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Perception as interacting psychophysical functions.

Could the configuring of features replace a specialised receptor?

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Abstract

This paper illustrates how perception is achieved through interactions among the psychophysical functions of judged features of an object. The theory is that the perceiver places processed features in a multidimensional space of discriminal processes. Each dimension is scaled in units of discrimination performance. The zero coordinate of each feature is its level in an internal standard (norm) established by previous experience of that category of object in context. The experiments reported here show that one, two or three concurrent single-featured objects matched the multiple features of another object in two ways. Either stimulation from the two objects had discrimination distances from norm that added or the stimulation by one object was processed through a concept describing stimulation by the other object. It follows that, in this case, perception via a receptor for the multi-featured object can be replaced by a point of balance among receptors for each single feature. The object with its own receptor is the gustatory stimulant L-glutamic acid as its monosodium salt. The features that stimulate diverse gustatory receptors of their own are sodium chloride, citric acid, sucrose and caffeine. A more complex approach to dimensional coding was developed earlier for photoreceptors in colour judgments. The present approach is modality independent, mathematically simple and economical in experimental data.

Keywords: multiple discriminations; multi-feature psychophysics; object recognition; gustation; glutamate taste receptor

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Introduction

Perception is the successful performance of judgments on sensed and conceptualised features of objects and situations. A psychophysical function from stimulus to response represents the causal influence of the environmental feature on the perceptual judgment. When a single feature has exclusive control, the judgment is termed 'analytical.' When a judgment integrates information from two or more features, as in the recognition of an object, their analytical psychophysical functions must be interacting in some way. These interactions can be diagnosed from the raw data for each psychophysical function, using the parameters of its discriminal process (Thurstone 1927).

The key step is to anchor all the judgments on a personal internal standard or norm which has been established by previous experience for the features of the object (Booth, Thompson & Shahedian 1983). Then the individual's perceptual processes during an experimental session can be modelled as multidimensional discrimination from that norm (Booth & Freeman 1993). This approach reconciles template and multiple-feature approaches to object recognition (Booth 1994; Lockhead 1992, 2004). It also spans the divide between sensory and semantic perception (Barsalou 2008; Medin & Barsalou 1987). We present here the first full calculation of interactions among concurrent psychophysical functions from an appropriately designed experiment. This normed discrimination modelling is used to address a contentious example of a generic issue. Can perceptual performance replace a receptor specific to a whole object by the sensory receptors for that object's features?

This modelling is innovative in being mathematically determinate as well as individualised, situationalised and session-specific. Yet it uses only long-established principles. The strength of a signal is measured by the acuity of variations in the output for variations in the input. This discriminative performance is calculated in accord with the classic formula for a JND from the psychophysical function of quantitative judgments for instances of the object that vary in the amount of a perceptible feature (Torgerson, 1958). Discrimination is often estimated from comparisons between test samples and a standard sample. The present approach compares each test sample with the multi-featured norm. This implicit memory holds each perceptible feature at a particular level, such as the most familiar or the most valued. A well learnt internal standard can provide the basis for highly accurate perceptual judgments. For example, the personally ideal level for the combined intensities of the taste, aroma and colour of a fruit drink was estimated as accurately as the level in a physical standard in the usual method of constant stimuli (McBride & Booth, 1986). In visual psychophysics, internal standards have recently been found to give at least as precise results as the traditional external standards (Morgan, Watamaniuk & McKee, 2000; Nachmias, 2006). Indeed, the evidence is that apparently absolute judgments are based on norms established temporarily within the experiment (Stewart, Brown & Chater, 2005).

When the range of a psychophysical function is sufficiently close to such a norm, a disparity in amount between two instances can be measured in units of the discriminative performance of the judgments relative to the norm (Booth, 1988; Conner, Haddon, Pickering & Booth, 1988). That is, each tested instance of the object can be placed at a JND-scaled distance from the internal standard used in the judgments.

These discrimination-scaled distances from norm can distinguish between features of an object that are processed as the same and features that differ (Booth & Freeman, 1993). That distinction can also be drawn when two objects have a feature in common while also having different features. The case considered in this paper is where the shared feature is the stimulation of a specific type of sensory receptor but one of the two objects also stimulates other types of receptor.

When the strengths of two signals summate, that is evidence that they are transmitted along the same channel. Hence the effects of two objects stimulating a single receptor concatenate along a dimension. That is, their instances' discriminative distances from the norm are summed. It is important to note that the amount of a feature can be above or below the value in the norm, i.e. a distance can be positive or negative.

At the other extreme, the two signals pass through separate channels up to the point of interaction that influences the integrative output. That is, features that stimulate different types of receptor have their distances placed on orthogonal dimensions, with the norm as the multidimensional zero point. Hence the resulting integrative judgments vary as the square root of the sum of squares of the instances' discriminative distances from norm. Since Pythagoras's theorem generalises across any number of dimensions, this formula accommodates as many features as are being processed in deciding the judgment. Squaring removes directionality from the distances before summing. Hence, in general, these multidimensional models of disparate features are not correlated with unidimensional models of shared features from the same set of data.

Multidimensional modelling of interactions between receptor-activated channels was proposed earlier as an account of the differences between trichromatic day vision and monochromatic night vision (Pugh 1988; Pugh & Kirk 1986). However that approach is mathematically complex. Our minimal theory is applied in this paper to a perceptual object that may have at least four distinct features. The main experiment tested the hypothesis that each of the object's four features is on the same dimension as another object that has only that one of the four features. The perceptual objects in this paper are large sets of extremely small physical entities identical to each other – namely, the molecules of a particular chemical compound, dissolved in water placed on the tongue to stimulate receptors in the taste pores. Rather few natural compounds stimulate only one type of gustatory receptor. Most compounds having any taste stimulate a profile of receptor types, as with light on retinal photopigments, sounds on the cochlea, volatile chemicals on olfactory receptors, tactile stimuli on mechanoreceptors, and so on. Furthermore, ordinarily consumed materials include a variety of tastants, even when each of those compounds stimulates a single receptor type. Hence, as with colours, pitches, odours and textures, the correct uses of a community's words for tastes need to be learnt (Wittgenstein 1953). Everyday gustatory vocabulary performs well enough for realistic conversation about complex mixtures such as ripe fruits, cooked meats, leafy vegetables, sugared drinks and salted foods. Verbal recognition performance becomes robust enough to overcome the severe challenge in traditional gustatory psychophysics of tasting unfamiliar pure compounds out of any context and therefore without a stable internal standard (Booth 2008a).

The multi-featured gustatory object tested in this paper is monosodium glutamate (MSG), a sodium salt of the free form of the most abundant component of proteins, glutamic acid. Solutions of MSG elicit each of the four terms for taste that society has built on four gustatory receptor types, namely in English *salty*, *sweet*, *sour* and *bitter* (O'Mahony & Ishii 1986). The single-featured objects used were common salt (NaCl), table sugar (sucrose), the main acid in citrus fruit (citric acid), and the widely tasted bitter compound, caffeine. The situation simulated in the experiment in order to provide a precise norm was having a drink of tomato juice. Pilot data on normed multiple discriminations had illustrated how a balance of salt, sugar, acid and alkaloid in a food can simulate MSG (Freeman, Richardson, Kendal-Reed & Booth 1993). Also a set of experiments on a familiar fruit-flavoured drink had tested the basic presupposition that two sugars will be processed over one channel into judgments under the concept behind the word *sweet*, and two acids into *sour* over another channel (Freeman 1996).

