interact (e.g Pangborn, 1960; Frank & Archambo, 1986). Type 2 models deal with mixture interactions in an indirect way. The input for Type 2 models consists of the specific taste sensations elicited by the mixture, i.e. the specific sensations *after* the mixture interaction has occurred. Implicit in these models is a serial processing view: first, the mixture components interact and, subsequently, the resulting specific sensations yield the total taste intensity of the mixture. The output of the interaction processes is used as an input for their integration model, implying that the Type 2 models do not have to account for the mixture interaction themselves.

Type 1 models use intensities of unmixed components as input, i.e. the sensations unaffected by mixture interactions. These models, therefore, have to account for mixture interactions in some way. The VS-1 model contains the parameter $\cos\alpha$, accounting for mixture interaction. For mathematical reasons, $\cos\alpha$ is restricted to values between -1 and +1, implying that it can effectively describe mixture suppression but no mixture enhancement, since this would imply $\cos\alpha>1$ (Berglund *et al.*, 1973).

Patte and Laffort (1979) have suggested to replace $\cos\alpha$ by a coefficient of proportionality without restricting this coefficient to values ranging from -1 to 1. In this way, however, the Vector Summation model is no longer a psychological model that represents sensory interaction by vector summation, but an arithmetical formula used to describe data in an ad hoc manner. The perceptual addition rule as given by Patte and Laffort, therefore, has lost the psychological meaning it had in Ekman's conception.

Another problem of the VS-1 model is the psychological interpretation of $\cos\alpha$. According to the original paper (Berglund *et al.*, 1973), $\cos\alpha$ reflects the degree of qualitative dissimilarity between the mixture components. However, if the VS-1 model is used to describe the intensity of a mixture of a substance added to itself (qualitative similarity) the estimate for α deviates from 0° (Moskowitz & Barbe, 1977). For example, the model yields α=100° in the case of sucrose added to itself, and α=97° for unmixed citric acid (Schifferstein & Frijters, 1990).

Apart from problems with the meaning of $\cos\alpha$, this coefficient does not appear to be an unbiased and precise measure of the degree of interaction between two sensations. According to Bartoshuk (1975), the value of $\cos\alpha$ is related to the form of the psychophysical functions of the mixture's components. In olfactory research, the values found for $\cos\alpha$ have been reported to suffer from low reproducibility (e.g. Laffort & Dravnieks, 1982). In addition, the values for α always appear to lie between 105° and 130°, so that the magnitude of this angle can not be considered to be specific for the qualities of a pair of odorants (Cain, 1975).

Another feature of the VS-1 model is that mixture interactions are necessarily symmetrical, since there is only one value of $\cos\alpha$ accounting for mixture interactions. Symmetry, in this case, means that for two equi-intense component sensations, the effect of component *A* upon component *B* must equal the effect of component *B* upon component *A*. Empirical investigation of specific taste sensations, however, has often noted asymmetry in mixture suppression (e.g. Schifferstein & Frijters, 1990, 1992).

Summarizing, it can be concluded that the Vector Summation model (VS-1) is not psychologically valid since it cannot account for certain phenomena, and since the psychological interpretation of $\cos\alpha$ remains obscure. With regard to the applicability of the VS-1 model in the perception of mixtures of tastants eliciting several taste qualities, it should be noted that assuming the mixture percept to be homogeneous is probably unjustified.

According to McBride's (1989) theoretical deduction of the DC-1 model, two dissimilar tasting substances are independently transduced at separate receptor sites, and independently processed into separate percepts as if they were unmixed. The subject selects the more intense of the two qualitatively different taste sensations in order to arrive at a judgment of the total taste intensity of the mixture. The DC-1 model allows no interaction between mixture components.

McBride (1989) formulated the DC-1 model because he found a significant sucrose × citric acid interaction in the ANOVA of the total taste intensity estimates. He reasoned that the sweetness of sucrose and the sourness of citric acid could not be additive (SS-2 model), since this interaction term was significant. We believe, in so doing McBride confused the sucrose × citric acid interaction with the sweetness × sourness interaction. The sucrose effect of a mixture in an ANOVA depends on the sucrose concentration (physical parameter) only. In contrast, the sweetness of a mixture (psychological construct) depends on both the citric acid concentration *and* the sucrose concentration of that mixture. Similarly, the citric acid concentration should be distinguished from the sourness of a mixture. Therefore, the sucrose × citric acid interaction and the sweetness × sourness interaction are two different concepts. The ANOVAs of the sweetness intensity estimates and the sourness intensity estimates both reveal a significant sucrose × citric acid interaction. Since total taste intensity is well predicted by the sum of sweetness and sourness (see the predictions of the SS-2 model), it can be anticipated that in most cases the sucrose × citric acid interaction will also be significant for the total taste intensity estimates.

Another reason why McBride (1989) argues in favour of the DC-1 model is the fact that the total intensity of 0.05 M citric acid remains virtually unaffected if 0.08 M to 0.80 M sucrose is added (see his Figure 15.4). According to McBride, this finding demonstrates that the sourness of 0.05 M citric acid is the subjectively dominant component in each mixture, and it therefore determines the mixture's total taste intensity. Schifferstein and Frijters (1990), however, found that the total taste intensity of sucrose/citric acid mixtures at high citric acid levels varied with sucrose concentration (see Figure 4A).

By means of another model, the *Algebraic Integration model*, McBride tries to account for the suppressed intensities of the component-sensations of a heterogeneous percept. This integration model states that specific taste sensations are not processed individually, but exhibit some degree of interaction. However, this integration model should only apply when perceived intensities of mixture components are being judged and not when the total taste intensity of a mixture is estimated. Therefore, according to McBride, the task performed by the subject determines the way in which each component of a taste mixture is perceived. This would imply that the instructions given by the experimenter affect not only the cognitive operations the subjects have to perform, but also affect the perceptual process.

