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Synergism among Ternary Mixtures of Fourteen Sweeteners

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Abstract

The purpose of the present study was to determine the degree of synergism of sweet taste among ternary mixtures of 14 sweeteners. A trained panel evaluated ternary mixtures of 14 sweeteners varying in chemical structure and type. The ternary mixtures that were tested were limited to those in which the compounds comprising the mixture were synergistic in binary combinations, according to an earlier study. All sweeteners in the ternary mixtures were isointense with 2% sucrose, according to a previously developed formulae. Each self-mixture was also tested (e.g. 2% sucrose + 2% sucrose + 2% sucrose). The triad with the highest mean sweetness intensity rating was alitame–neohesperidin dihydrochalcone–rebaudioside-A (10.8). This represents an increase of 99.4% when compared with the average of the self-mixtures. While this is greater than the maximum of 74% increase found for binary mixtures, more dyadic combinations of sweeteners tested previously exhibited synergism than ternary combinations tested here. However, most ternary mixtures were synergistic (significantly greater than the average of the three self-mixtures) to some degree.

Introduction

Synergistic taste interactions occur for some sweetener combinations such that the total sweetness intensity of a mixture is greater than the theoretical sum of the intensities of the individual components (Bartoshuk, 1975; Bartoshuk and Cleveland, 1977; Frank *et al.*, 1989; Ayya and Lawless, 1992; Schiffman *et al.*, 1995; Birch, 1996, 1999; Hutteau *et al.*, 1998; Lawless, 1998). In a study of binary combinations of 14 sweeteners, two factors found to influence whether a mixture would exhibit synergy were: (i) the presence of a high potency sweetener in the mixture and (ii) the concentrations of the component sweeteners in the mixture. For some sweeteners, mixtures of two components at concentrations that were isosweet with 3% sucrose were more likely to exhibit synergy than mixtures of two components that were isosweet with 5% sucrose or 7% sucrose. For other sweeteners, the converse was true. Overall, the presence of a high potency sweetener in the binary mixture produced more synergistic effects than the presence of sugars (Schiffman *et al.*, 1995). In another study of binary mixtures of sweeteners, synergy was reported to be influenced by water structure and the nature of hydration of the sweetener molecules (Hutteau *et al.*, 1998).

The purpose of the present study was to evaluate ternary mixtures of the same sweeteners found to produce synergy in binary combinations by Schiffman *et al.* (Schiffman *et al.*, 1995). The goal was to determine if the blend of three sweeteners in a mixture provides a greater or lesser synergistic effect than the blend of two sweeteners.

Materials and methods

Subjects

A trained panel of 18 subjects, ten females and eight males, participated in the study. The maximum number of subjects participating in any given taste session was 18 and the minimum number was nine. All subjects were from either the Duke University or Durham, NC communities. Their mean age was 46 $\pm$ 15 years. All subjects were paid for their participation.

Stimuli

Fourteen sweeteners were tested in the study: three sugars (fructose, glucose, sucrose); two polyhydric alcohols (mannitol, sorbitol); two terpenoid glycosides (rebaudioside-A, stevioside); two dipeptide derivatives (alitame, aspartame); one sulfamate (sodium cyclamate); one protein (thaumatin); two *N*-sulfonylamides (acesulfame-K, sodium saccharin); and one dihydrochalcone (neohesperidin dihydrochalcone).

Procedure

Ternary mixtures of 14 sweeteners were tested with a trained panel. Sweeteners in every mixture were at concentrations determined to be isointense with 2% sucrose, according to formulae determined by DuBois *et al.* (DuBois *et al.*, 1991) (see Table 1). Not all ternary combinations of sweeteners were tested. The ternary mixtures that were tested were limited to those for which the three sweeteners in the mixture were synergistic in binary combinations according to an earlier study by Schiffman *et al.* (Schiffman *et al.*, 1995). Each self-mixture of all 14 sweeteners was also tested (e.g. 2% sucrose + 2% sucrose + 2% sucrose).

