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Sweetness magnitudes and sweetness differences: multiple psychological scales for sucrose

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Abstract. Two experiments used sucrose solutions at different concentrations and the method of magnitude estimation to assess: (i) the rule of integration underlying judgments of sweetness intervals, (ii) the sweetness scale operative in judgments of sweetness intervals and (iii) the sweetness scale operative in judgments of individual sweetness magnitudes. Results were consistent with a model of linear subtraction for judgments of sweetness differences. However, the scales that underlay the subtractive interval judgments were non-linearly related to the scales that underlay the (presumably additive) magnitude of sweetness judgments. This outcome suggests multiple psychological representations for sweetness, accounting for at least some of the scale variance observed in previous research.

Introduction

The simple two-parameter version of the power function $P = aS^b$, where P is subjective magnitude, S is stimulus intensity, and a and b are constants, has been widely used in taste psychophysics. A particularly appealing and parsimonious feature of this approach is that the shapes of the psychophysical functions are determined by the value of the exponent b. Unfortunately, however, the exponents of the scales for particular tastants have been found to vary considerably. Some of this variability probably reflects the influence of stimulus parameters (effecting physicochemical properties and biophysical factors) that have yet to be systematically clarified. The method of stimulus application, the flow rate of the stimulus, as well as its locus and temperature all seem important (e.g. Bartoshuk and Cleveland, 1977). This is especially true of sucrose where reported exponents spread over a range of 3:1, i.e. from ~0.6 to ~2.0 (e.g. Beebe-Center and Waddell, 1948; Lewis, 1948; MacLeod, 1952; Ekman and Åkesson, 1965; Gregson and Russell, 1965; Stevens, 1969; Moskowitz, 1970; Meiselman, 1971; Bartoshuk, 1975; Bartoshuk and Cleveland, 1977; McBride, 1983a,b, 1986).

The purpose of the present study was to offer an additional, psychologically substantive reason for scale variance. Our basic notion is that genuinely different perceptual relationships may underlie scales of sweetness under different judgmental conditions. Specifically, we suggest that one scale acts on discrete judgments of taste intensity, but another scale operates when subjects are called upon to make relational judgments of taste intensity, such as evaluating the difference in sweetness between two stimuli. Note that only the former task has been employed in previous research; although combinational operations were implicit in many of the judgmental conditions included in past research (notably in the perception of mixtures or their constituents), no study used explicit judgments of taste intensity differences or intervals.

The dual sweetness scales hypothesis is based on a pluralistic theory developed by Mark (1979) for other sense modalities, most notably for loudness. Faced with the discrepancy between the psychophysical functions for loudness produced by magnitude estimation and difference estimation (Marks, 1974), Marks suggested that judgments of loudness and loudness difference are based on separate perceptual scales. The present study captures the spirit of Marks's scheme; it argues that underlying the perception of sweetness difference is a subjective continuum distinct from that underlying the perception of sweetness itself.

Although this study is the first to formally suggest (and, we hope, demonstrate) the explicit existence of a separate scale underlying the perception of sweetness dissimilarity, this scale has been approximated by several experiments using methods like bisection (MacLeod, 1952), fractionation (Lewis, 1948) or category rating (McBride, 1983a; Schutz and Pilgrim, 1957). The upshot of these is that representations like the present (notably compressive) sweetness−difference scale appeared.

In the present study, we had subjects judge the difference in sweetness between pairs of solutions derived from a factorial design of all combinations of five concentrations of sucrose. This type of design enables one to test the integration rule underlying the overt difference judgments. Algebraic models of integration have recently been established for (discrete) sweetness judgments of several binary mixtures of sugars (McBride, 1986). The present study accomplishes this for judgments of sweetness intervals of a single sugar tastant. Apart from its theoretical importance, the rule of composition provides the needed criterion to validate the overt numerical judgments (Anderson, 1970). Finally, for the sake of completeness, we included a regular magnitude judgment condition for the same sucrose stimuli. To anticipate, the sweetness scale that underlay the subtractive interval judgments differed from (i.e. was non-linearly related to) the sweetness scale that underlay the traditionally derived discrete magnitude judgments.