Implicit in McBride's view of mixture perception is a parallel processing of mixture components. Both for the mixed and the unmixed components an intensity is perceived when a mixture is tasted. According to McBride, four different variables are accessible at the central level to enable the subjects to make judgments of two specific taste intensities and the total taste intensity. Since subjects are often requested to judge all three attributes at the same trial (e.g. McBride, 1989), this task would demand a considerable amount of cognitive effort. Serial processing theories incorporating Type 2 models suggest that much less effort is needed, since these theories require access to only two variables.

Another feature of the experimental data is that the total intensity of a mixture may be higher or lower than the total intensity of an unmixed component. In the experimental data we see that mixture intensity is higher than component intensity for all the NaCl/sucrose data (Figure 3). For the sucrose/citric acid mixtures and the QHCl/NaCl mixtures the curves cross the diagonal implying that mixture intensity is sometimes lower than component intensity (Figures 4 and 5). The DC-1 model does not allow either of these outcomes, since mixture intensity always equals the intensity of one of the unmixed components. In general, the DC-2 model does not allow a mixture to be more intense than an unmixed component. Only if the specific taste intensity of one component increases with the addition of a dissimilar tasting component (taste enhancement), the theoretical possibility exists that the DC-2 model predicts the mixture total intensity to be higher than the intensity of the unmixed component. In most cases, however, the predicted mixture intensity is lower, since the dominant sensation is suppressed by the other component. The VS-1 model and the SS-2 model can account for both empirical outcomes.

An overview of the empirical phenomena the models can account for is given in Table II. Comparing this overview with the quality of the predictions made by each model (Table I), the SS-2 model appears to be the best model since it is able to account for all the phenomena observed and its predictions are good. The Vector Summation model and the DC-1 model have been shown to be unable to account for several mixture phenomena. In addition, the predictions made by the two dominant component models are inferior to those made by the VS-1 and the SS-2 models.

Table II. Overview of the empirical phenomena that have been found in taste mixture research and the ability of the four integration models to account for these findings. A positive sign implies that the basic principles of the model allow a description of the empirical phenomenon, a negative sign implies the opposite.

phenomenon	VS-1	DC-1	DC-2	SS-2
mixture suppression	+	-	+	+
mixture enhancement	-	-	+	+
asymmetrical interaction	-	-	+	+
mixture > unmixed component	+	-	-	+
mixture < unmixed component	+	-	+	+

Notes:
1. According to the DC-1 model, the mixture components do not interact when subjects are instructed to judge total taste intensity. Mixture suppression is accounted for by a separate model. The DC-2 and the SS-2 models use the output from the mixture interaction process as input for their combination rule and are, therefore, compatible with all mixture interaction phenomena.
2. Theoretically, the DC-2 model could predict a mixture intensity to be higher than the intensity of an unmixed component if taste enhancement occurred.

Differential weighting

On the basis of the empirical data and the theoretical discussion presented above, it can be concluded that subjects experience the total taste intensity of a mixture as a combination of specific taste sensations. It remains to be established, however, whether this combining process is a simple additive process (as in the SS-2 model) or whether the combination rule must be refined to incorporate deviations from the linear additive rule. According to Anderson (1981, p. 22), algebraic models of perceptual integration should not be tested using 'weak inference methodology' (scatterplots and correlation coefficients) since the violation of a linear additive model remains almost unnoticed under these circumstances. In addition, the best model does not necessarily give the highest correlation coefficient (Birnbaum, 1973). A factorial graph is more sensitive in detecting an inadequacy of the linear additive model. In order to make such a factorial graph for the algebraic model underlying the integration of specific taste sensations into total intensity, several levels of one specific taste sensation have to be combined with several levels of the other specific taste sensation.

For most binary taste mixtures, such combinations are almost impossible to construct in practice, because both specific taste intensities change with the concentrations of both compounds. Fortunately, an exception to this finding are QHCl/NaCl mixtures. Schifferstein and Frijters (1992) have shown that the bitterness of the QHCl/NaCl mixture is highly dependent upon the NaCl concentration, whilst the saltiness remains virtually unaffected by QHCl. Therefore, mixtures equal in NaCl concentration will produce equal saltiness intensities within the mixture percept. For each NaCl concentration, the QHCl concentration giving rise to a certain bitterness intensity can be interpolated from the experimentally obtained bitterness intensities (Schifferstein & Frijters, 1992: their Figures 3 and 8). Subsequently, these QHCl concentrations can be used to estimate the corresponding total taste intensities (Schifferstein & Frijters, 1992: their Figures 4 and 9).

Schifferstein and Frijters (1992) performed two experiments on QHCl/NaCl mixtures. In the first experiment, the intensities elicited by single stimuli were rated on 150 mm line scales. The second experiment employed De Graaf *et al.*'s (1987) two-stimulus procedure. Scale values were calculated from a matrix of reported 'difference' responses on 250 mm visual analogue scales. In the second experiment, the interval properties of the response scale were tested and confirmed. In the first experiment such a test could not be performed. For the present analysis, the total taste intensities of the solutions must have been assessed on an interval scale. Since the mean total taste intensity scores of the first experiment were approximately linearly related to the total taste intensity scale values obtained in the second experiment (Schifferstein & Frijters, 1992: their Figure 12), the total taste intensity scales of both experiments will approximate interval scales. Therefore, the results of both experiments can be used to investigate the validity of the linear additive perceptual integration rule.

For the present analysis, functions relating concentration to the bitterness or total taste intensity of unmixed QHCl were estimated using second order polynomials in which the natural logarithm of the concentration and its squared value were the independent variables and the obtained scale values were the dependent variables. For each NaCl concentration, a mixture function was fitted using second order polynomials in which the QHCl concentration and its squared value were the independent variables. The calculated polynomials were considered to be appropriate for the estimation of the intensities and concentrations required, in view of the good fit (Table III).

