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SHORT COMMUNICATION

Theoretical Note: Tests of Synergy in Sweetener Mixtures

Harry T. Lawless

Department of Food Science, Stocking Hall, Cornell University, Ithaca, NY 14853, USA

Correspondence to be sent to: Harry Lawless, Department of Food Science, Stocking Hall, Cornell University, Ithaca, NY 14853, USA

Abstract

Some methods for examining the additivity of sweeteners and their synergy in mixtures depend upon setting component concentrations on the basis of sweetness equivalence, usually to a sucrose reference. These methods may under- or over-predict the sweetness of a mixture, leading to spurious claims of synergy or mixture suppression. This paper points out one problem with one such popular method, in that the method can lead to a conclusion that a substance would synergize with itself. To the extent that self-synergy is an illogical conclusion for a mixture comparison, such a method should be avoided in tests of synergy. The sweetness equivalence approach is contrasted with a simpler approach based on concentrations that does not lead to conclusions of self-synergy.

The claim of mixture synergy implies that a combination of two stimuli is perceived as more intense than a prediction of the resulting intensity based on the properties of the components of that mixture. This conclusion often has commercial importance, insofar as synergistic results may permit reductions in ingredients and thus cost savings in food formulations. However, from the psychophysical side, the demonstration of synergy is not straightforward, and depends upon the model that one adopts for making the critical comparison. Synergy is thus a controversial issue. One critical view of this phenomenon is that if you find synergy, you merely have failed to predict your result—in other words, you have a bad model (D.A. Stevens, personal communication).

Most researchers today agree that a model should take into account the psychophysical functions of the components. The psychophysical functions are usually non-linear, and may follow mathematical relationships between concentration and intensity that follow the power function of Stevens or the semi-hyperbolic equation of Beidler, depending in part on the scaling method employed and the range of stimuli that are examined. Several years ago, Bartoshuk and colleagues recognized the potential connection between empirical observations of mixture synergy (or suppression) and the curvature of the psychophysical function, proposing that substances with negatively accelerated psychophysical functions (power function exponents less than one) would tend to show suppression, while substances with accelerating dose–response curves (power function exponents greater than one) would synergize (Bartoshuk, 1975; Bartoshuk and Cleveland, 1977). Later, Frijters and co-workers demonstrated that with equiratio mixtures, the psychophysical function would usually produce an exponent between that of the components' individual functions, a kind of compromise model (Frijters and Oude Ophuis, 1983; De Graff and Frijters, 1987, 1988).

Frank *et al.* (1989) took this logic one step further, and asked whether a claim of synergy was valid, unless the mixture intensity was in fact higher than one would predict based upon consideration of the psychophysical functions of the components. Thus, the whole functions could be compared, rather than combinations tested against individual points. This approach had the appealing benefit of being able to test and sometimes demonstrate synergy in the response surface even though the individual component functions were negatively accelerated.

However, the test for individual concentrations remains a common phenomenon, since foods are formulated at specific ingredient optima, and the entire psychophysical function is rarely considered. A simple extension of the equiratio approach with the consideration of psychophysical functions is to compare mixtures to components based on a slice through the response surface, connecting points of equal intensity. Thus, a concentration of each component equisweet to 10% sucrose could be chosen, and the intensity of the 50/50 mixture (or 75/25 or 25/75, etc.) compared to the component intensities (or their average if they are not quite matched).

Now, the question remains of what is to form the mixture components. In the model shown in Figure 1, the slice