Experiment 1: judgments of sweetness intervals and psychophysical functions for the sweetness of sucrose

Method

Stimuli. The taste stimuli were four concentrations of sucrose (0.001, 0.01, 0.1 and 1 M) dissolved in deionized water and a deionized water null stimulus. Stimuli were presented at room temperature (~23°C) in cups containing ~10 ml. Before and after tasting each stimulus, subjects rinsed their mouths thoroughly with distilled water.

Procedure. Stimulus pairs were generated from a 5 × 5 (first solution × second solution) factorial design based on the concentration levels specified above. This made 25 different stimuli (pairs of tastants) in all. Pairs were presented one at a time to the subjects for judgment. Each stimulus comprised the following sequence: sipping and spitting the first solution, pause (i.e. rinsing the mouth), sipping and spitting the second solution.

To minimize adaptation and fatigue, each session consisted of a single replication of one half of the stimulus matrix; either the higher concentration of a pair always appeared first (or both members had the same concentration level) or always appeared second. Thus, each session contained 15 different stimuli (combinations on the diagonal—equally intense stimulus pairs—were always included). The order of presentation of the two halves of the matrix alternated between sessions for each subject. Within a session, the order of presentation was pseudorandom (in that orderly sequences that occasionally arise in random selection were intentionally avoided) and was different for each subject. Each subject served in six sessions (separated by at least 1 day), thus giving six judgments per stimulus pair in all.

The method used was that of Stevens (1958) called 'interval estimation' or what is otherwise known as magnitude estimation of intervals or differences. The subjects were told that every stimulus would contain a sequence of two solutions and that the task was to try to assign numbers in proportion to the size of the interval of difference in sweetness between the tastants.

Subjects. Nine young men and women (six and three, respectively, between 19 and 36 years), all volunteers from the Bar-Ilan community, served as subjects. Four of them had experience with the method of magnitude estimation, though not necessarily in judging sweetness. None reported any history of sensory deficits or diseases.

Results and discussion

For each stimulus for each subject, the arithmetic mean was calculated across the numerical estimates. These means pooled over subjects are presented in Figure 1. The mean estimates are plotted against the level of the second stimulus; each curve represents a different constant concentration of the first stimulus. We use the convention of assigning a negative value when the first solution was, on average, judged sweeter. We observed virtually no order effects (nor the well-known time-order error); for all subjects the mean of the log[(drier−sweeter)/(sweeter−drier)] judgments did not differ significantly from zero.

If the subjects behave in compliance with the instructions, the data should conform to a subtractive structure operating on the psychological representations of sweetness. A subtractive model predicts that the curves in Figure 1 should be parallel. This is so because a given increase in the concentration level of any one of the sucrose solutions

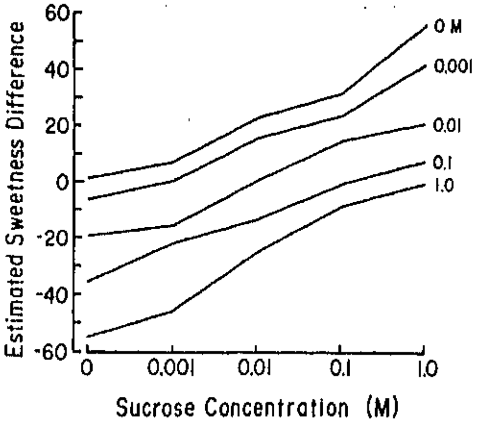

Fig. 1. Sweetness intervals. The average magnitude estimates of the sweetness difference between successive sucrose stimuli, plotted as a function of the concentration level of the second solution. Each curve represents a constant concentration of the first solution. By convention, the estimates were assigned negative values when the first stimulus was judged greater than the second.