Table III. Goodness of fit indices (R^2) for the second order polynomial functions for bitterness and total taste intensity of unmixed QHCl and QHCl/NaCl mixtures that were used in the construction of Figure 6 (data from Schifferstein and Frijters, 1992).

Sensation judged	NaCl concentration (M)					
	0.000	0.03125	0.0625	0.125	0.25	0.50
Experiment 1						
Bitterness intensity	0.9985	0.9995	0.9923	0.9977	0.9929	0.9942
Total taste intensity	0.9983	0.9970	0.9960	0.9970	0.9932	0.9745
Experiment 2						
Bitterness intensity	0.9953	0.9949		0.9824		0.9995
Total taste intensity	0.9858	0.9911		0.9956		0.9838

The two factorial plots of Figure 6 show the estimated total taste intensity of QHCl/NaCl mixtures as a function of the saltiness intensity of these mixtures, with a separate curve for each bitterness intensity level. Only those estimated data points that were within the range of the intensities obtained experimentally are depicted. The saltiness intensities of the mixtures correspond to the saltiness intensities elicited by the concentrations of unmixed NaCl.

If saltiness and bitterness combine in a linear additive fashion, the curves must be parallel. Both plots, however, show a convergent pattern. This convergence demonstrates that the weights w_α and w_β in Equation IV are not constants, but depend upon the intensities of the specific taste sensations. The vertical separation between curves for different bitterness intensity levels (i.e. the effect of the bitterness intensity upon the total taste intensity) decreases for increasing saltiness intensity levels. Therefore, the convergent pattern demonstrates that the salience (weight) of the bitterness sensation decreases if the intensity of the saltiness sensation increases (Anderson, 1981, p. 65).

If the weight of a sensation changes with an increase in its intensity, the perceptual integration of two specific taste intensities can be best described by a *Differentially Weighted Sum of Sensations (DWSS-2)* model:

$$\Psi_{\tau ij} = w_{\alpha ij} * \Psi_{\alpha i} + w_{\beta ij} * \Psi_{\beta j} \qquad \text{(VII)}$$

In this model, each weight depends on the intensities of both specific taste sensations and, therefore, on the concentrations of both components. These results point out that the idea underlying the DC-2 model may be, to some degree, correct. The DC-2 model implies that the sensation with the highest intensity gets a weight of 1, whilst the other sensations get a weight of 0. Therefore, the DC-2 model is an all-or-none model. The present results, however, indicate that the weights vary in a continuous way, with high-intensity sensations having higher weights than low-intensity sensations.

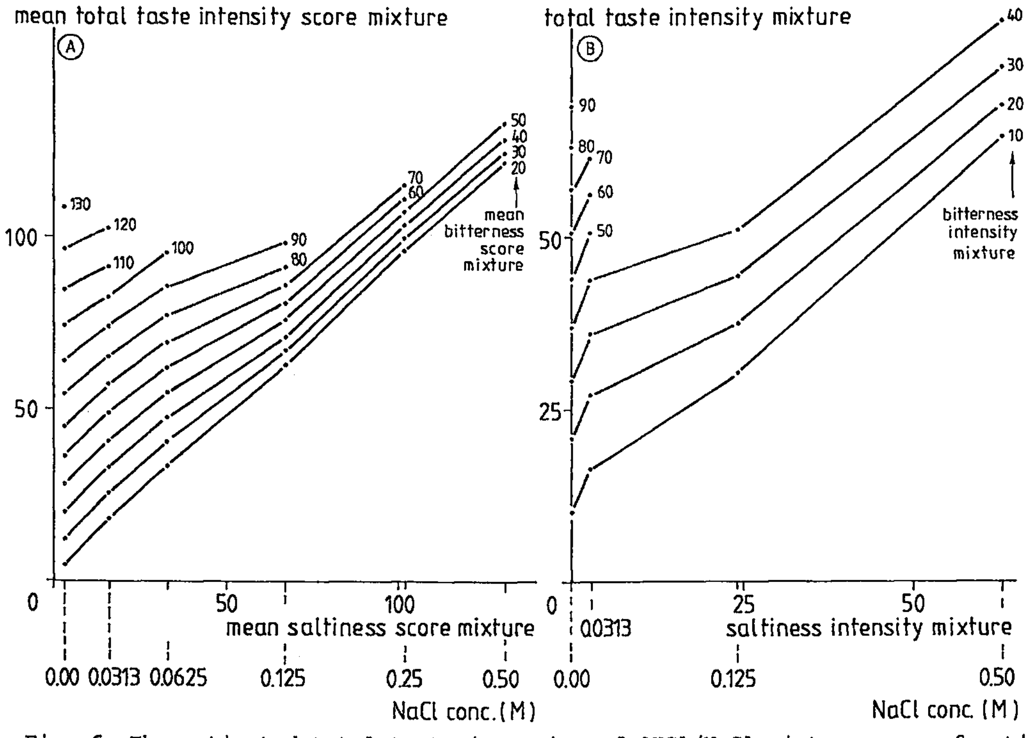

Fig. 6. The estimated total taste intensity of QHCl/NaCl mixtures as a function of the saltiness intensity of these mixtures, with a separate curve for each bitterness intensity level. The saltiness intensities of the mixtures was approximated by taking the saltiness intensities elicited by unmixed NaCl. Panel A shows the results for the data of Schifferstein and Frijters, 1992: Experiment 1. Panel B shows the results for the data of Schifferstein and Frijters, 1992: Experiment 2.

It can be questioned whether the observed convergence is due to differential weighting of the two taste qualities or whether it is caused by the incorrect assumption that the saltiness of NaCl is not affected by the presence of QHCl. In Schifferstein and Frijters' (1992) first experiment, the saltiness intensity was significantly suppressed by the highest QHCl concentration at 0.03125 and 0.125 M NaCl. At no other QHCl or NaCl level was the degree of saltiness suppression significant. At these two NaCl concentrations, the mean bitterness scores were 121 and 94, respectively. Consequently, saltiness suppression is unlikely to have affected the results for the mean bitterness scores lower than 90, which also clearly show a convergent pattern. Therefore, the small decrease in saltiness intensity cannot account for the convergence observed in Figure 6.