Prior to evaluating the mixtures, each trained panelist tasted six sweet taste references according to the method described by DuBois *et al.* (DuBois *et al.*, 1991): 2 sweet (2% sucrose), 5 sweet (5% sucrose), 7.5 sweet (7.5% sucrose), 10 sweet (10% sucrose), 12 sweet (12% sucrose) and 15 sweet (16% sucrose). These sucrose standards have been used previously in a variety of studies on sweeteners (Schiffman *et al.*, 1994, 1995; Portmann and Kilcast, 1996; Hutteau *et al.*, 1998). Panelists also tasted bitter references labeled 2.2 bitter (0.02% caffeine) and 4 bitter (0.03% caffeine), and sour references labeled 2.1 sour (0.01% citric acid) and 7.4 sour (0.08% citric acid). Bitter and sour references were based upon previous evaluations by the present panelists, as well as other trained panelists.

At any given taste session, subjects provided sweetness intensity ratings, as well as other flavor profile notes, for five ternary mixtures. The five mixtures tested on any given day were randomized in accordance with a random number table. Panelists received 15 ml of each mixture in 30 ml plastic medicine cups which were labeled with a random three-digit number. The order of presentation of the five samples chosen at any given taste session was randomized across panelists. After tasting all references and rinsing their mouths with deionized water, panelists would swirl the unknown samples around in their mouths before expectorating. Panelists would then perform a full flavor profile of the sample, including all tastes, aromatics and feeling factors. In doing a flavor profile, panelists would make a mark on a 15 cm line scale that was anchored at 0, 5, 10 and 15 cm, and would then measure the length of the mark with a ruler. These marks reflected the intensities perceived for each flavor note by the individual panelist. Subjects also indicated the time of onset of maximum sweetness intensity by circling either early, middle or late. Between evaluations of the five sweeteners on any given test day, panelists would rinse their mouths with deionized water and eat unsalted top crackers in order to eliminate lingering tastes in their mouths. Subjects refrained from smoking, eating or drinking anything but water for 30 min prior to each panel session.

Table 1 Concentrations of sweeteners tested [isointense with 2% sucrose (DuBois *et al.*, 1991)]

Sweetener	Abbreviation	Concentration, p.p.m. (M)
Acesulfame-K	ace	97.92 (4.87×10^{-4})
Alitame	ali	4.44 (1.34×10^{-5})
Aspartame	apm	80 (2.72×10^{-4})
Fructose	fru	15400 (8.55×10^{-2})
Glucose	glu	33700 (0.187)
Mannitol	man	36800 (0.202)
Na cyclamate	cyc	766.42 (3.81×10^{-3})
Na saccharin	sac	39.23 (1.91×10^{-4})
Neohesperidin dihydrochalcone	neo	13.59 (2.22×10^{-5})
Rebaudioside-A	reb	50 (5.18×10^{-5})
Sorbitol	sor	51400 (0.282)
Stevioside	ste	103.8 (1.29×10^{-4})
Sucrose	suc	20000 (5.84×10^{-2})
Thaumatin	tha	0.89 (4.05×10^{-8})

Results

Table 2 gives the least squares mean of each triad, as well as the associated 95% two-sided confidence interval. An analysis of variance (ANOVA) was conducted comparing the (least squares) mean of any given triad with the average of its three constituent sweetener self-mixtures. This method of determining synergism is discussed in an earlier paper (Schiffman *et al.*, 1995). Also included in Table 2 is the numerical difference in the two aforementioned means, which is under the column headed 'Synergy estimate' and the corresponding *P*-value of the *t*-test against '0' ('Synergy *P*-value'). For the self-mixtures, the synergy estimate and *P*-value columns are not applicable. Fifty-six of the 79 combinations containing three different sweeteners showed synergism. Of the 23 combinations that were not synergistic, 21 contained at least one bulk sweetener (e.g. fructose, glucose, mannitol, sorbitol, sucrose). Figures 1–14 show the least squares mean sweetness intensity ratings of each ternary combination containing acesulfame-K, alitame, aspartame, fructose, glucose, mannitol, Na cyclamate, Na saccharin, neohesperidin dihydrochalcone, rebaudioside-A, sorbitol, stevioside, sucrose and thaumatin, respectively. A dashed line is given to indicate a nominal response (i.e. an additive response).