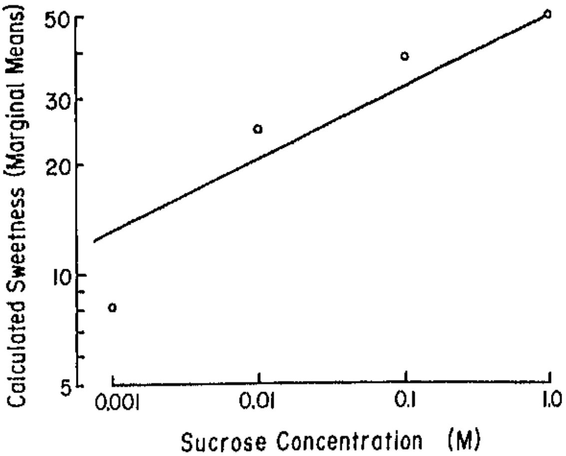

Fig. 2. Average sweetness function for sucrose, derived from the marginal means of the data plotted in Figure 1.

increases (or decreases) overall dissimilarity by a constant amount regardless of the level of the other solution. Because sweetness-difference estimates are plotted on a linear scale, the hypothesis of linear subtraction may be assessed by visual inspection. Indeed, the curves do appear parallel; neighboring pairs of functions appear to be separated from one another by a constant amount. Despite some small variability, the overall form of the functions suggests that a subtractive structure holds for the present data, at least to a first-order approximation. An analysis of variance confirmed this conclusion; the interaction term was nonsignificant, $F(16,64) = 1.58$.

What sweetness scale underlies these judgments of sweetness intervals? To answer this question, we computed marginal means of the judgment matrix for the first stimulus and for the second stimulus and then averaged the two sets. As Anderson (1970) has pointed out, given a factorial design of the type used in this experiment and results consistent with subtractivity in the response domain, the marginal means provide estimates of the internal scale values. As Figure 2 shows, the sweetness function given by the marginal means approximates a power function (straight line in the log–log coordinates). The slope (exponent of the power function) is 0.25; the fit to the power transform, though satisfactory, is moderate ($r^2 = 0.918$). In fact, a logarithmic function can describe these data equally well.

However, the present design entails further indicants of the underlying scale values. These derive from only a subset of the results, namely, data for presentations that contained the null-stimulus as a member of the pair (i.e. data from either the first column or the first row of the factorial design). Because they derive from the entire response matrix, the marginal means have, of course, a fuller basis than do these essentially unifactor sweetness judgments. Nevertheless, both derivations are valuable in providing converging evidence for a validated psychophysical function characterizing a specific taste experience. The magnitude estimation function derived from the first row of the matrix has a slope of 0.29, and the judgments in the matrix's first column grow as the 0.32 power of sucrose concentration. The functions derived from trials on which one member of a pair had a level of 'zero concentration' resemble, therefore, the function given by the marginal means, as indeed they should if a subtractive model applies. Again, the fits to the power approximations are quite (though not fully) satisfactory; r^2s equal 0.913 for the row function and 0.945 for the column function.

The sweetness functions derived here on the basis of difference judgments do not approximate the prototypical scales for sweetness of sucrose (with exponents around unity) that come from simple magnitude judgments of intensity. The present exponents trail previous—often expansive—estimates of growth by almost an order of magnitude. In fact, they are smaller than even the most compressive values reported hitherto by a ratio of 3:1 or 2:1. Notable, too, is the fact that the present data were collected by having subjects sip the sucrose solutions (at room temperature) and then spit them into a sink. The sip and spit method commonly produces higher values of exponent for a given tastant than alternative procedures of stimulus presentation (Meiselman, 1971; Bartoshuk and Cleveland, 1977). Hence, the disparately low value of exponent that, nonetheless, was obtained in this experiment, may tap an inherently different psychophysical relation for sweetness. This scale underlies the perception of a sweetness difference between two tastants.

The establishment of the metric structure for judgments of sweetness intervals is of special importance. We demonstrate that the overt difference judgments rest on an inherently non-interactive, linearly subtractive structure. Besides providing the explicit cognitive algebra used when people judge to what extent one stimulus tastes sweeter than another, the subtractive model confers validational support on the corresponding psychophysical function(s). The latter demonstrate that, when tastes are perceived in a comparative relation, they assume a distinctive set of psychological values. The underlying scale is markedly more compressive than the one that operates in the perception of discrete, unitary judgments of sweetness.

The same stimuli presented via equivalent methods, however, would yield the prototypical (i.e. significantly steeper) psychophysical scale for sweetness if judgments of sweetness (as magnitudes) are required. This is shown in the next experiment.