A significance test for the degree of convergence is not necessarily confined to the calculated data points of Figure 6, it can also be performed on the original data. A test based on the original data is preferable, since errors in the estimation of hypothetical data points will not affect its result. In addition, a test on the original data is not limited to the data of the QHCl/NaCl mixtures, since it can also be performed on the data of the sucrose/NaCl and the sucrose/citric acid mixtures.

Since the contribution of each specific taste sensation to the total taste intensity in the DWSS-2 model depends upon the intensities of both specific taste sensations, Equation VII can be altered into a model in which the specific taste sensations interact, e.g.

$$\Psi_{\tau ij} = w_\alpha * \Psi_{\alpha i} + w_\beta * \Psi_{\beta j} + w_{\alpha\beta} * \Psi_{\alpha i} * \Psi_{\beta j} \qquad \text{(VIII)}$$

If a multiple regression equation of this form is fitted through the origin, a significant regression coefficient for the product $\Psi_{\alpha i} * \Psi_{\beta j}$ argues in favour of the DWSS-2 model. Table IV shows the regression coefficients found for the three studies under discussion. For each of the three studies, $w_{\alpha\beta}$ is found to be negative, pointing at convergence in plots like Figure 6. The coefficients are significantly different from zero for the sucrose/NaCl mixtures and the quinine/NaCl mixtures [one-tailed *t*-test, $p<0.05$], but not for the sucrose/citric acid mixtures [$p=0.3$]. These analyses demonstrate that, at least for several mixture percepts, the way in which specific taste intensities are combined deviates from additive integration. These deviations can be attributed to sensation weights that vary with sensation intensities or to interaction between specific taste sensations.

Table IV. Regression coefficients and standardized regression coefficients ($b*s_x/s_y$; between parentheses) for specific taste intensities and the product of specific taste intensities, obtained using multiple linear regression through the origin (Equation VIII).

Mixture type	w_α		w_β		$w_{\alpha\beta}$
	sweet	bitter	salty	sour	
sucrose/NaCl	1.11 (0.65)		1.09 (0.61)		-0.010 (-0.15)
sucrose/citric acid	0.96 (0.65)			1.09 (0.50)	-0.001 (-0.01)
QHCl/NaCl		1.13 (0.51)	0.93 (0.72)		-0.006 (-0.08)

Summarizing, it can be stated that during perceptual integration, specific taste sensations are combined in an approximately additive way in the formation of a mixture percept. Deviations from the additive integration rule may occur because the weight of a sensation increases with the intensity of the taste sensation in several cases.

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Chapter 6

GENERAL DISCUSSION

The general discussion focuses upon the locus of mixture suppression and the effect of cognitive variables upon the mixture interactions as inferred from the observable responses.

THE LOCUS OF MIXTURE SUPPRESSION

As noted in the introduction, tastants can interact anywhere in the pathway from aqueous solution to the observable response. Psychophysical restrictions with regard to the locus of the mixture suppression mechanism follow from adaptation studies and split-tongue experiments. Sip-and-spit experiments designed to study central mixture suppression mechanisms using a habituation paradigm failed because the subjects did not habituate using this stimulation procedure (Chapter 4).

Adaptation to one of the mixture components generally releases the specific taste intensity elicited by the other component from suppression (Lawless, 1979; Bartoshuk, 1980; Gillan, 1982). Therefore, mixture suppression mostly takes place central to the locus of the adaptation mechanism. Bitterness suppression in a quinine/NaCl mixture, however, is not released from suppression after adaptation to NaCl (Bartoshuk, 1980), which indicates that the bitterness is suppressed peripherally to the adaptation mechanism (see Chapter 3). Another finding that supports this notion is the fact that adaptation to NaCl is equally effective in decreasing quinine bitterness as is adaptation to quinine (Meiselman, 1968). This suggests that the quinine bitterness suppression is caused by blocking of quinine receptors by NaCl. Most substances eliciting different taste qualities do not cross-adapt (McBurney and Bartoshuk, 1973), suggesting that these use separate reception mechanisms. A split-tongue experiment has also demonstrated the existence of peripheral quinine bitterness suppression by NaCl, whilst the suppression by sucrose was entirely central (Kroeze and Bartoshuk, 1985).

In Chapter 2, it was argued that citric acid sourness suppression is unlikely to be a peripheral phenomenon since perceptually equal components give similar sensory interactions. The inferences regarding the locus of the suppression mechanism that can be made from this result depend upon the assumptions concerning the site in the perceptual system where the afferent signals for the equisweet sweetener concentrations are similar. For example, if the neural responses to two sweetener concentrations are similar at the level of the chorda tympani, the mixture suppression could take place at this neural level. If the output from the receptor cells is similar for two substances, the substances could even interact at receptor level. This could be the case if there is only one receptor for sweet tasting substances. If this sweet receptor retains low concentration sweeteners (e.g. aspartame, saccharin) longer than high concentration sweeteners (e.g. sucrose, sorbitol), the receptor cell may respond similarly to two equisweet concentrations of chemically different substances.

The locus of mixture interactions in the afferent neural system depends upon the extent to which the neural messages, resulting from the presence of the mixture components at their respective receptor sites, can interact in the afferent pathways. According to Across Fibre Pattern Theory (Pfaffmann, 1959), one nerve fibre may respond to both mixture components. If the afferent signals for the perception of both mixture components is conducted by the same nerve fibres, the mixture interaction can then take place within the afferent fibres.