Table 3 gives a comparison of the responses of the ternary mixtures in this study with the responses of the binary mixtures in a previous paper (Schiffman *et al.*, 1995). In addition to the least squares mean perceived sweetness of each triad tested, Table 3 also gives the mean responses of the associated self-mixtures and the percentage difference of the mean response of each triad from the average of the mean responses of its constituent self-mixtures. The mean responses for the self-mixtures were based on experimental measurements, because the dose–response curves for sweeteners are generally nonlinear (DuBois *et al.*, 1991). For comparison, Table 3 gives the average of the mean responses of the associated dyads [found in Schiffman *et al.* (1995)], the average of the mean responses of the constituent dyadic self-mixtures, as well as the percentage difference of the

Table 2 Results of analysis of variance

Triad	LS mean[a]	95% LCL[b]	95% UCL[b]	Synergy est.[c]	Synergy (*P*)[d]
ace–ace–ace	5.33	4.37	6.30	–	–
ace–apm–cyc	9.24	8.28	10.21	2.92	c
ace–apm–neo	9.49	8.52	10.46	3.70	c
ace–apm–sor	8.96	7.96	9.95	2.01	c
ace–apm–ste	9.87	8.78	10.97	3.80	c
ace–cyc–fru	9.82	8.87	10.76	3.16	c
ace–cyc–glu	8.71	7.61	9.80	1.72	b
ace–cyc–neo	8.76	7.77	9.76	2.06	c
ace–cyc–sor	10.10	9.18	11.02	2.23	c
ace–cyc–ste	9.93	8.96	10.90	2.95	c
ace–fru–neo	8.76	7.58	9.95	2.64	c
ace–fru–sor	8.74	7.80	9.68	1.46	b
ace–fru–ste	8.25	7.28	9.21	1.85	c
ace–glu–neo	8.06	7.11	9.00	1.61	b
ace–glu–sor	8.65	7.70	9.59	1.04	a
ace–glu–ste	7.85	6.79	8.90	1.12	a
ace–man–neo	7.25	6.30	8.19	1.15	a
ace–man–sor	8.16	7.16	9.15	0.90	NS
ace–man–ste	8.18	7.13	9.24	1.80	b
ace–neo–sor	8.78	7.78	9.77	1.45	b
ace–neo–ste	9.73	8.79	10.68	3.29	c
ali–ali–ali	4.40	3.43	5.37	–	–
ali–neo–reb	10.81	9.76	11.87	5.39	c
ali–neo–ste	9.83	8.86	10.80	3.69	c
apm–apm–apm	5.45	4.48	6.42	–	–
apm–cyc–neo	7.90	6.98	8.82	1.15	a
apm–cyc–reb	8.36	7.31	9.42	2.05	c
apm–cyc–sac	8.57	7.33	9.82	2.28	c
apm–cyc–sor	8.55	7.58	9.52	0.65	NS
apm–cyc–ste	9.52	8.52	10.51	2.50	c
apm–neo–reb	8.06	7.06	9.05	2.28	c
apm–neo–sac	8.24	7.25	9.24	2.49	c