Such multiple categorical discriminations can be accommodated by detection analysis of data from many trials (Macmillan & Creelman 2004). However, the theory of discrimination from norm provides a determinate and exhaustive analysis of data within a much more economical measurement paradigm. For a four-featured object, a minimum of five instances of an object can disconfound the four psychophysical regressions from levels of those features to judgments on an integrative concept. Nevertheless, of course, when more instances are tested, the conclusions can be more precise. Furthermore, adding feature-specific judgments can enrich the findings and increase their explanatory power.

A purely behavioural method has provided clear evidence for the existence of at least one distinct type of gustatory receptor. The identification of ranges of concentrations at which different compounds are indiscriminable shows them to be perceptually equivalent. This has been achieved with different sugars (Breslin, Beauchamp & Pugh 1996), demonstrating what we think is best called the 'unisapidity' of those compounds. Similar evidence for a single receptor type was briefly presented for acidic tastants (Breslin & Beauchamp 1995).

The issue with glutamate, however, is its 'multisapidity' (multiple unisapidities). A method is needed to measure the multiple indiscriminabilities between a compound that stimulates two or more types of receptor and each compound that stimulates only one of those receptor types. The technique of finding concentrations of two compounds at which they become indiscriminable (Breslin *et al.* 1996) cannot be extended directly to categorising multisapid substances.

This difficulty is overcome by working within the context of a personally familiar category of food or drink to construct a psychophysical function for each unisapidity that may comprise the multisapidity (e.g., sucrose concentration ratios against sweetness intensity ratings). Then the point of perceptual equality between MSG and each of the other tastants can be specified by interpolating within each unisapid function to the multi-featured norm for that comestible. The signal from salt to the learnt judgments specifically of saltiness should be indiscriminable from that from MSG to the concept of saltiness. The same should be true for signals from sucrose to the word *sweet*, citric acid to *sour*, and caffeine or another compound to *bitter*. Caffeine would not be the appropriate tastant if none of the family of bitter receptors was stimulated both by glutamate and also by caffeine. Nevertheless, caffeine was used in this first attempt to resolve the issue behaviourally, because this compound is one of the commonest bitter constituents of the diet and is readily available in pure form.

Tomatoes are rich in glutamate and so provide a good opportunity to acquire a glutamate-dependent integrative concept of the flavour of a particular vegetable. A familiar drink made from juiced tomatoes was the most convenient product in which to manipulate concentrations of tastants. Thus the tomato juice was varied in its levels of MSG and of four tastants, each having one of the four classic tastes, with the mixtures all well tolerated as examples of the drink. Data from such a design provide tests for multiple indiscriminability of the sucrose, citric acid or caffeine from the glutamate, as well as the indiscriminability of the sodium ions in the two salts (a trivial fact but providing some validation of the method).

Dispensibility of the glutamate receptor for perception of MSG could be shown by performance in either or both of two ways. The signals from MSG and each unisapid compound might summate over the same across-fibres perceptual channel from receptors to learnt recognition of the drink and its overall taste. The other behaviour is modulation of a signal from MSG to recognition of the taste of tomato by a unisapid descriptive signal, such as successfully discriminative judgments of how *sweet* different concentrations of sucrose are.

This second criterion of multisapidity is a recent development of the original multipsychophysical theory (Booth & Freeman 1993). It was recognised at the start that an integrative judgment could be influenced by covert processes. Stimulation may influence a response directly; that is to say, the participant bases the response simply on information from the stimulus. Yet alternatively the integrative response could be based on the conceptualisation behind another response, modelled from those other judgments: for example, merely considering the idea of how salty the drink is might control an overall judgment of closeness in taste to the usual tomato juice.

Further into the mind from the observed stimuli and responses, the integrative judgment might be influenced by the effect of a manipulated stimulus feature on the analytical response to it. Applying a response concept to a stimulus material is a process of describing. Such an effect of a description on a response concept gives greater depth of meaning to that concept in its influence on the integrative response. For example, sweetness described as lack of the sourness of citric acid might have a substantial influence on an integrative judgment of savouriness of tomato.

Finally, close to a stimulus rather than to a response but equally deep in the mind, a descriptive process could in theory modulate a stimulatory process in the course of deciding the integrative judgment. Sensory processing coming under a description in this way is a minimal characterisation of the achievement of a conscious percept or the construction of a sensation. For example, the influence of sodium chloride concentration on overall balance of taste could be modulated by describing the salt as being sweet like sugar. Hence such a perceptual process (or having a sensation) can be distinguished from any of the processes of being stimulated, having a concept, describing or giving meaning. Crucially to the present paper, if this stimulation-descriptive explanation of judged similarity in overall taste to the usual tomato juice includes one tastant as the source of the stimulation and a different tastant in the descriptive process, that is evidence that those two tastants are operating over the same channel.

To sum up, we are not questioning the evidence that MSG stimulates gustatory receptors for glutamate on the human tongue. The issue is whether or not human beings are totally dependent on such receptors in order to recognise the distinctive pattern of gustatory stimulation by glutamate in a dietary material. In other words, can the rated strengths of the taste specific to a particular savoury foodstuff be accounted for by stimulation of each of the known types of gustatory receptor identified with the four classic tastes?

The discrimination-additive criterion of unisapidity was validated initially on the rated sweetness of two sugars in a familiar fruit-flavoured drink using a limited range of these normed multipsychophysical models (Freeman 1996; Freeman & Booth 1997). Those results are presented in full for the first time in this paper as the initial set of experiments. The more recent experiment on mixtures including MSG reported here is the first full-scale use of normed discrimination to diagnose multisapidity.

Method

Participants

The experiments were carried out in accord with the ethical guidelines of the British Psychological Society. Each participant in an experiment gave informed consent at the start and was free to withdraw at any stage, although none did. The initial validation of this test for unisapidity had ten female and eight male participants with ages between 20 and 35 years; they were all familiar with an orange-flavoured drink available on a departmental vending machine. For the work on perception of monosodium glutamate (MSG), 35 female and male students and staff of the investigators' department took part. All these participants were familiar with the locally marketed beverage of (salted) tomato juice used in the experiment. They volunteered to taste samples of the juice containing varied amounts of materials having different tastes that occur in the ordinary diet. Some participants attended two or three sessions.

Materials

The initial validation used mixtures of varied concentrations of sugars and acids in an uncarbonated drink with an orangey flavour. A constant visual and olfactory context for those gustatory variations was provided by dissolving a manufacturer-donated flavouring, colouring and clouding powder (without sweetener or acidulant) in mains water at the concentration used in the vended drink. The tastants added were analytically pure sucrose, fructose, citric acid and malic acid. Samples were presented at room temperature, at which this drink was delivered by the vending machines.

The experiment on MSG used samples prepared from Del Monte Premium tomato juice bought from supermarkets in 1 litre tetrapaks. Portions were dialysed against mains water through cellophane, until the taste and aroma were indistinguishable with the eyes shut from those of the water. This removed salts, sugars, fruit acids, free amino acids and other low molecular weight ions and compounds, without changing the particulate colouring and visual and tactile texture of the beverage product. Analytical grade MSG and sodium chloride (NaCl), citric acid, sucrose and caffeine were then added to give a known concentration of each tastant in the familiar-looking product. The commercial product had little aroma to be lost during dialysis. Furthermore, the samples were tested after a period in open vessels, as normal for consumption of the juice. It is therefore extremely unlikely that volatiles from the samples were at sufficient concentrations to affect discriminations between levels of tastants. Hence the issue of olfactory contributions to the usual 'taste' of the juice does not arise in this approach and so inclusive descriptive analysis was not attempted.