Doetsch and Erickson (1970) performed a study in which they compared the form in which neural messages for taste quality are represented across populations of nerve cells in the chorda tympani (CT) and in the nucleus of the solitary tract (NTS) of Sprague-Dawley rats. When an attempt was made to arrange the gustatory stimuli into a multidimensional space using the response patterns of the CT neurons or the NTS neurons, the sucrose stimulus could not be fitted into the two-dimensional space that fitted the other eleven stimuli. This suggests that the sucrose message makes use of other neural channels to arrive at the central nervous system than the other tastants. As regards mixture interactions, this could imply that mixture interactions in which sucrose is involved are mostly of a central origin, whilst other stimuli may also interact at more peripheral neural levels.

THE EFFECT OF COGNITIVE FACTORS UPON THE DEGREE OF MIXTURE SUPPRESSION

Mixture interactions are mostly regarded as the outcome of psychophysical and psychosensory processes. According to the S-O-R approach, however, the obtained experimental findings may be affected by cognitive processes involved in encoding the sensory intensity, comparing subjective intensities, and selecting an appropriate response. Insight in these cognitive processes is vital for the inferences that can be made concerning the psychophysical interaction processes.

The effect of cognition on the degree of mixture suppression in the responses has been demonstrated in experiments where the stimulus set was manipulated. In these studies, contextual or sequential effects appeared to differentially affect mixtures and unmixed stimuli. Kroeze's (1982, 1983) habituation studies can be classified among these studies. However, Kroeze's results appear to be typical for gravitational flow stimulation, since sip-and-spit studies do not yield a differential effect for mixtures and unmixed stimuli (see Chapter 4). The observation that the saltiness response for a NaCl/sucrose mixture increases with the relative number of mixtures in the stimulus set (Kroeze, 1982) is not necessarily related to changes in the degree of mixture suppression but could also have a judgmental origin.

In Chapters 1 and 2, it was already noted that the degree of analysis of the mixture percept depends on the task requirements. In addition, the number of descriptors used to describe a complex mixture depends upon whether the subjects are requested to adopt an analytical attitude or are free to chose any descriptors they like (O'Mahony *et al.*, 1990).

Different task instructions have also been shown to yield different mixture interaction patterns. In an experiment on QHCl/citric acid mixtures, Frank, van der Klaauw, and Schifferstein (1992) found the mixture interaction pattern to vary with response task. In the condition where subjects were instructed to judge only the bitterness of the samples, the responses to the mixtures exhibited mixture enhancement. If the subjects were instructed to judge the total intensity of the stimulus and subsequently break this rating up into eight component ratings, the bitterness responses exhibited mixture suppression. Frank *et al.* argued that the discrepancy between the two conditions stems from a difference in the cognitive categorization process under the different task instructions. Due to confusion of sourness and bitterness, sourness intensity is (partly) included in the bitterness judgments during the first task, but not during the second task.

A related issue was brought up by Pangborn (1961). She demonstrated that mixture interaction patterns determined with a one-stimulus procedure were different from those obtained with a two-stimulus procedure. When subjects judged the sweetness of sucrose/citric acid mixtures on a 9-point category scale, the sweetness judgments decreased no more than approximately one category unit (her Figure 2). In addition, the mixtures containing 0.007% citric acid got higher sweetness ratings than the unmixed sucrose concentrations. When instructed to judge the sweetness difference between two solutions, however, higher citric acid levels always implied a lower sweetness intensity. The difference in sweetness difference rating between mixture and unmixed sucrose could be as high as 3 units (on a scale from 1 to 7) for the lowest sucrose level mixed with the highest citric acid level (her Figure 4). Pangborn's results demonstrate that the mixture phenomena as assessed by a one-stimulus procedure may deviate substantially from those obtained with a two-stimulus procedure.

Pangborn's results are directly relevant for our findings on quinineHCl/NaCl mixtures as reported in Chapter 3. In our investigation, the degree of bitterness suppression deviated substantially between the single stimulus and the two stimulus procedure.

As can be concluded from the discussion above, mixture interactions as observed at the level of the obtained responses are affected by changes in stimulus set and task requirements. Different tasks require different types of decision making and will, therefore, yield different results. Consequently, every result has to be interpreted in relation to the method by which it was obtained. Just like the metric structure of the multidimensional space for taste stimuli (Chapter 1), mixture interactions depend upon experimental variables. A separation of the sensory processes from cognitive processes seems necessary to study mixture interactions. It can be argued, however, that such a separation cannot be obtained since perception not only affects responses, but the task requirements may also influence perception. This notion eventually leads to a discussion of the appropriateness of the Whorfian hypothesis (e.g. Whorf, 1956). Whorf stated that language affects thought and perception and several authors have provided evidence in support of the Whorfian hypothesis (see Hunt and Agnoli, 1991). The existence of top-down processing is evident in perceptual research, for example in the appearance of subjective contours in vision (e.g. Dember and Warm, 1979). There are no reasons to assume that similar top-down mechanisms do not operate in the sense of taste (see Kroeze, 1989).

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SUMMARY

Chapter 1

The intensities and qualities of the taste sensations, elicited by a mixture of dissimilar tasting substances usually depend upon the concentration levels of all mixture components. Mixture interactions may result from both peripheral and central mechanisms. The complexity or heterogeneity of the mixture percept is not only affected by the intensities and qualities of the taste sensations within the mixture percept, but also by their temporal properties and by the area of the tongue or the oral cavity stimulated. In addition, the way in which the percept is organized may affect its perceived complexity. With sufficient processing time available, any complex percept can be analyzed into its components upon request. Differences in cognitive task requirements and in stimulus features can lead to discrepancies in the metrical structures of multidimensional spaces for taste stimuli.

Throughout the dissertation the conceptual framework from De Graaf and Frijters (1989) is used. This framework describes the most important relationships between the physical and the psychological variables involved in taste mixture research. The scaling methods used are based upon Norman Anderson's theory of Functional Measurement. The research in this dissertation will mainly be concerned with the relationships between the variables specified in the conceptual framework. In addition, specific chapters focus upon the locus of the mixture suppression mechanism, PROP-sensitivity, and research methodology.