apm–neo–sor	9.23	8.14	10.33	1.86	b
apm–neo–ste	9.09	8.10	10.09	2.60	c
apm–reb–sac	8.22	7.28	9.17	2.90	c
apm–sac–sor	8.49	7.31	9.68	1.58	a
apm–sac–ste	8.99	8.02	9.96	2.95	c
apm–sor–ste	8.78	7.81	9.74	1.13	a
cyc–cyc–cyc	8.19	7.22	9.16	–	–
cyc–fru–neo	7.97	7.00	8.94	0.89	NS
cyc–fru–sor	8.64	7.58	9.70	0.41	NS
cyc–fru–ste	8.48	7.24	9.73	1.13	NS
cyc–glu–neo	7.00	6.05	7.94	–0.40	NS
cyc–glu–sor	8.69	7.70	9.69	0.13	NS
cyc–glu–ste	8.34	7.38	9.31	0.66	NS
cyc–glu–suc	7.27	6.21	8.32	–0.26	NS
cyc–neo–reb	7.79	6.82	8.75	1.10	a
cyc–neo–sac	8.80	7.86	9.74	2.13	c
cyc–neo–sor	8.16	7.17	9.16	–0.12	NS
cyc–neo–ste	8.77	7.78	9.77	1.37	b
cyc–neo–suc	8.88	7.64	10.13	1.64	a
cyc–neo–tha	7.10	6.11	8.10	0.34	NS
cyc–reb–sac	8.62	7.56	9.67	2.38	c
cyc–reb–suc	8.51	7.45	9.57	1.70	b
cyc–sac–sor	8.91	7.99	9.84	1.09	a
cyc–sac–ste	9.30	8.24	10.35	2.35	c
cyc–sor–ste	9.83	8.90	10.75	1.27	a
cyc–sor–suc	9.78	8.69	10.87	1.38	a
cyc–ste–suc	9.30	8.20	10.39	1.77	b
cyc–ste–tha	7.76	6.81	8.70	0.71	NS
fru–fru–fru	6.45	5.48	7.41	–	–
fru–neo–ste	10.02	9.05	10.99	3.20	c
fru–sor–ste	7.98	6.80	9.17	0.00	NS
glu–glu–glu	7.43	6.46	8.40	–	–
glu–neo–sor	7.94	6.99	8.88	–0.09	NS
glu–neo–ste	9.04	8.08	10.01	1.90	c
glu–neo–suc	8.55	7.45	9.64	1.56	b
glu–sor–ste	8.13	7.20	9.05	–0.18	NS
glu–sor–suc	8.65	7.71	9.60	0.50	NS
glu–ste–suc	8.01	7.04	8.97	0.74	NS
man–man–man	6.38	5.42	7.35	–	–
man–neo–sac	7.43	6.49	8.38	1.37	b
man–neo–sor	8.02	7.05	8.99	0.34	NS
man–neo–ste	8.20	7.21	9.20	1.41	b
man–sac–sor	7.94	6.76	9.13	0.72	NS
man–sac–ste	7.98	7.01	8.95	1.63	b
man–sor–ste	8.10	7.10	9.09	0.14	NS
neo–neo–neo	6.59	5.67	7.51	–	–
neo–reb–sac	9.19	8.23	10.16	3.49	c
neo–reb–suc	8.75	7.78	9.72	2.47	c
neo–sac–sor	8.13	7.16	9.10	0.84	NS
neo–sac–ste	9.07	8.13	10.01	2.66	c
neo–sor–ste	9.42	8.45	10.39	1.39	b
neo–sor–suc	8.80	7.80	9.79	0.93	NS
neo–ste–suc	9.29	8.11	10.48	2.30	c
neo–ste–tha	9.83	8.89	10.78	3.32	c
reb–reb–reb	5.28	4.29	6.28	–	–
sac–sac–sac	5.23	4.26	6.19	–	–
sor–sor–sor	10.06	9.10	11.03	–	–
sor–ste–suc	8.73	7.48	9.97	0.58	NS
ste–ste–ste	7.42	6.45	8.39	–	–
suc–suc–suc	6.96	5.99	7.93	–	–
tha–tha–tha	5.53	4.47	6.59	–	–