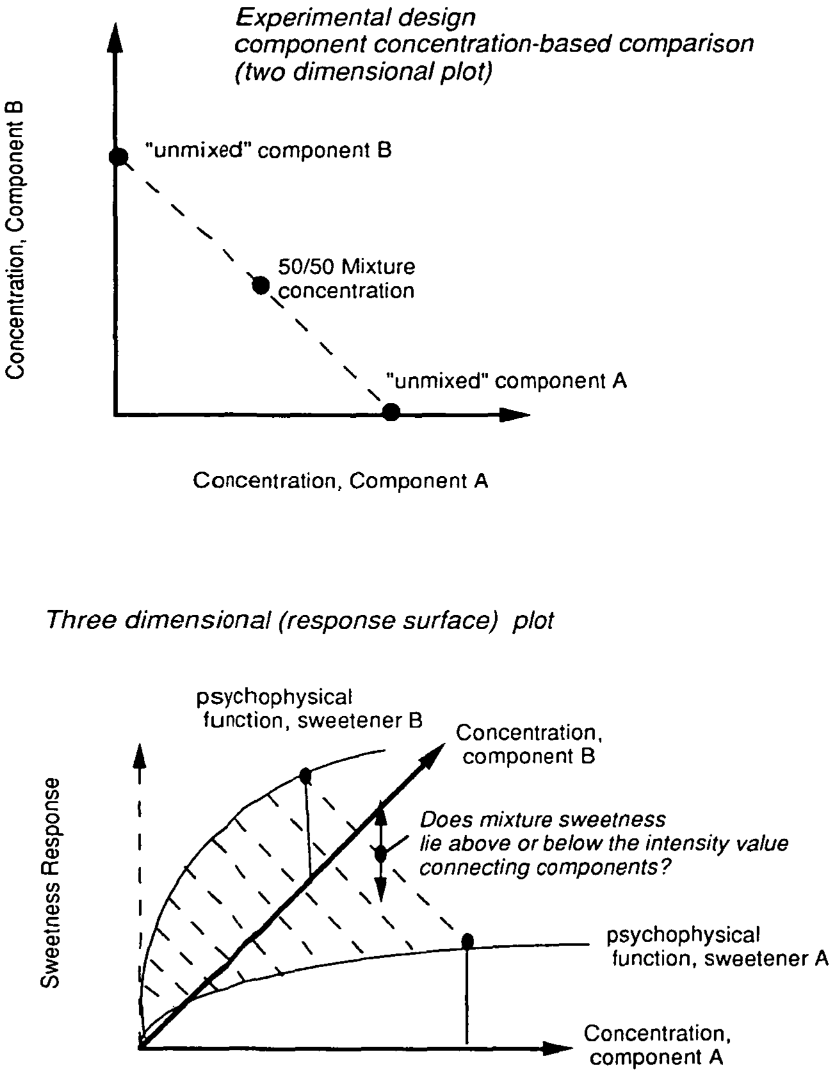
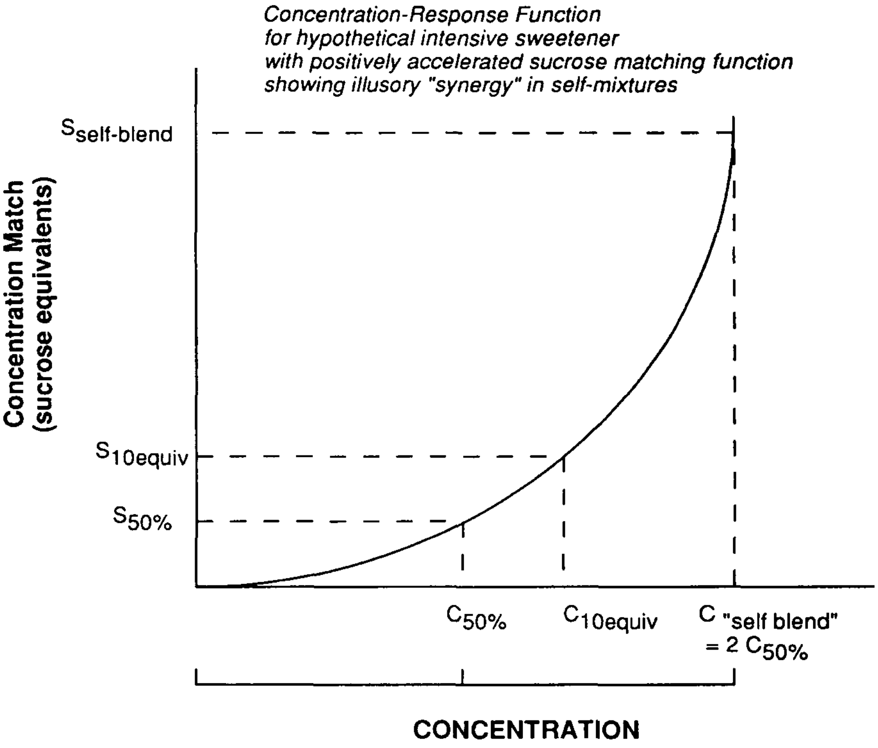


Figure 1 Component concentration-based test of sweetener synergy. Mixtures are constructed along a constant sum (100% total) concentration line (upper panel), generally connecting concentrations of the two components adjusted to be equally sweet. The lower panel shows the three-dimensional plot for a response surface. The test of synergy asks whether the obtained sweetness of the 50/50 mixture lies on a response surface above the sweetness levels of the unmixed components. In a more complete test, the psychophysical function on the response surface connecting all 50/50 mixtures can be compared to the psychophysical functions of the unmixed components.

through the response surface uses the 50% concentration points in constructing the mixtures. The mixture can readily be made by combining equal volumes of the parent (100% solutions). We will refer to this as the component concentration comparison. This is a common approach (e.g. Ayya and Lawless, 1992). It makes the sensible prediction that a substance added to itself will show simple additivity. However, the perceived intensities at the 50% concentration levels may not represent one-half the intensity of the 100% points, due to the curvature of the psychophysical function. They may also be different in sweetness from the 50% level of sucrose based on the equivalency match at the higher (100%) level.