Chapter 2

In the first part of this chapter, the perceived sweetness, sourness, and total taste intensity of unmixed sucrose, unmixed citric acid and several citric acid/sucrose mixtures were assessed. Citric acid was found to suppress the sweetness of sucrose and, inversely, sucrose suppressed the sourness of citric acid. However, this suppressive effect was not symmetrical for the concentrations used. While the degree of sweetness suppression depended only on the citric acid level, the degree of sourness suppression depended on the sucrose as well as the citric acid concentration. Where the perceived total taste intensity of citric acid/sucrose mixtures was concerned, it was shown that the sum of sweetness and sourness of the mixture approximately equals the total taste intensity.

In the second part of chapter 2, different sweeteners were matched with regard to perceived sweetness intensity in order to obtain perceptually similar stimuli. Every equisweet sweetener concentration was mixed with each of four citric acid concentrations. Equisweet sweeteners were found to suppress the perceived sourness intensity of citric acid to the same degree in every citric acid/sweetener mixture. The side tastes of the sweeteners, if present, did not have a substantial effect upon the degree of sourness suppression. These results show that perceptually similar taste stimuli can give rise to the same sensory interactions when mixed with a substance of a different taste quality. Therefore, these results indicate that sourness suppression is probably a perceptual phenomenon and not the result of physical or chemical interactions or competition for receptor sites.

Chapter 3

The first study in this chapter investigated the relationship between individual sensitivity differences for PROP and the perception of KCl, NaCl, quinine, and quinine/NaCl mixtures. The sensitivity to PROP is mainly determined by hereditary factors and has been related to the perception of many bitter and non-bitter substances. In the present study, the obtained bitterness, saltiness, and total taste intensity ratings for KCl, NaCl, and quinineHCl were not affected by the sensitivity for PROP. It is hypothesized that the significant differences in the perception of PTC-unrelated compounds between 'tasters' and 'non-tasters' reported by other investigators may, in part, be the result of errors made during the classification procedure and of inappropriate methods of statistical analysis.

In the second part of this chapter, quinineHCl/NaCl mixtures were investigated using two different experimental procedures. Both experiments showed that quinine bitterness is largely suppressed by NaCl, whilst the saltiness intensity elicited by NaCl remains virtually unaffected. In both experiments, the perceived total taste intensity of a mixture could be well predicted by the weighted sum of the saltiness and bitterness intensities within the mixture percept. Although the saltiness and total intensity estimates agreed well for the two experiments, the bitterness estimates were found to vary with experimental procedure.

Comparing the two procedures, the main advantage of the one-stimulus procedure was found to lie in its simplicity. In addition, it enables the determination of a scale value for water. However, the obtained ratings are context-dependent and are affected by end effects of the response scale. The most important benefit of the two-stimulus procedure is that it allows for a post-experimental verification of the linearity of the response-output function. This check ensures that all scale values are assessed on an interval scale. If water can be assumed to be tasteless, ratio scale values can be obtained.

Chapter 4

In gravitational flow studies, repetitious stimulation with one of the components of a mixture has been shown to increase the estimated intensity of the sensation elicited by the other component within the mixture. This increment is hypothesized to be the consequence of successive contrast and suppression release. According to the successive contrast hypothesis, the specific taste sensation of the mixture percept judged is overestimated because its taste stands out against the preceding perceived sensations. The suppression release hypothesis states that the sensation judged is released from suppression because the subject is habituated to the taste elicited by the preceding stimuli. Since habituation is a central process, central mixture interaction processes can be studied by habituating subjects to one of the mixture components.

In the first experiment, the bitterness intensity of a quinineHCl/NaCl mixture, a KCl solution, and an unmixed quinineHCl solution were judged after repetitive stimulations with NaCl solutions using a sip-and-spit procedure. No release of bitterness suppression was found in this experiment. In order to investigate whether this finding was substance-specific or was caused by the absence of habituation during the experimental procedure used, two experiments were conducted that replicated the original gravitational flow studies using a sip-and-spit procedure. In these experiments, sucrose/NaCl mixtures and unmixed NaCl stimuli were used as test stimuli.

Similar to the first experiment, no suppression release was found. The increment in saltiness estimates after repeated stimulations with sucrose could be fully accounted for by successive contrast. The results of the first experiment are, therefore, not necessarily due to a peripheral bitterness suppression mechanism, but could also be attributed to the absence of habituation during the sip-and-spit procedure.

Chapter 5

The fifth chapter focuses upon the relationships between the psychological intensity variables involved in taste mixture perception. Four models are evaluated designed to predict the total taste intensity of a mixture percept from the total taste intensities of the unmixed components, or from the specific taste intensities of the components within the mixture percept. The predictions of the two Dominant Component models are inferior to those made by the two other models. Predictions made by the Vector Summation model are accurate, but the model contains theoretical weaknesses which make it an invalid psychological integration model. The Sum of Sensations model predicts total intensity with a similar accuracy as the Vector Summation model, but is more parsimonious. Furthermore, it can handle all the empirical phenomena observed.

A closer inspection of the data uncovers deviations from the simple Sum of Sensations model. In order to account for these deviations, a Differentially Weighted Sum of Sensations model is proposed. In this model, more intense specific taste sensations are more heavily weighted.

Chapter 6

In the last chapter, it is argued that the loci of the mixture interactions for the two main types of mixtures investigated in this dissertation (sour-sweet and bitter-salty) are markedly different. Whilst the citric acid sourness suppression by sweeteners seems largely central, the quinine bitterness suppression by NaCl is probably peripheral in origin.

Subsequently, it is noted that the degree and type of mixture interaction found in an experiment depends upon the experimental procedure followed. Outcomes of studies in which only one stimulus attribute is rated may differ from those in which several attributes are judged simultaneously. Difference judgments may reveal different interaction patterns than single stimulus judgments. Insight in these judgmental processes is vital for the inferences that can be made concerning the psychophysical interaction processes.