In pilot work, each tastant was added in approximately equal-ratio steps no larger than 1.3, to allow for finely discriminating participants, going up and down from 4 g of NaCl in one litre (0.4%) and MSG.H_2O at around 12 g.l^{-1} (1.2%), with six steps on either side to allow for any large individual differences in perceived usual concentration and/or very poor discrimination. In the experiment reported here, extremes in norm or discriminative sensitivity were accommodated by having two sets of mixtures. One set with medium ranges of concentrations was used for participants who appeared from their responses to the first two or three samples to be finely discriminating. The other set of test mixtures had wide ranges for those who initially showed relative insensitivity, or unrealistic perception of the concentrations in the marketed juice.

Each sample of juice was presented at a volume of 25 ml in a small cup that had been held at 10^{o} C by immersion in a temperature-controlled waterbath.

Quantitative judgments

The physical layouts for responding are not reproduced. What matters is the rationale for each aspect of a response format and so that is presented verbally here.

In the early validating experiment on an orangey drink, how *sweet* and *sour* each sample was judged to be were rated by indicating a position on a strip of tape labelled *most* *familiar orange drink* at its middle and *not at all* at the left-hand end. No other anchor was provided, thus ensuring linear responding (Booth 2009b).

The layout for rating the strength of taste of a sample of tomato juice was a horizontal row of squares, with the middle box highlighted in bold and labelled symmetrically above and below as *usual [...] taste of tomato juice*, with *salty*, *sweet*, *sour* or *bitter* in the place of the square brackets or, for assessment of overall taste, with *usual tasting* above the box and *tomato juice* below. The seventh box to the left of the middle was also highlighted and labelled *not [...] enough [...] for me*, using one of the four descriptors in the place of the first bracket, or *taste* instead of the second bracket to serve as the low anchor for the integrative response. There was an arrow labeled *weaker* below the third to fifth boxes on the left and another arrow labelled *stronger* at the corresponding place on the right. To deal with any extreme response that was elicited despite the effort to minimise biases, *How many more boxes do you need?* was written beyond the ninth box on either side of *usual*, with space to write in a number.

After completing the ratings of each sample, the assessor was asked to state if each of the five tastes was too strong, too weak or just right (or *don't know*). The responses helped to guide selection of the next sample in an effort to pre-empt biases (Conner, Land & Booth 1987; Poulton 1989; Riskey, Parducci & Beauchamp 1979), particularly response end effects and stimulus range bias.

Procedure

Each session on tomato juice began with a sample of the commercial product, not to be rated but to be sipped when wished while reading through the rating formats to check that they were comprehensible and for mental rehearsal of their completion. Participants were required to take at least one sip of uncarbonated mineral water at the end of that induction and also after they had finished rating each test sample.

The experimenter tailored the selection of samples to each participant's norms and discriminations for each tastant, in order to estimate those individual characteristics as accurately as possible within a set of samples amounting to a total volume that was usual for a drink of the juice. The principles of sequencing selected samples are therefore crucial. Hence this rationale is described below and the many concentrations of tastants in each sample tested in each individual are not listed.

To minimise centring bias, the first rated sample contained levels of tastants that were no more than one step away from those in the commercial product (above and below in alternate assessors). These concentrations were usually far enough from marketed levels to see if the level of each tastant was perceived to be above or below its usual intensity in tomato juice. The second sample was chosen by the investigator to provide levels on the opposite side of what the participant judged to be the usual taste, but further away from usual than the first sample turned out to be for that individual. The data from the first two samples were used to select a third sample that elicited ratings within a box or two of *not enough* or the corresponding unlabelled box on the strong side. Subsequent samples were chosen to equate the number of ratings on each side of *usual* and to space ratings as evenly as feasible, thus minimising range and frequency biases.

Multi-psychophysical hypothesis testing

Participants had been set the task of judging the distance of each tasted sample from the familiar form of the material, in strengths both of overall taste and of saltiness, sweetness, sourness and bitterness. Since only one sample was available at any one time, any discrimination achieved over the whole session must have been by comparison between each presented instance of the material and some standard in explicit or implicit memory. Therefore the theory on which these data were analysed was that each quantitative judgment on a sample compared the level of a signal from that sample with the level of that signal generated by previously consumed samples of the same sort of material. Hence each signal from a sample had a distance from this internal standard that could be scaled in units of half-discrimination (HD: halfway between no discrimination and perfect discrimination) in accord with Thurstone's (1927) equal-variances model for his method of comparisons (Booth *et al*. 1983; Conner *et al*. 1988). Also, that personally familiar concentration of a tastant in that context (the norm) could be interpolated from the psychophysical function.

A normed psychophysical function is folded (Coombs 1964) with the learnt level of the feature at its peak (the norm point, NP) and the linear gradient of intradimensional stimulus generalisation or dissimilarity on each side (Shepard 1957). Thus, when concentrations of a tastant are plotted in units of the observed HD ratio, the function forms an isosceles triangle if the context is ideal -- that is, if all the other attended features are at their learnt usual levels, on the multi-feature NP at the apex of all the triangles.

For a familiar mixture of two tastants, these psychophysical triangles are in orthogonal planes. That is, with an integrative rating on the vertical axis, the psychophysical function for the mixture forms the surface of a cone with its apex at the joint NP, with its two horizontal axes being the levels of each tastant (Booth & Freeman 1993). When both components are scaled in HDs, the cone is symmetrical.

For mixtures of three tastants, the horizontal plane for two stimuli is replaced by a cube and a multipsychophysical cone around the vertical axis of response strength can no longer be visualised. Hence three or more stimulus components form the orthogonal axes of an unvisualisable 'hyperplane,' with the response vertical generating a 'hypercone.' Nevertheless, Pythagoras's theorem for the length of the hypotenuse of a right-angled triangle generalises across any number of 90^o angles and so the analysis of such data remains arithmetically straightforward (Booth & Freeman 1993).

The average level of a tastant over a session may not coincide with its NP for the participant. In such cases, the observed function for any other tastant should fit a vertical cut through the (hyper)cone, as far away from the apex as the session's average level of the other stimulus in a binary mixture or the average context of all the other processed stimuli in mixtures of several tastants (and non-gustatory features). In general, therefore, the normed psychophysical function is a perpendicular conic section -- a right hyperbola.

Thus, the first step in analysis of the raw data from an individual's session is, for each tastant and each rating, to fit the logarithm of the concentration of the tastant to the score for each judgment to the formula for a hyperbola with its peak at the score for a response in the box labeled *usual ... taste* (Figure 1). The fitting to this causal equation is done by least-squares regression. The NP is at the intersection of the tangents of the hyperbola (the triangle to which it is asymptotic). The HD is calculated from the slope of the tangents and the mean square error of the regression line in accord with the formula for a JND (Conner *et al*. 1988). However we avoid the terms 'just-noticeable difference' and 'difference limen' because half-discrimination is a threshold-free measure of observed performance, regardless of whether or not any difference in magnitudes of sensation is consciously noticeable (Torgerson 1958).

Figure 1 about here

The same hyperbolic regressions are also calculated from each rating to each other rating of each sample that was made by the assessor at the same session. Since the input levels for a concept (a symbolic rather than a material affordance) are the untransformed ratings (Booth & Freeman 1993), these discriminations are of differences, not of ratios (logarithmic differences) as for the input levels from materials. Because discrimination can be between either material ratios or symbolic intervals, we use the term 'disparity' for what is half-discriminated (hence the acronym HDD).