[a]Least squares mean.

[b]LCL and UCL refer to the lower confidence limit and the upper confidence limit respectively.

[c]Synergy estimate = the difference between the ls mean of the mixture and the average of three ls means of the self-mixtures.

[d]a < 0.05; b < 0.01; c < 0.001; NS = not significant.

→

Figures 1–14 The least squares mean sweetness intensity ratings of every ternary combination tested containing acesulfame-K, alitame, aspartame, fructose, glucose, mannitol, Na cyclamate, Na saccharin, neohesperidin dihydrochalcone, rebaudioside-A, sorbitol, stevioside, sucrose and thaumatin, respectively. A dashed line is given to indicate a nominal response (i.e. an additive response).

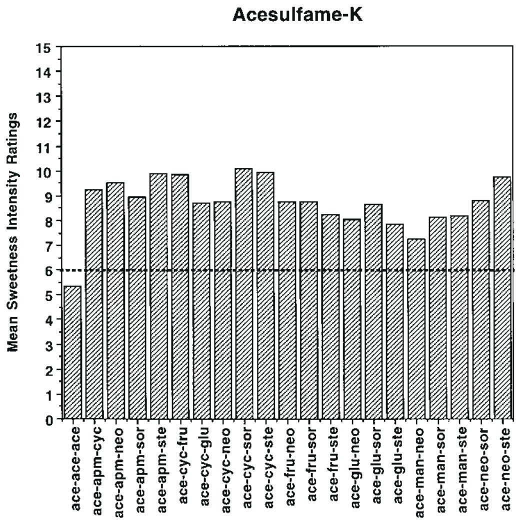


Figure 1

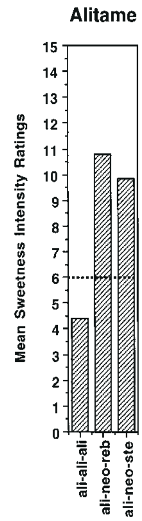


Figure 2

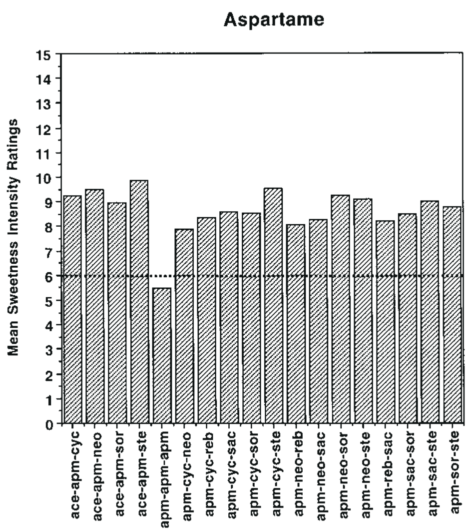
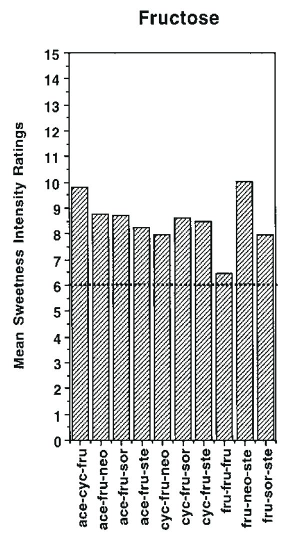


Figure 3



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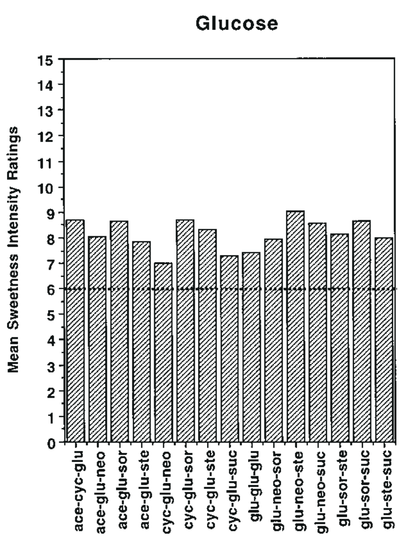
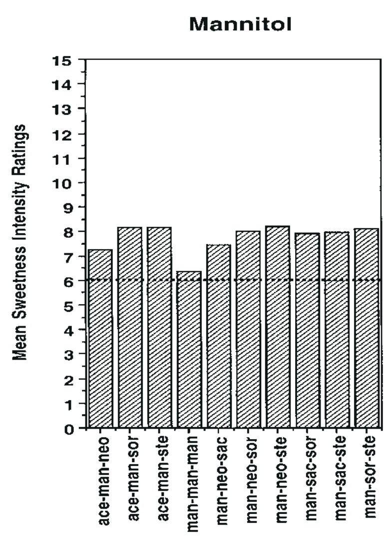