Experiment 2: Judgments of sweetness magnitudes and psychophysical functions for the sweetness of sucrose

To derive magnitude estimation functions in the traditional way, the five concentrations of sucrose from the previous experiment could be presented to the subjects, one at a time, for an intensity judgment. Yet, to make the contextual features resemble more closely the conditions of the previous experiment, a larger set of stimuli was generated in the following way. The five values of concentration were combined (i.e. added to) factorially with the same values to create a unique set of 15 sucrose solutions (including concentrations derived by adding each value to itself). That is, all values at and above the main diagonal of the 5 × 5 matrix were used. Note that since the set of five concentrations included a 'zero' (0 M sucrose) stimulus, the larger set contained the original values as a subset.

It should be clearly recognized that, despite the use of a factorial plan for the preparation of the stimuli, this experiment is of a unidimensional nature. The factorial scheme served merely as a logical tool for the experimenter to specify the levels of the pure unmixed sucrose solutions. Nevertheless, as will become apparent shortly, this set up allowed for some revealing comparisons with the outcome of Experiment 1.

Method

Stimuli. The set of stimuli comprised 15 sucrose solutions determined from all additive combinations of the five concentrations used in Experiment 1. These concentrations—dissolved in deionized water—were presented at room temperature (~23°C) in cups containing ~10 ml of solution. Just before each sip, the subjects rinsed their mouths thoroughly with distilled water.

Procedure. Each subject participated in five experimental sessions, conducted on different days. In a given session, the subject judged two replicates of the stimulus array. Thus, each subject gave 10 judgments per stimulus in all. The order of presentation of the stimuli was irregular and was different for each subject.

The method was magnitude estimation. Subjects were instructed to assign to the first stimulus whatever number seemed most appropriate to represent its sweetness; then subjects were instructed to assign numbers, in proportion, to succeeding stimuli. If no sweetness was detected, the subjects were to assign the number 0. Subjects were told that they could use whole numbers, decimals and fractions as needed.

Subjects. Five young men and women (three and two, respectively, between 21 and 33 years) from the Bar-Ilan community participated. None had experience with judging taste, though two were familiar with the method of magnitude estimation.

Results and discussion

The magnitude estimates given to each stimulus were averaged across subjects for the entire set of sucrose concentrations. The psychophysical function conforms to a power transform characterized by an exponent of 0.63 (r^2 = 0.968). This exponent is notably greater than the corresponding value based on the matrix of responses in Experiment 1. Sweetness as a magnitude grows at a considerably faster rate with concentration than does the scale that surfaces in assessments of sweetness differences.

Perhaps an even better comparison with the results of the previous experiment is provided by examining the magnitude judgments given to the original set of five concentrations. Note that the full set of concentration values yields a rather skewed distribution and is characterized by a larger range; hence, even from a purely statistical point of view this comparison may prove superior. The log–log plot of the average data for the original (marginal) concentration levels is presented in Figure 3.

The fit to the power relation is excellent (r^2 = 0.999). The exponent is 0.78; again, the present magnitude scale for the sweetness of sucrose differs from the previously derived difference scale for the sweetness of sucrose.

Particularly revealing is the contrast between the scale depicted in Figure 3 and the scales derived on the basis of the same (marginal) concentrations in Experiment 1 (data from the first row and the first column of the response matrix in Experiment 1). Note that in both cases (i.e. subsets of trials) subjects were presented with identical stimulus values and faced seemingly similar judgmental tasks. In Experiment 1, the subject had

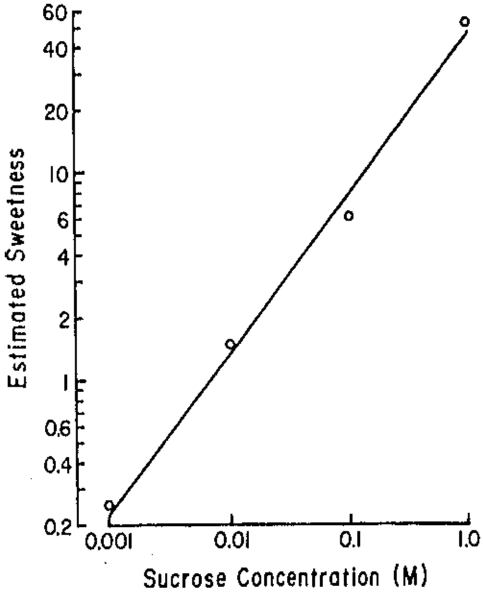

Fig. 3. Magnitude estimates of the sweetness of sucrose. These data are subsets of the data collected in Experiment 2.