Potential interactions among these HDD-scaled, norm-anchored psychophysical functions are tested by simple linear regression from the hypothesised multidimensional distance from norm to the response to be explained. In the experiment on MSG in tomato juice, these cognitive models were constructed for the integrative judgment, *tastes like tomato* *juice*. In the earlier validating experiments on sugars and acids in an orange-flavoured drink, the judgments to be explained were how *sweet* or *sour* each sample was.

In the simplest case, one of the tastants directly stimulates the response. This HDD-scaled psychophysical function is called a stimulatory (S) model, as distinct from the processes described next, which are further from the receptors. There are five sorts of these less directly stimulus-driven processes. These are estimated as follows.

A signal directly to an integrative judgment (such as *the usual overall taste*) might be generated by the conceptualising process that drives an analytical judgment, such as how *sweet* each sample is. To estimate the causal power of this signal between concepts, a least-squares regression from such an analytical rating to the integrative rating is calculated using the distance of each sample from the NP, scaled in HDD intervals as explained above. The proportion of variance accounted for by this regression tests the hypothesis that the assessor's integrative processing involves the concept behind that analytical rating. Hence the formula is labelled an R element and regarded as the model of a process of verbal conceptualisation that influences the integrative judgment.

The characteristics are then estimated of each of four types of covert causal process that may influence the judgment being modelled, also by linearly regressing their discrimination distances from norm onto the scores for that response. As indicated in the Introduction, the levels of tastant to be regressed onto the integrative ratings can be scaled in HDDs from NP for an analytical function (such as from sugar to sweetness). This produces an S/R element, modelling descriptive control of the cognitive integration, e.g., saltiness like that in salt determines how similar each sample is to the usual juice.

Still deeper levels of processing can be diagnosed. Regression from descriptive (S/R) distances onto levels of a response (R) gives an S/R//R element for testing on the integrative judgments. One interoretation of this model is that an analytical response has been given affective meaning such as emotion or intention. Regressing from stimulus levels (S) onto the same stimulus-response (S/R) HDDs from NP gives an S//S/R element, representing a percept; cf. Figure 2 and Table 1 in Results.

Finally, the function of one analytic response on another can be used to account for the integrative ratings. That gives an R/R element, representing a process of moving from one verbal concept to the other in the act of achieving the overall judgment, e.g. a deductive inference.

Each of those six calculations produces a distinct set of numerical values from the data on stimuli and responses from an individual's session. These elemental models and the theoretically specified multidimensional combinations among them are compared by the variance in the modelled response that they account for in simple linear regression. A combination of two elements into a formula has to account for more variance in the modelled response than does either of the component elements. The better model is then combined with further elements to test for further increase in variance accounted for. The results reported in this paper are of formulae built up from elements only of the same type (e.g., in Figure 2, Results).

There are just two simple ways to combine an element with another element or an already validated combination of elements. These calculations implement the logical primitive of the distinction between same and different, in the form of two operators that can be represented in dimensions of Euclidean space. The operator testing for something in common across elements sums their discrimination distances from norm. That is, it treats them as being on a single dimension. The operator testing for a difference between single or summed elements is the square root of the sum of the squares of the values for each sample, i.e. the elements being on orthogonal dimensions. As pointed out in the Introduction, Pythagoras's square of the hypotenuse is equal in area to the sum of the squares on any number of 'sides' at 90^{o}, and so this operator (capital gamma, Γ, symbolizing a right-angled triangle) is unlimited in scope, as addition (+) also is: the conical response surface for two tastants generalises to unvisualisable 'hypercones' for three or more tastants. In S models, for example, each tastant can occupy its own dimension orthogonal to dimensions for other tastants. The same variety of multidimensional models is testable for any of the other types of information processing (S//S/R, S/R, S/R//R, R or R/R).

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Thus the formula A + B represents two information-transforming processes (A and B) operating over the same channel (a one-dimensional model) while A Γ B represents the two signals transmitted over separate channels (a 2-D model) in their combined influence on the modeled response (R_M). Regression from [(A+B) Γ A Γ B] to R_M estimates a 3-D transformation of the information in the stimuli to A and B into the integrative judgment, R_M, i.e. HDD-scaled contributions by both similarity between A and B and also by their distinctive features. To the extent that the mind works in normed discrimination processes, an individual who performs in a self-consistent manner throughout a session produces data for which there is a multiple discrimination formula that accounts for virtually all of the variance in R_M.

The initial validation of this approach in its simplest form (Booth & Freeman 1993) used mixture of sugars and acids in an orange-flavoured drink (Freeman 1996). Samples were rated for acceptability, sweetness and sourness. At that time, the modelling tool tested just 1-D and 2-D models -- in this case, whether any two tastants were unisapid or not. Also, just three mediating cognitive processes were tested, the two direct influences on the judgment, stimulatory (S) and conceptual (R), and the simplest indirect influence, descriptive (S/R). This paper presents those findings for ratings of closeness to the usual sweetness and sourness of the drink

In the recent experiment on which this paper centres, ratings of closeness in overall taste to tomato juice were modelled using a new algorithmic tool that calculates the most explanatory process from an individual's data for a session, however many dimensions it involves, and whichever of six types of cognitive process. With five tastants and six ratings, there is an extremely large number of arithmetically possible dimensions with summated elements and multidimensional combinations. However, there is rapid convergence because each additional element has to increase the variance accounted for. Hence the key issue is how much of the variance in the modelled response is accounted for by the best model from an individual's data in a session.

As stated in the Introduction, there were two criteria for multisapidity of MSG. One was that the HDD distances from norm for MSG and one or more unisapid tastants summated in the best model for the taste of tomato juice (coded as + in Table 1 in Results). The other was a perceptual model (S//S/R) that included MSG and a unisapid tastant or a pair, trio or quartet of the unisapid tastants (coded // in Table 1).

The old data on sugars and acids in an orangey drink from the first experiments using this approach were analysed at the time using a program in QuickBasic. That fitted each raw psychophysical function to a straight line (the unfolded isosceles triangle) instead of an hyperbola, and modelled only the S, R and S/R processes stated by Booth and Freeman (1993), not the S//S/R, S/R//R and R/R processes explicated later. The recent data from MSG in tomato juice were analysed by a dedicated software tool in Java at an advanced stage of its second generation (Co-Pro 2.29). This program started by fitting hyperbolic regressions to the raw data taken in randomised sequences (psychophysics). It then ran algorithms for the above-specified tests for interactions among separate channels (cognitive modelling).

Results

Unisapidity in discriminations from norm

The use of multiple discriminations from norm to measure unisapidity was validated by three experiments on mixtures of tastants in a familiar orange-flavoured drink. In the first experiment, the separation of the potential unisapidities of sugars and acids was tested on mixtures of sucrose and citric acid. Two other experiments tested for unisapidity between sugars, with the third experiment also testing for unisapidity between acids.

In all three experiments, individuals' integrative multiple-discrimination processing of stimulation from sugars and acids into the sweetness or sourness of the orange-flavoured drink was found almost always to be descriptive (best fitting an S/R model). Neither the stimulation by the tastants (S models) nor the conceptualisations as sweet or as sour (R models) in either one-channel or two-channel combinations explained more than a few percent of the variance of the individual's rated sweetness or sourness of each sample of the drink.

This indirect processing of receptor-stimulatory information occurred despite the fact that sucrose concentration ratios accounted for most of the variance in ratings of sweetness. For example, in the twelve assessors of binary mixtures of sucrose and citric acid in the drink, the r^2 for sugar on *sweet* ranged from as high as 0.82 down to 0.30 (a median of 0.71). Citric acid accounted even better for sourness ratings of the same samples (range 0.99 to 0.50; median 0.74).