Figure 5



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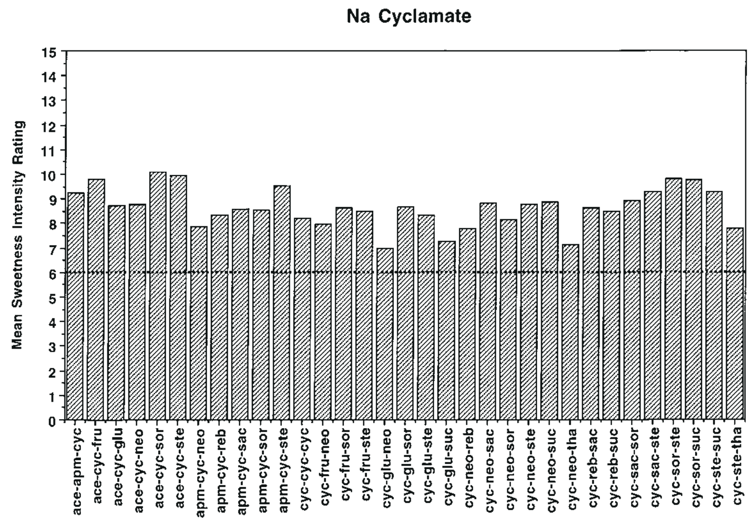

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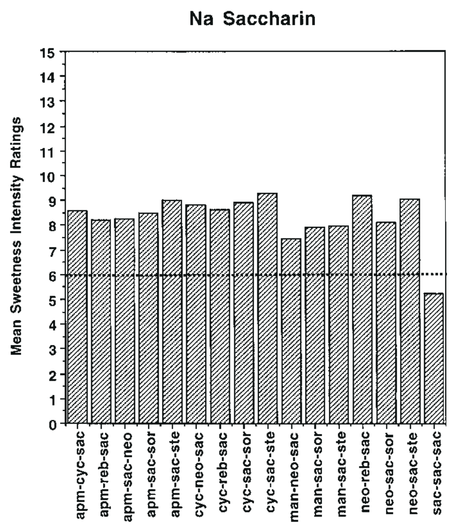

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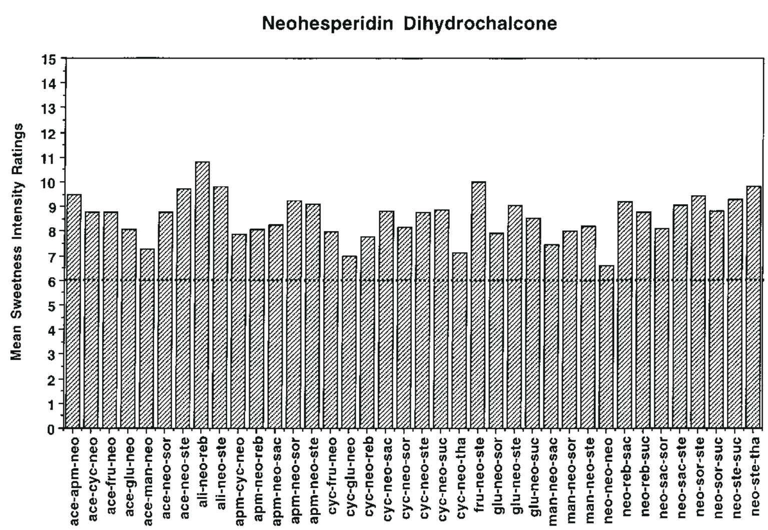