to assess the difference in sweetness between a suprathreshold sucrose solution and a 'zero' solution (one containing 0 M sucrose and, hence, presumably lacking sweetness). In Experiment 2, the same non-zero sucrose solutions were presented, one at a time, for a magnitude of sweetness judgment. Given the stimulus dynamics, one could expect a common scale to underlie the growth of sweetness in both subsets of judgments. Clearly, this is not the case. Inherently different scales seem to underlie the two representations of sweetness; the exponents governing the two functions differ by a factor of at least 3:1.

That the two scales are non-linearly related can be seen in Figure 4, which plots one versus the other for the same values of input. The relation is curvilinear; the difference scale is a concave-downward function of the magnitude estimation scale.

It would appear, therefore, that one can speak of at least two different scales of sweetness. One scale underlies the sweetness of a given tastant; the other scale underlies the perception of a sweetness difference between two tastants. Each scale has its own componential structure: it is subtractive for the latter, partly additive for the former (though the rule of integration underlying sweetness magnitude could not be specified here, it has been approximated by others, e.g. McBride, 1986). However, the scales assign different relative psychological values to the very same stimulus levels. A sucrose solution of, say, 1 M has one representation when it is judged for sweetness, but has another representation when it is judged for sweetness *relative* to the sweetness of another

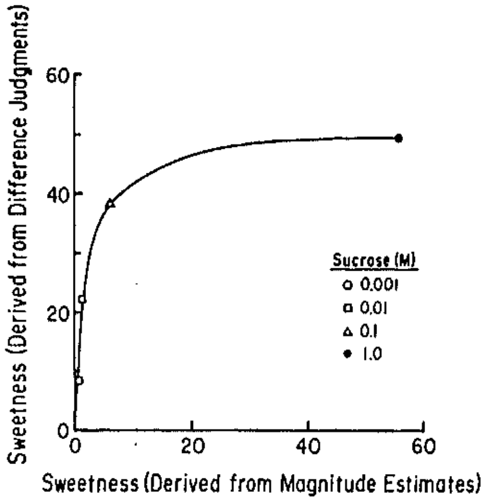

Fig. 4. Sweetness scale values derived on the basis of difference judgments (data from Experiment 1) plotted against the corresponding scale values based on magnitude estimates (data from Experiment 2).

sucrose stimulus of, say, 0.5 M. The comparative sweetness judgment is proportional only to the latter scale; that is, the difference in sweetness between 1 and 0.5 M does not equal their calculated difference on the magnitude of sweetness scale.

Discussion

The factorial design used in the derivation of sweetness differences (Experiment 1) enabled us to establish the underlying metric structure for the perception of sweetness dissimilarity. It comprised a veridical, fully subtractive, rule of integration. Unfortunately, the corresponding metric structure for sweetness magnitude (Experiment 2) cannot be derived on the basis of a single sugar tastant. Different concentrations of (at least) two sugars must be covaried within a factorial design to permit the determination of the respective integration rules for unitary judgments of sweetness. Exactly such designs were employed by McBride (1986) to uncover the integration rule(s) operative in the sweetness of binary mixtures of sucrose, fructose and glucose. Similar to the results obtained here, in all cases, mixture sweetness was found to approximate simple additivity at all but high levels of concentration. At high levels, a consistent subadditive pattern appeared.