Nevertheless this simple type of psychophysical function also provided evidence for central interactions between the afferent channels. The variance of one of the sugar/*sweet* and acid/*sour* (homologous) functions was often almost matched, and in some cases exceeded, by the variance of one of the heterologous functions, sugar/*sour* or acid/*sweet*. The influence of sucrose on the ratings of *sour* intensity gave r^2 values in the range 0.78 to 0.18 (median 0.43).

The control of sweetness by citric acid was similar (range 0.74 to 0.19, median 0.48). In this connection it should be noted that members of the culture using the orange-flavoured drink categorised it as a sweet beverage, not as a sour (or savoury) one. Hence variations in concentration of citric acid may be more salient than those of sugar.

In this experiment on mixtures of sucrose and citric acid in the orange drink, the two-channel combinations of homologous descriptive models (regressed from the distances from norm of sugar/*sweet* and acid/*sour*) more often accounted for a greater part of the variance in ratings of how *sweet* or *sour* the drink samples were than did the single-channel combinations. That is consistent with sugars having a unisapidity which is distinct from the unisapidity of acids.

Of six participants new to such experiments, the five with $r^2 > 0.3$ for their best model had much better two-channel combinations. For integration into sweetness, the model for orthogonal dimensions of sugar/*sweet* and acid/*sour* had a mean r^2 of 0.61, with $F(1,4) = 9.00$, $p < 0.04$, $\eta^2 = 0.69$, against the single-channel combinations (mean $r^2 = 0.21$). Similarly, integration into sourness had a mean r^2 of 0.65 for two channels and 0.38 for one channel, $F(1,4) = 7.14$, $p < 0.06$, $\eta^2 = 0.83$.

The prior experience of such experiments in six other participants seemed to strengthen the integral concept of a sweet drink. Only three of these participants gave evidence of two descriptive channels into sweetness, one showing a tie with the unidimensional hypothesis at $r^2 = 0.60$, and two integrating sugar/*sweet* and acid/*sour* with a mean r^2 of 0.56 for two channels and of 0.48 for one channel. In addition, these six experienced participants generally did not integrate the homologous descriptions into sourness of the drink as effectively as they did into sweetness. Instead, each of them used two channels for this task (mean $r^2 = 0.45$), not a single channel (mean $r^2 = 0.22$), $F(1,5) = 12.9$, $p < 0.02$, $\eta^2 = 0.72$. Both this poorer integration into ratings of sourness and its clearer two-channel processing could have arisen from the lack of a stereotype of sourness for this drink, since it was merely orange-flavoured, and not as strongly tasting both sour and sweet as the real juice of oranges.

The unisapidity of sugars was identified by norm-anchored multiple discrimination scaling in two other experiments with the orange drink. One was on binary mixtures of sucrose and fructose. The other had quaternary mixtures of those sugars and citric and malic acids.

One of the nine participants tested on the binary mixtures performed no integration of sucrose/*sweet* and fructose/*sweet* HDDs from NP into the sweetness judgments on the drinks (r^2 =< 0.03). The other eight all combined these descriptive processes into rated sweetness over a single channel with mean r^2 of 0.57 and range of 0.85 to 0.32. These r^2 values were greater than those for two-channel combination by a mean of 0.25 (range 0.54 to 0.06), $F(1,7) = 15.6$, $p < 0.01$, $\eta^2 = 0.69$.

All eight of the assessors of the quaternary mixtures integrated the homologous descriptive processes. Seven of them gave evidence of unisapidity for sugars. The single-channel mean r^2 value was 0.61 (range 0.45 to 0.78). The mean difference in r^2 values from two-channel combinations was 0.17 (range 0.52 to -0.07), $F(1,7) = 8.19$, $p < 0.025$, $\eta^2 = 0.54$.

Evidence on the unisapidity of acids came from the heterologous acid/*sweet* descriptive processes rather than homologous acid/*sour* processes. The latter showed a difference between r^2 values greater than 0.1 in only one assessor, who achieved an r^2 of 0.67 over a single channel and 0.26 over two channels. Presumably because fruit-flavoured drinks are regarded as in the sweet category, the acid/*sweet* descriptive processes of the two acids were better integrated in most assessors, at least over a single channel, mean $r^2 = 0.61$ (range 0.38 to 0.78), in contrast to a mean $r^2 = 0.21$ for two-channel integration, $F(1,7) = 149$, $p < 0.001$, $\eta^2 = 0.96$. This is evidence for the unisapidity of acids, even though the main effect of gustatory stimulation by an acid in a sugary drink is to suppress how *sweet* it is rated to be.

Gustatory integration performed on tomato juice

The main experiment was conducted on samples that looked and felt the same as a familiar drink of salted tomato juice. Nevertheless, the samples varied in concentrations of the glutamate inherent in tomatoes, in the form of the flavouring monosodium glutamate (MSG), and of the table salt (sodium chloride) added during production of the packs of juice, together with experimentally varied sucrose, citric acid and caffeine.

Each of twelve participants assessed a personally tailored set of eight samples of these mixtures in at least two sessions. The median r^2 for the best multidinsional model of overall similarity to tomato juice improved from 0.75 in the first run to 0.89 in the second run, Wilcoxon Z = 1.69, one-tailed $p < 0.046$. Only three of the twelve participants performed no better at the second run; however, these three had little scope to improve because the r^2 values of their best models were the highest of the twelve in their first run (0.92, 0.95, 0.97).

Four of the twelve participants had three sessions, with a different set of mixtures each time. The most variance accounted for (r^2) by any of the tested models of multiple discrimination improved from one session to the next in each assessor, with medians of 0.63, 0.89 and 0.98 in the first, second and third runs respectively, Friedman $\chi^2(2) = 8.0$, $p < 0.018$. The linear contrast among runs had repeated-measures $F(1,10) = 16.7$, $p < 0.026$ (quadratic $p > 0.24$). This steady improvement in cognitive integration, in effect to perfection within three runs, supported the hypothesis that MSG stimulates a particular balance of the gustatory receptors for sodium chloride, sucrose, citric acid and caffeine. The systematic trend also confirmed that the best models constructed by discrimination scaling are not statistical accidents, because those would occur at random across runs.

One participant attained an r^2 of 0.99 in the third run (Figure 2). The cognitive processing diagnosed in this person was at the level of conscious percepts (an S//S/R model). That is, each element was the modulation of the processing of a tastant's stimulation by the description of a tastant, as follows.

Figure 2 about here

Two different complex gustatory percepts or sensations controlled this person's overall evaluation of similarity to tomato juice throughout this session (Figure 1, formula labelling the horizontal axis). The more dominant sensation (listed first in the formula of the model) was modulation of sensory processes from citric acid (S4) and (less) from salt (S2), respectively, by the concept of sweetness (R3) being used to describe stimulation from salt (S2) and from MSG (S1). That is to say, tomato juice as remembered in each judgment had a sweetness as sensed in (presumably less of) citric acid and also in salt that characterized the feature in common between the elements of sensation that were driven by salt and MSG. It should be noted that the phenomenology of a sensation could hardly be less complex than this objective perceptual performance of modulating a pattern of stimulation by a description that used a verbal concept and/or a stimulatory pattern that was sometimes of another category.

In this case, however, the memory of the taste of tomato juice was even more complex than that. It had a second feature of similarity between the sourness of MSG describing stimulation by salt and the bitterness of salt describing stimulation by MSG (right-hand sum in the label of the horizontal axis of Figure 2).