Because perceived intensity of the 50% components is not considered in the concentration-based comparison, others have proposed that the comparison should be based on a 50% intensity level, rather than concentrations. The 50% concentration level might be considerably off from the 50% intensity level or from the sucrose equivalent match to one-half the unmixed component concentrations. Carr *et al.* (1993) and Schiffman *et al.* (1995), in several extensive studies of sweetener interactions, chose to work on the intensity basis in choosing the 50% level for a binary mixture. In this model, the comparison is based on the concentrations that produce an intensity match to sucrose at one-half the unmixed component concentration. For example, in order to test the additivity of two sweeteners at the 6% sucrose intensity level, the component concen-



$S_{10\text{equiv}}$ = concentration of sweetener equisweet to 10% sucrose

$S_{50\%}$ = concentration of sucrose at one-half, i.e. 5%

$C_{50\%}$ = Concentration matching $S_{50\%}$, to be used in "blend"

$C_{\text{"self blend"}}$ = twice $C_{50\%}$ (= $C_{50\%} + C_{50\%}$)

$S_{\text{"self blend"}}$ = sucrose equivalent in response to $C_{\text{"self blend"}}$

Since $S_{\text{"self blend"}} >> S_{10\text{equiv}}$, we conclude synergy.
But this is an illusion due to the nonlinear sweetness matching function.

Figure 2 The problem of illusory synergy arises when a substance has a non-linear matching function to sucrose, and the components concentrations are based on intensities relative to sucrose equivalence. The concentration of the component is shown on the abscissa, and the sucrose concentration match plotted on the ordinate. In the function shown here, the sweetener is positively accelerated relative to sucrose. Therefore, the concentration chosen as a 50% point in the blend (based on the y-axis) produces a much greater than predicted sucrose match when doubled as a self-mixture. Thus, anchoring to the sucrose equivalent intensity level would lead to a conclusion that the substance had synergized in a mixture with itself.

trations in the blend would be chosen such that they were matched to 3% sucrose. This model tends to anchor to the psychophysical function of sucrose, but does not choose component concentrations in the blend that might be too high or two low on their own psychophysical functions. It also has the attractive property of producing simple additivity when sucrose itself formed the components. Obviously, adding 3% sucrose to 3% sucrose will evoke the same response as 6% sucrose. This we will refer to as the intensity-anchored comparison.

Carr *et al.* (1993, p. 226) formalized this test of synergy with the following equation:

$$\%\ \text{synergy} = 100\ [\text{SE(blend)}/(\text{SE(100\% A)} + \text{SE(100\% B)}/2) - 1]$$

where SE(blend) is the sucrose equivalent concentration of the blend obtained from the experiment, SE(100% A) is the sucrose equivalent of unmixed component A and SE(100% B) is the sucrose equivalent of the unmixed component B. In this test, the components of the mixture, if equisweet, would be the concentrations of A and B producing sucrose equivalents equal to one-half the sucrose concentration matching 100% A and that matching 100% B, respectively (see Figure 2).

The problem with this comparison is that it can lead to a demonstration of synergy when a substance is added to itself. If we accept the premise that adding along a substance's own psychophysical function is, by definition, simple additivity, then the method of comparison must be flawed. So, by definition, a compound cannot synergize with itself (this is my premise) as mixing it with itself only follows its own psychophysical function. Here is the problem: if the substance has a non-linear concentration relationship in its isointensity plot against sucrose, the self-blend can move either too high or too low on its own psychophysical function and produce the appearance of synergy or suppression. The shape of the iso-intensity function against sucrose has not been taken into account, and any change in function shape from linearity can 'cause' illusory synergy or suppression.

The following example will help illustrate this point. Let us take 50/50 mixture blends as an example. The author's comparison is to find the concentration producing that level of sweetness which is equal to the sucrose concentration at 50% of the parent concentrations (parent concentration being equisweet to 10% w/v sucrose, a common benchmark). So the location of the concentration to be present in the blend requires finding the 50% sweetness level on the response axis and then interpolating the appropriate concentration, but when the concentration–response function is curved relative to sucrose and positively accelerated, the curvature in the response function causes the self-mixture blend 'to synergize' as the self-mixture concentration is higher than the parent concentration. If we accept the premise, then, that self-mixtures cannot synergize, this model leads to a false conclusion and therefore must be flawed. The opposite effect can be shown for psychophysical functions that are negatively accelerated, i.e. that they will show a false suppression effect in self-mixtures under this model.