There are obvious differences, though, between the perception of sweetness of binary mixtures and the perception of sweetness intervals for single sugar tastants. For one, the latter procedure does not, by definition, involve mixtures. Hence, for these, necessarily sequential, presentations chemical interaction between components as well as interaction at the receptor level (i.e. competition for receptor sites) are largely irrelevant. By contrast, peripheral interactions, though unlikely, cannot be entirely ruled out for binary mixtures of sugars. Second, judgments of sweetness-differences in the present study were evidently analytic. The combination of components (onto a dissimilarity judgment) was discretionary, coming under cognitive control. Integration was optional, not automatic, for it was induced by directing the subjects to compare sweetnesses. For unitary judgments of the sweetness of mixtures, on the other hand, combination of components is automatic, falling under the operation of the sensory system. Nonetheless, mixture perception may well be similarly analytic (e.g. Bartoshuk and Gent, 1985; but see Erikson and Covey, 1980).

Notwithstanding the different compositional and judgmental characteristics, the present results are consistent with McBride's (1986) conclusion that the perception of sweetness (induced by homogeneous components) rests on simple algebraic models, such as additivity or subtractability. Put in the context of some general problems in taste psychophysics, the present results further reinforce the usefulness, if not indispensability, of information integration analysis for both data reduction and theoretical interpretation. Using such analyses in tandem with traditional psychophysical methods yields diversified but compatible sets of results.

The main finding of different power function exponents for sweetness magnitude and sweetness difference can be accounted for by two different, indeed, mutually incompatible explanations. According to one interpretation, there is a single underlying scale, but various response biases alter the observed value of the exponent, especially for a magnitude estimation response [see Birnbaum and Elmasian (1977) and Birnbaum (1978) for a general exposition of this view, and McBride (1983c) for a somewhat similar argument for taste]. The second explanation, and, obviously, the one preferred here, argues for the existence of two separate scales, reflecting, respectively, the different operations defined by the tasks given to the subjects. The fact that both scales are associated with essentially linear metric (numeric) structures supports the dual scheme claim (i.e. it militates against a response-bias explanation). However, in fairness to the former interpretation, we again note that the association of an additive model with the present magnitude scale rests on across-studies comparisons—hence, on indirect evidence.

On this second view, then, different sweetness scales are associated with each compositional operation. One scale is approximated by results of experiments that use unbounded methods like magnitude estimation to quantify the subjective intensities of sugars (in particular, those of sucrose). The scale generated by these methods grows, roughly, as the 0.9 power of concentration. This does not mean that the results of any given experiment in which sweetness is scaled by magnitude estimation necessarily yields a close approximation to this value. Even a partial review (see Introduction) shows that the exponents of the power functions obtained in the different studies cover about a twofold range. Moreover, in addition to several stimulus factors (e.g. method of delivery, locus), there are well-known systematic effects (e.g. range, modulus) that affect the outcome. Still, typical values of the exponent relating sweetness judgments to concentration of sucrose fall largely in the range 0.7–1.2.

However, when a subtractive combinational process is evoked, it acts on scale values different from those underlying summation. This scale is proportional to about the 0.3 power of sucrose concentration, not the 0.9 power (and surely not the >1 values of power often obtained for magnitude judgments). Clearly, this second scale is markedly more compressive than the one underlying judgments of sweetness magnitudes. The relation between the two scales can be captured from Figure 4, whose negatively accelerated curve looks much like analogous functions that result when plotting category ratings or interval judgments against magnitude estimates (e.g. Stevens and Galanter, 1957; Stevens, 1971; Marks, 1974).

According to the present notion, a sugar solution has a sweetness based on an underlying magnitude scale. Two solutions have a sweetness relation, based on difference in values on another underlying (dis)similarity case. The main thing to keep in mind is that perception difference in sweetness or sweetness dissimilarity (i.e. an interval on the second scale) is not the same as the difference between the respective individual sweetnesses (an interval on the first scale).

As hinted earlier, the present multirepresentational scheme for sweetness should come as no surprise to students of perceptual processes in other sensory departments. The comprehensive review of Marks (1974) revealed a similar magnitude–difference duality for scales of loudness and brightness. Mark's (1979) formalization of the notion in his hierarchical theory of loudness led Algom and Marks (1984) and Popper *et al.* (1986) to show its viability for several domains of auditory processing. The demonstration of the possibility for dual scales of sensation in taste may pinpoint a powerful organizational principle underlying intensity processing in all sensory modalities (see Marks, 1978).

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