In other words, discrimination between levels of MSG had three roles in this person's perception of the tastants in the samples of tomato juice presented during this session. Each role of MSG relied on a distinct concept -- sweetness, sourness and bitterness. In this individual at least, the concept of saltiness was not involved. This indicates that the other three classic concepts of taste involved in this sensation were evoked by the glutamate ion in MSG, not by the sodium ion.

Three of the four components in this person's perception of tomato juice reflected the undoubted unisapidity of the sodium ions in MSG and salt (Figure 2). More interestingly, citric acid and sodium chloride were unisapid by the same criterion. Receptor interactions between citrate and chloride are conceivable. Another possibility is that these two receptor types form part of the basis for a Gestalt of MSG that was read down into this sensation.

Tastants indiscriminable from components of MSG in tomato juice

MSG was identified 47 times in twelve assessors over two (N = 8) or three (N = 4) sessions on an information-processing channel through which the mixtures of five tastants influenced the judgments of overall closeness to tomato juice (Table 1: first nine rows of counts). However, on only three of those occasions was MSG the sole tastant represented in transmission over a channel (top row, Table 1). On nine occasions (in the first four rows marked + in Table 1), MSG shared a stimulatory channel (lower-level sensory processing) with one of the other four tastants: that is, a feature of the complex taste of MSG was indiscriminable from the taste of that other compound.

Table 1 about here

Five of these nine cases of stimulatory unisapidity between a classic tastant and a moiety in MSG arose from assessments of mixtures before the participant was asked to rate the samples on specific descriptors (*salty*, *sweet*, *sour* and *bitter*), in modelling that did not include these analytical ratings from the next run (column headed ‘None in Model’ in Table 1). That is, in the majority of these nine cases, the indiscriminability of the tastant from some of the gustatory stimulation by MSG could not be ascribed to confusion arising from insufficiently precise conceptualisation of a taste term such as *sour* or *bitter*.

Differences among these four tastants, despite each being similar to an aspect of MSG, were confirmed by their modelling onto separate channels by themselves without their analytical concepts being presented verbally to the assessors or represented in the modelling (Table 1, None in Model column, last four lines).

In the remaining 38 cases, MSG and the other tastant shared a stimulation-descriptive channel or sensation (rows of MSG and another tastant in Table 1, marked // for an S//S/R model). An example was the element sucrose//MSG/*sweet*. This represents modulation of the stimulatory processing of sucrose by the descriptive process 'sweet MSG.' That is to say, a single channel processed information both from sucrose and MSG, under the concept of sweetness.

Whether these cases of unisapidity between MSG and one of the other tastants were a stimulation-descriptive element or the addition of stimulatory elements on one dimension, they were typically observed within a cognitive model having two or three channels, often each transmitting information from another pair of tastants (see the next section of Results). That is, as well as a feature of MSG being indiscriminable from a classic tastant, that tastant was readily distinguished from other tastants and from other features of MSG. The complex taste of MSG is not confused but it is an integration of 'simple' tastes that each retains its distinctiveness at some level. This finding conflicts with the claim by Laing and colleagues (Laing, Link, Jinks & Hutchinson 2002; Marshall, Laing, Jinks & Hitchinson 2006) that all mixtures of four tastants completely mask each of the four tastes. The finding shows that not to be true of the familiar mixture in tomato juice and mixtures sufficiently like it when assessed appropriately.

Indiscriminable pairs and trios of components of MSG

A pair of the four classic tastants was identified 52 times in total as being processed on a single channel into the overall taste of the juice (Table 1, lines 10 to 21 of counts). In eight of these cases (Table 1, column 'None in session', lines 3, 5 and 7), MSG was processed perceptually with one of the tastants NaCl, sucrose or citric acid. When the four descriptors were made explicit and included in the modelling, caffeine as well in some cases was the tastant integrated perceptually with MSG (Table 1, columns for First, Second and Third explicit, line 9). All these instances provided evidence against the claim that a fifth type of receptor is needed to recognise the taste of MSG.

In two cases, a feature of MSG was indiscriminable from one of two other tastants (no cell available in Table 1). That is, all three compounds contributed over the same channel to the taste of tomato juice. Both cases were performance at the stimulation-descriptive level (S//S/R), one on sucrose and citric acid as well as MSG, and the other on caffeine and citric acid with MSG.

Discussion

Multi-psychophysical recognition of an object

The logically simplest theory of the cognitive mechanisms required for perception of familiar situations, objects and materials (Booth & Freeman 1993) was applied to assessment of the realism of mixtures of tastants in a material with which the assessors were familiar. The theory was applied to glutamate in a pilot study by Freeman *et al*. (1993). The approach was developed initially for single tastants in well learnt contexts by Booth *et al*. (1983) and Conner *et al*. (1988). That Booth-Freeman-Conner theory implies that the ratios matching the taste of the food containing glutamate and sodium represent the most realistic balance or the best overall quality of taste in that food, whereas higher and lower concentrations in ratio represent a stronger or weaker taste of that sort within the limits of constancy of taste quality in the components (Booth & Freeman 1993; Booth, Konle & Sharpe 2008).

The theory specifying such matching was supported by its successful use to test for multiple unisapidities of MSG. Regions of indiscriminability from the corresponding moieties in MSG were shown not only by sodium chloride but also by citric acid and sucrose, and perhaps caffeine. This is the multi-feature analogue of the unisapidity for sugars demonstrated by Breslin *et al*. (1996) and replicated by this approach in initial experiments reported here (Freeman 1996).

Of course this finding of the multisapidity of MSG does not show that the gustatory glutamate receptor on the human tongue is never used. The fact that wavelengths in the range of one type of photoreceptor can be discriminated in its absence does not imply that the photoreceptor is unused when present.

What the present evidence does is to expose grave difficulties faced by any endeavour to measure the discriminative sensitivity of a type of receptor that also has another sensitivity in common with a different receptor type. In the gustatory modality, the signal from such a receptor might activate only the across-fibre channels driven from receptors of the four classic types, even at an early stage of sensory processing. Indeed, there is now evidence of convergence between receptor types at the lowest level, within a single taste bud onto a primary afferent fibre (Tomchik, Berg, Kim *et al*. 2007). The mapping of dissimilarity ratings (Schiffman & Dackis 1975) or responses of single neurons (McCabe & Rolls 2007) for MSG separately from other tastants does nothing to undermine that possibility. The specificity to MSG of a map location or neural unit could arise from configuring and convergence respectively of the four channels at levels of processing closer to output.

This account's presupposition of four gustatory concepts (behind the words *salty*, *sweet*, *bitter* and *sour*) was cast in question by Erickson (2008) on the basis of a briefly reported study comparing amino acids with other tastants. Yet the data presented there showed clear evidence for these four ideas of taste. There was a remarkable predominance of overlaps between the two sodium salts, the chloride (NaCl) and the glutamate (MSG), the two nitrogenous compounds quinine and ammonium chloride (NH_4Cl), sucrose and the sweet amino acid, proline, and the unique taste of hydrochloric acid and an aspect of both MSG and NH_4Cl (Booth 2008a). Furthermore, the taste of MSG itself was a balance of NaCl-dominated lysine, acids-dominated acetylglycine, sucrose-dominated proline and quinine-dominated phenylalanine. In sum, the data reported by Erickson (2008) are entirely consistent with the present evidence that gustatory stimulation by MSG can be a particular balance of activations of receptors specific to tastants each described using only one of the four classic taste concepts.