SAMENVATTING

Hoofdstuk 1

De intensiteiten en kwaliteiten van de smaaksensaties, die worden opgewekt door een mengsel van ongelijk smakende stoffen, hangen meestal af van de concentratieniveaus van alle mengselcomponenten. Menginteracties kunnen zowel uit perifere als uit centrale mechanismen voortkomen. De complexiteit of heterogeniteit van het mengpercept wordt niet alleen beïnvloed door de intensiteiten en kwaliteiten van de smaaksensaties binnen het percept, maar tevens door hun temporele eigenschappen en door het deel van het tongoppervlak of de mondholte dat gestimuleerd wordt. Bovendien kan de organisatiestructuur van het percept de waargenomen complexiteit beïnvloeden. Elk complex percept kan op verzoek in zijn componenten ontleed worden, indien er genoeg verwerkingstijd beschikbaar is. Verschillen in cognitieve taken en in stimulus eigenschappen kunnen leiden tot verschillen in metrische structuur van multidimensionele ruimten voor smaakstimuli.

In dit proefschrift zal het conceptuele schema van De Graaf en Frijters (1989) gebruikt worden. Dit schema beschrijft de belangrijkste relaties tussen de fysische en psychologische variabelen die een rol spelen in het smaakonderzoek. De gebruikte schaaltechnieken zijn gebaseerd op Norman Anderson's Functional Measurement theorie. Het onderzoek in dit proefschrift zal zich vooral richten op de relaties tussen de variabelen in het conceptuele schema. Daarnaast spitsen bepaalde hoofdstukken zich toe op de locatie van het mengonderdrukkingsmechanisme, PROP-gevoeligheid, en onderzoeksmethodologie.

Hoofdstuk 2

In het eerste gedeelte van dit hoofdstuk werden de waargenomen zoetheid, zuurheid en totaalintensiteit van ongemengd saccharose, citroenzuur en een aantal saccharose/citroenzuurmengsels bepaald. Citroenzuur bleek de zoetheid van saccharose te onderdrukken en omgekeerd bleek saccharose de zuurheid van citroenzuur te onderdrukken. Deze onderdrukking was echter niet symmetrisch voor de gebruikte concentraties. Terwijl de mate van zoetheidsonderdrukking alleen afhankelijk was van het citroenzuurniveau, was de mate van zuurheidsonderdrukking afhankelijk van zowel de saccharose als de citroenzuurconcentratie. Voor de totaalintensiteit van de citroenzuur/saccharosemengsels werd aangetoond dat deze ongeveer gelijk was aan de som van de zoetheid en de zuurheid van het mengsel.

In het tweede gedeelte van hoofdstuk 2 werden verschillende zoetstoffen op zoetheid gematched om perceptueel gelijkwaardige stimuli te verkrijgen. Elke equizoete zoetstofconcentratie werd gemengd met vier citroenzuurconcentraties. Equizoete zoetstoffen bleken de waargenomen zuurheid van citroenzuur in gelijke mate te onderdrukken in elk citroenzuur/zoetstof mengsel. De bijsmaken van de zoetstoffen, indien aanwezig, hadden geen wezenlijk effect op de mate van zuurheidsonderdrukking. Deze resultaten laten zien dat perceptueel gelijkwaardige smaakstimuli aanleiding kunnen geven tot dezelfde sensorische interacties wanneer ze gemengd worden met een anders smakende stof. Derhalve wijzen deze resultaten erop dat zuurheidsonderdrukking waarschijnlijk een perceptueel fenomeen is en niet het resultaat van fysische of chemische interacties of van competitie voor receptor sites.

Hoofdstuk 3

De eerste studie in dit hoofdstuk onderzocht de relatie tussen individuele gevoeligheidsverschillen voor PROP en de waarneming van KCl, NaCl, kinine en kinine/NaCl mengsels. De gevoeligheid voor PROP wordt met name bepaald door erfelijke factoren en is in het verleden in verband gebracht met de waarneming van vele bittere en niet-bittere stoffen. In de huidige studie werden de verkregen bitterheids-, zoutheids- en totaalintensiteitsresponsen voor KCl, NaCl, en kinineHCl niet beïnvloed door de gevoeligheid voor PROP. Het kan gesteld worden dat de door andere onderzoekers gevonden significante verschillen in de waarneming van niet aan PTC gerelateerde verbindingen tussen 'proevers' en 'niet-proevers' gedeeltelijk het gevolg zijn van misclassificaties en het gebruik van ongeschikte statistische procedures.

In het tweede deel van dit hoofdstuk werden kinineHCl/NaCl mengsels onderzocht met behulp van twee verschillende experimentele procedures. Beide experimenten lieten zien dat de bitterheid van kinine grotendeels onderdrukt wordt door NaCl, terwijl de zoutheid van NaCl vrijwel onaangetast blijft. In beide experimenten kon de waargenomen totaalintensiteit van een mengsel goed voorspeld worden door de gewogen som van zoutheids- en bitterheidsintensiteit binnen het mengpercept. Ofschoon de vastgestelde zoutheids- en totaalintensiteiten goed overeenkwamen bij de twee experimenten, verschilden de gevonden bitterheidsintensiteiten tussen de twee procedures.

Bij het vergelijken van de twee procedures bleek de eenvoud het grootste voordeel van de 1-stimulus procedure te zijn. Bovendien maakt deze procedure het mogelijk om een schaalwaarde voor water te bepalen. De gevonden waarden zijn echter context-afhankelijk en worden beïnvloed door eindeffecten van de responsschaal. Het belangrijkste voordeel van de 2-stimulus procedure is de mogelijkheid om de lineariteit van de respons-output functie na afloop van het experiment te toetsen. Deze controle verzekert de onderzoeker ervan dat alle schaalwaarden op interval niveau gemeten zijn. Als kan worden aangenomen dat water geen smaak heeft kunnen ratio schaalwaarden verkregen worden.