In conclusion, a variety of models have been applied to test the additivity of mixtures. One approach is simply to add the component intensities, and compare that sum to the intensity of a mixture which contains both components at their original intensity level. However, this method of adding together mean ratings assumes that the scale used has interval properties and is unbounded. Frank *et al.* (1989) recognized that a bounded scale would show hypoadditivity at higher levels and thus a test of synergy must look beyond simple additivity of responses. With bounded scales such as category ratings or line-marking techniques, perceptual-based additivity is bound to fail as the top of the scale imposes an upper limit on response values. Also, as the search for a true interval scale remains elusive, most researchers avoid this simple test. Even unbounded scales such as magnitude estimation have their detractors who question whether such allegedly ratio scales have even interval properties (Anderson, 1974; Birnbaum, 1982; McBride, 1983).

So some researchers in the area of mixtures have turned to tests based on fractional concentrations, rather than addition of intensities. One common approach has been to choose equi-intense concentrations of two components, and then blend them in various percentages of those concentrations to produce a constant total of 100%. This component concentration approach has good functional value, as synergistic combinations (those producing higher intensity than the components alone) logically entail the possibility of reductions in concentrations to maintain equal intensity and thus a cost savings in product development. However, critics of this view point out that the non-linear nature of the dose–response curve may result in selection of component concentrations (e.g. 50% of each component's starting concentration) which are much greater than 50% of their parent concentration's intensities, so 'synergy' from such combinations should be in no way surprising. The alternative proposed is to choose the concentrations based on a 50% sucrose intensity match. However, as shown above, this can lead to the questionable outcome of a substance synergizing with itself, which many would not accept as a true case of mixture synergy. The same problem will occur if a simple 50% intensity level is chosen as the basis for the component concentrations in the blend. That is, the y-axis in Figure 2 can be changed to sweetness intensity (rather than the sucrose match) and produce the same demonstration of apparent synergy in a self-blend when the psychophysical function is concave upward.

As previously demonstrated by Schiffman *et al.* (1995), the component concentration comparison and the intensity anchored comparison do not always produce the same results when tests of synergy are applied to binary sweetener mixtures. Claims of so-called taste enhancement may be possible to substantiate by the choice of a more or less conservative model, or one that is favored by the psychophysical intensity relationships of the components. It is incumbent upon researchers in the fields of taste and olfaction to question carefully what model and test was applied in any 'demonstration' of synergy, and whether the assumptions and implications of that model are in fact reasonable.

References

Anderson, N.H. (1974) *Algebraic models in perception*. In Carterette, E.C. and Friedman, M.P. (eds), Handbook of Perception. Academic Press, New York, Vol. 2, pp. 215–298.

Ayya, N. and **Lawless, H.T.** (1992) *Quantitative and qualitative evaluation of high-intensity sweeteners and sweetener mixtures*. Chem. Senses, 17, 245–259.

Bartoshuk, L.M. (1975) *Taste mixtures: is mixture suppression related to compression?* Physiol. Behav., 14, 642–649.

Bartoshuk, L.M. and **Cleveland, C.T.** (1977) *Mixtures of substances with similar tastes: a test of a psychophysical model of taste mixtures interactions*. Sens. Proc., 1, 177–186.

Birnbaum, M.H. (1982) *Problems with so-called 'direct' scaling*. In Kuznicki, J.T., Johnson, R.A. and Rutkiewic, A.F. (eds), Selected Sensory Methods: Problems and Approaches to Hedonics. American Society for Testing and Materials, Philadelphia, pp. 34–48.

Carr, B.T., Pecore, S.D., Gibes, K.M. and **Dubois, G.E.** (1993) *Sensory methods in sweetener evaluation*. In Ho, C.-T. and Manley, C.H. (eds), Flavor Measurement. Marcel Dekker, New York, pp. 219–237.

Frank, R.A., Mize, S.J.S. and **Carter, R.** (1989) *An assessment of binary mixtures interactions for nine sweeteners*. Chem. Senses, 14, 621–632.

De Graaf, C. and **Frijters, J.E.R.** (1987) *Sweetness intensity of a binary sugar mixture lies between intensities of its components, when each is tasted alone and at the same total molarity in the mixture*. Chem. Senses, 12, 113–129.

De Graaf, C. and **Frijters, J.E.R.** (1988) *Assessment of the taste interaction between two quantitatively similar-tasting substances: a comparison between comparison rules*. J. Exp. Psychol.: Hum. Percep. Perform., 14, 526–538.

Frijters, J.E.R. and **Oude Ophuis, P.A.M.** (1983) *The construction and prediction of psychophysical power functions for the sweetness of equiratio sugar mixtures*. Perception, 12, 753–767.

McBride, R.L. (1983) *A JND-scale/category scale convergence in taste*. Percep. Psychophys., 34, 77–83.

Schiffman, S.S., Booth, B.J., Carr, B.T., Losee, M.L., Sattely-Miller, E.A. and **Graham, B.G.** (1995) *Investigation of synergism in binary mixtures of sweeteners*. Bran Res. Bull., 38, 105–120.

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