Nevertheless, the present approach would be feasible with any set of descriptors that were each relatively specific to one of the unisapid tastants used. This was demonstrated in our work on discrimination analysis of the cognitive processes used to configure the aroma of fresh strawberries from olfactory stimulation by mixtures of four volatile compounds conceptualised quite broadly as sweet, fruity, leafy and buttery (Booth, Freeman & Kendal-

Reed 1995; Booth, Kendal-Reed & Freeman 2010; Kendal-Reed & Booth 1992). Even though the descriptors *salty*, *sweet*, *sour* and *bitter* probably could not be bettered for sodium salts, citric acid, sucrose and caffeine, they were not as finely discriminating between levels of their respective tastants as they were between levels of MSG (Booth, Konle, Wainwright & Sharpe submitted). This reflects the precision of overall memory for the glutamate and salt in the usual tomato juice beverage relative to memory for its judged saltiness, sourness, sweetness and bitterness when such analytical attention is required.

This sensitivity to separate gustatory features in discriminative performance on MSG as a component of tomato juice contrasts with that of descriptive assessment out of a familiar context. In such tasks, the attribution of sweetness to glutamate is masked by attribution of sourness (Breslin & Spector 2008). Multisapid sensitivity also explains why the most preferred levels of MSG in foods can be lower than those at which MSG is recognised in the usual tests (Schiffman, Sattely-Miller, Zimmerman *et al*. 1994).

Indeed, the theory of comparison with learnt norms (Booth & Freeman 1993) points to a critical flaw in traditional mixture psychophysics -- the use of unfamiliar mixtures. Also the presentation of diverse mixtures makes it impossible to build an artificial internal standard during the experimental session (Booth 1995; cp. Marchant & de Fockert 2009). Lack of an analysable configuration could also explain the phenomenon of mixture suppression -- reduction of the intensity of a tastant by mixing with another tastant. This suppression extends to the extreme of rendering indescribable the components of unfamiliar mixtures of three or four tastants or odorants (Laing, Link, Jinks & Hutchinson 2002; Marshall, Laing, Jinks & Hitchinson 2006). In addition, the normed discrimination model of suppression implies a determinate quantitative theory that is currently lacking for mixtures of two tastants (Keast & Breslin 2003), including those between MSG and nucleotides (Yamaguchi 1967).

In contrast, the evidence presented here is that a solution of a mixture of sucrose, citric acid, caffeine and sodium chloride in appropriate proportions would provide a good match to the taste of monosodium glutamate within the familiar context of drinking a tomato juice. This conclusion was not reached by statistical analysis of many data from a sensory panel trained to recognise the taste of glutamate in an "umami"-rich food (cp. Konosu, Hayashi & Yamaguchi 1987). Instead, we relied on ordinary eaters' ability from experience in life to recognise the taste of glutamate and sodium ions at the levels in food after acquiring the concept of a savoury type of food (Booth, Gibson, Toase & Freeman 1994; Freeman *et al*. 1993). Such multisensory integration is now widely acknowledged to be feasible (e.g., Auvrey & Spence 2008; Köster, Prescott & Köster 2004).

Multimodal discrimination theory

The theory of discriminations from an implicit multi-feature norm has much greater potential for understanding perception and attention than the gustatory cognition presented here (Booth 1994; Freeman & Booth 1997). The approach was shown to be equally applicable to familiar aromas mimicked by mixtures of a few odorants (Booth 1995; Booth *et al*. 1995). Across sensory modalities, the theory can resolve the cognitive effects observed in the interactions of taste and odour in flavour (Davidson, Linforth, Hollowood & Taylor 1999; Pfeiffer, Hort, Hollowood & Taylor 2006; Stevenson, Boakes & Prescott 1998), flavour and colour (French, Read, Booth & Arkley 1993; Spence, Levitan, Shankar & Zampini 2010) and flavour and texture (Booth 2005; Booth, Wainwright, Sharpe *et al*. 2006). This approach's use of both regression slope and mean square error creates considerably more flexibility and precision than combining only the response probability distributions (Ernst & Banks 2002).

Beyond such receptor-specific stimuli, physically broad affordances can also be accommodated. The combinations of foods in courses and of courses in meals are amenable to discrimination analysis in which superordinate multisensory dimensions represent each food (Santos 1998). Mixtures of tastants and/or odorants are configured with a particular degree of stretch in the wall of the stomach in classically conditioned appetites and satieties

(Booth 2009a; Gibson & Booth 2000; Kissileff, Booth, Thornton *et al*. 2008). Expected sensory, somatic and social effects of the nutrient contents of foods in pictures stimulate appetite through multimodal discriminations (Galea, Chechlacz, Booth *et al*. 2008) that are reflected in orbitofrontal and limbic activation in fMRI (Chechlacz, Rotshtein, Klamer *et al*. 2009)

Furthermore, discrimination scaling spans the divide between sensory and semantic processes, sidestepping issues about the material 'grounding' of concepts (Barsalou 2008; Quine 1960). The equal-variances model of comparisons (Thurstone 1927) applies to disparities in levels of symbolic input when scaled as differences, alongside material inputs that scale in ratios at the moderate levels used in this experiment and normally encountered in life. Hence, for example, a whole eating situation is susceptible to multiple discrimination analysis of the main features to which a person is attending on a particular occasion, including the sight, naming and labelling of foods and the verbalised attributions to them (Booth & Freeman 1995; Freeman & Booth 1993, under review; Freeman *et al*. 1993; Galea *et al*. 2008), as well as companions and ambience (Booth 2008b).

The normed psychophysical function from a stimulus to a response fits a hyperbola. The characteristics of each hyperbola can be used in mathematically determinate calculations to test a scientific theory of the information processing mechanisms involved in carrying out a perceptual task (Booth & Freeman 1993). In contrast, models just of responses (such as preference or familiarity) use quadratic functions with the values of coefficients fitted statistically to each set of data, without seeking replications or theoretical esplanation of those values (Ashby & Ennis 2002). Hence normed discrimination scaling provides an important way forward for multisensory research, despite the present results being on gustation alone (Lockhead 1994). Such psychological measurement of the individual's integration of the salient features of a situation provides new opportunities too for brain imaging (Galea *et al*. 2008) and for cultural analysis (Freeman & Booth 1993, 2010, submitted). Furthermore, this advance in the fundamental theory of perceptual processes illustrates what can be gained from tightly designed experimental investigation of complex but familiar real-life stimuli.

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Footnote

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Table 1. Tastants indiscriminable from monosodium glutamate (MSG): group frequencies of tastants operating over a single sensed channel, either stimulatory (+) or perceptual (//) to influence the samples' closeness of overall taste to that of tomato juice for each assessor under five conditions of presentation or modeling (N: number of assessors in group).

Channel		Individuals operating over the channel					
Tastants	Stim. Perc.	None in Model [a]	None in session	First explicit	Second explicit	Third explicit	Total count
		(N = 6)	(N = 6)	(N = 12)	(N = 6)	(N = 4)	(N=34)
MSG	-	1	1	0	0	1[b]	3
MSG &	+	2	0	0	0	1	3
NaCl	//	-	1	1	2	1	5
MSG &	+	1	0	0	1	0	2
Sucrose	//	-	3	4	2	3	12
MSG &	+	0	0	0	0	0	0
Citric a.	//	-	4	2	2	0	8
MSG &	+	2	2	0	0	0	4
Caffeine	//	-	0	3	3	4	10
NaCl &	+	0	0	2	0	1	3
Sucrose	//	-	2	2	1	0	5
NaCl &	+	0	0	0	0	0	0
Citric a.	//	-	0	3	0	3	6
NaCl &	+	0	0	0	0	0	0
Caffeine	//	-	2	4	2	2	9
Sucrose	+	0	0	0	0	1	1
& Citric	//	-	1	2	2	1	6
Sucrose	+	2	0	0	1	1	4
Caffeine	//	-	2	4	3	1	10
Citric &	+	0	0	1	0	0	1
Caffeine	//	-	1	4	0	2	7
NaCl	-	2	0	0	0	0	2
Sucrose	-	1	0	2[b]	0	0	3
Citric a.	-	5	0	0	0	0	5
Caffeine	-	2	0	1[b]	0	0	3

Key

+ Stimulatory as a complex dimension, e.g. Sn + Sm.