Hoofdstuk 4

In studies waarbij de onderzoeker de oplossing op het tongoppervlak aanbrengt met behulp van een 'gravitational flow' systeem is gebleken dat herhaaldelijke stimulatie met één van de mengselcomponenten de geschatte intensiteit van de sensatie opgewerkt door de andere mengselcomponent verhoogt. Deze toename wordt verondersteld veroorzaakt te worden door successief contrast en het opheffen van mengonderdrukking. Volgens de successief contrast hypothese wordt de specifieke smaaksensatie van het beoordeelde mengpercept overschat omdat deze smaak opvalt in vergelijking tot de voorafgaande waargenomen sensaties. De hypothese die zegt dat de mengonderdrukking wordt opgeheven stelt dat de beoordeelde sensatie wordt bevrijd van mengonderdrukking omdat de proefpersoon gehabitueerd is aan de smaak van de voorafgaande stimuli. Omdat habituatie een centraal proces is kunnen centrale menginteractieprocessen bestudeerd worden door proefpersonen te habitueren aan één van de mengselcomponenten.

In het eerste experiment worden de bitterheid van een kinineHCl/NaCl mengsel, een KCl oplossing en een ongemengde kinineHCl oplossing beoordeeld na herhaalde stimulatie met NaCl tijdens een 'sip-and-spit' procedure. Er kon geen opheffing van mengonderdrukking worden aangetoond in dit experiment. Om na te gaan of deze bevinding specifiek was voor de gebruikte stoffen of veroorzaakt werd door de afwezigheid van habituatie tijdens de gebruikte experimentele procedure, werden twee experimenten uitgevoerd die de originele 'gravitational flow' studies repliceerden met behulp van de 'sip-and-spit' procedure. Deze experimenten gebruikten saccharose/NaCl mengsels en ongemengd NaCl als test stimuli.

Net als in het eerste experiment werd er geen opheffing van mengonderdrukking gevonden. De toename in zoutheidsschattingen na herhaalde stimulaties met saccharose kon volledig worden verklaard door de successief contrast hypothese. De resultaten van het eerste experiment worden derhalve niet noodzakelijkerwijs veroorzaakt door een perifeer bitterheidsonderdrukkings-mechanisme, maar kunnen ook toegeschreven worden aan de afwezigheid van habituatie tijdens de 'sip-and-spit' procedure.

Hoofdstuk 5

Het vijfde hoofdstuk spitst zich toe op de relaties tussen de psychologische intensiteitsvariabelen. die een rol spelen bij de waarneming van smaakmengsels. Vier modellen, die ontworpen zijn om de totaalintensiteit van een mengpercept te voorspellen met behulp van de totaalintensiteiten van de ongemengde componenten of met de specifieke smaakintensiteiten van de componenten binnen het mengpercept, worden geëvalueerd. De voorspellingen van de twee Dominante Componenten modellen zijn slechter dan die gemaakt zijn door de twee andere modellen. De voorspellingen van het Vector Sommatie model zijn nauwkeurig, maar het model bevat theoretisch zwakke punten, die de psychologische validiteit van het model schenden. Het Som van Sensaties model voorspelt totaalintensiteit met dezelfde nauwgezetheid als het Vector Sommatie model, maar bevat minder parameters. Bovendien wordt het model niet geschonden door empirische gevonden verschijnselen.

Een nadere inspectie van de data brengt afwijkingen van het eenvoudige Som van Sensaties model aan het licht. Om deze afwijkingen te kunnen beschrijven, wordt een Differentieel Gewogen Som van Sensaties model voorgesteld. In dit model krijgen sterkere specifieke smaaksensaties een groter gewicht.

Hoofdstuk 6

In het laatste hoofdstuk wordt betoogd dat de lokaties van de mengonderdrukkingsmechanismen voor de twee hoofdtypen mengsels die in dit proefschrift onderzocht zijn (zuur-zoet en zout-bitter) merkbaar verschillen. Terwijl de zuurheid van citroenzuur vooral centraal wordt onderdrukt door zoetstoffen, wordt de bitterheid van kinine door NaCl waarschijnlijk op perifeer niveau onderdrukt.

Vervolgens wordt er opgemerkt dat de mate en het type menginteractie in een experiment afhangt van de gevolgde experimentele procedure. Uitkomsten van studies waarbij één enkel attribuut wordt beoordeeld kunnen verschillen van studies waarbij verschillende attributen tegelijkertijd worden beoordeeld. Verschilbeoordelingen kunnen andere interactiepatronen te zien geven dan beoordelingen van 1 stimulus. Inzicht in deze beoordelingsprocessen is noodzakelijk voor de conclusies die getrokken worden betreffende de psychofysische interactieprocessen.

CURRICULUM VITAE

Hendrik Nicolaas Jozef Schifferstein werd geboren op 31 mei 1964 te Maastricht. Na het behalen van het Gymnasium β diploma aan het Stedelijk Lyceum te Maastricht, begon hij in 1982 zijn studie 'Voeding van de mens' aan de Landbouwuniversiteit te Wageningen. In september 1988 slaagde hij (met lof) voor het doctoraalexamen met als afstudeervakken Voedingsleer, Levensmiddelenchemie en Marktkunde. Tijdens zijn studie verbleef hij onder meer enkele maanden aan de École Nationale Supérieure de Biologie Appliquée à la Nutrition et à l'Alimentation (ENS.BANA) bij dr. François Sauvageot te Dijon.

In september 1988 kwam hij in dienst van de Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO) als Onderzoeker In Opleiding. Het in dit proefschrift beschreven onderzoek voerde hij uit bij de Sectie Sensorisch Onderzoek, Vakgroep Levensmiddelentechnologie aan de Landbouwuniversiteit. Daarnaast maakte hij in 1992 een studiereis naar de Verenigde Staten, waar hij onder andere samenwerkte met dr. Robert Frank van de Department of Psychology van de University of Cincinnati.