// Perceptual, e.g., Sn//Sm/Rp.

- Not applicable (column 2: not two tastants to compare; column 3: no descriptors in modeling)

[a]Data analysed without descriptive ratings from the first session with descriptors provided.

[b]Perceptually solo: a description of the tastant modulating tastant-stimulation processing.

Captions to Figures

Figure 1. Effect of monosodium glutamate (MSG) on rated similarity of the sample to usual tomato juice (second session with assessor 10; graphs from software tool). Horizontal axes: concentration of MSG in the test sample of juice (in logarithmic units). Vertical axes: rating of strength of overall taste (first and last) or how salty, sweet, sour or bitter (0 = usual taste). The numbers used as data points are the sequence of presentation of samples. Continuous curved line: best fitting hyperbola. Broken straight lines: tangents to the hyperbola. Note that a hyperbolic function is theoretically required by Pythagoras's Theorem; hence it would be incorrect to attempt to fit a straight line to the data.

Figure 2. The best model ($r^2 = 0.99$) of rated overall taste like tomato juice (R1; identical scored zero) of each sample mixture for the experimenter's third run of Assessor 2 (graphic output from software tool). Data points are ordinal numbers of sequence of presentation: in this case, the 2nd, 7th and 6th samples received the same rating. The diagnosed level of processing was 'Perceptual'(S//S/R), i.e. 'Descriptive' processing (S/R) of 'Stimulatory' processing (S) – most likely a (conscious) sensation of taste. This percept had two complex features (dimensions), each having two SSR elements: ¬ = keyboard character for root sum of squares of distances (Γ in the printed text); + = addition of distances. S1 = MSG, S2 = NaCl, S4 = citric acid, R3 = sweet, R4 = sour, R5 = bitter. See text for interpretation.

Figure 1 *Setter: these graphs can be reproduced in greyscale; colour is* *<u>not</u>* *required.*

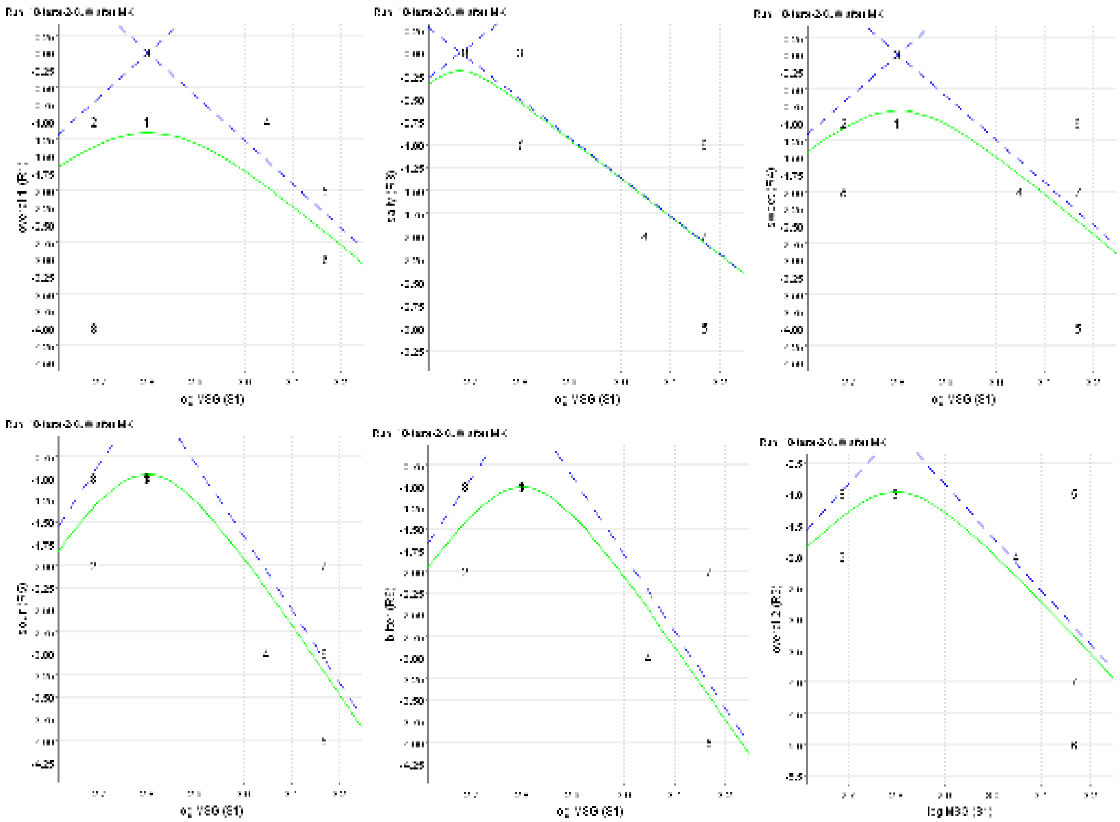
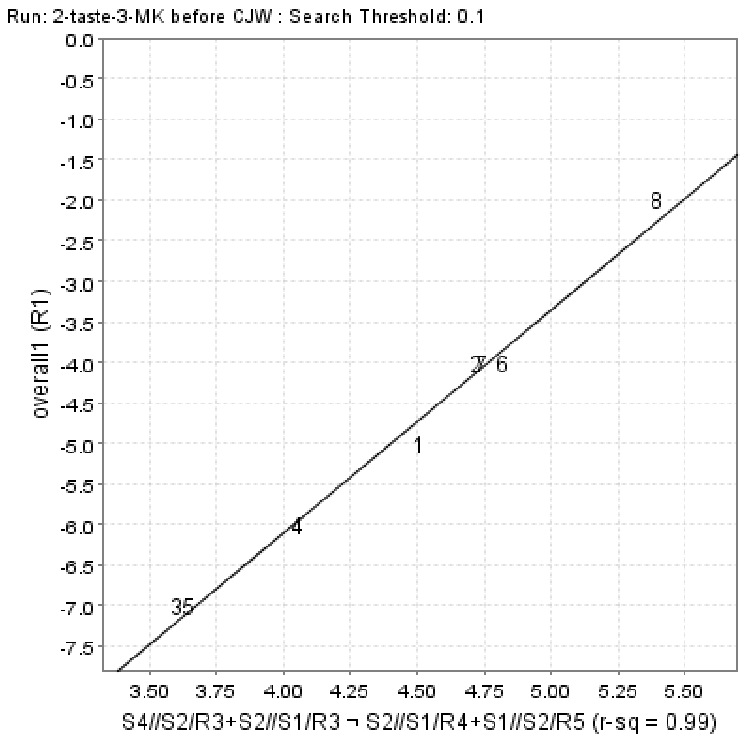


Figure 2.


Run: 2-taste-3-MK before CJW : Search Threshold: 0.1
overall1 (R1)
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
-5.5
-6.0
-6.5
-7.0
-7.5
3.50
3.75
4.00
4.25
4.50
4.75
5.00
5.25
5.50
S4//S2/R3+S2//S1/R3 ¬ S2//S1/R4+S1//S2/R5 (r-sq = 0.99)
8
6
1
4
35