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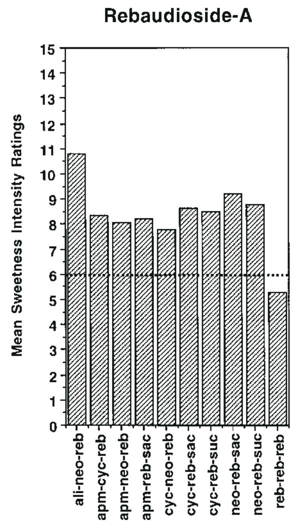
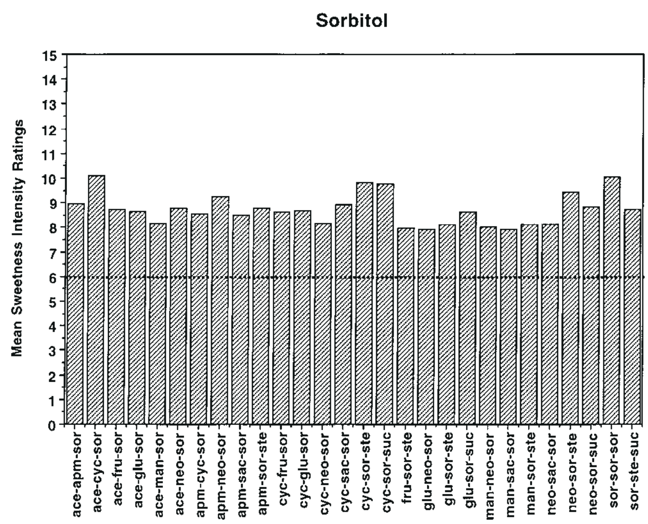


Figure 10



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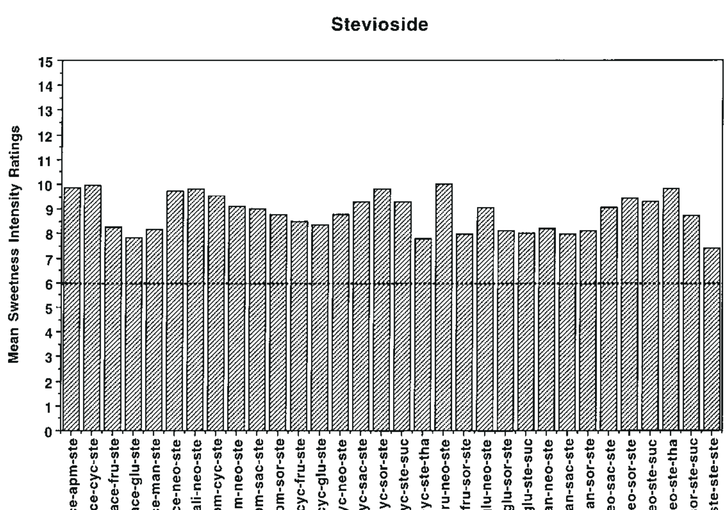

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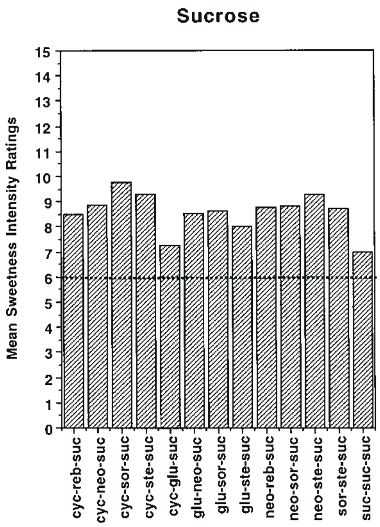

Figure 13

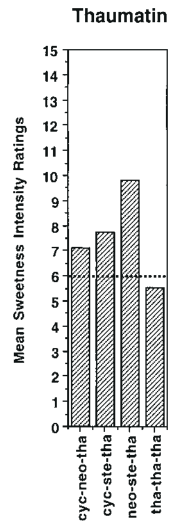

Figure 14

Table 3 Comparison of ternary and binary mixtures (percentage difference of the mean response of each triad from the average of the mean responses of its constituent self-mixtures versus the percentage difference of the average response of the associated dyads[a] from the average response of their self-mixtures)

Triad	Triadic mixtures			Dyadic mixtures		
	Mean perceived sweetness of each triad	Average of the mean responses of the triadic self-mixture	Percentage difference between triads and their self-mixtures (%)	Average of the mean responses of the associated dyads	Average of the mean responses of the dyadic self-mixtures	Percentage difference between dyads and their self-mixtures (%)
ace–ace–ace	5.33	–	–	–	–	–
ace–apm–cyc	9.24	6.32	46.2	7.86	5.02	56.6
ace–apm–neo	9.49	5.79	63.9	8.05	5.94	35.5
ace–apm–sor	8.96	6.95	28.9	7.70	5.96	29.2
ace–apm–ste	9.87	6.07	62.6	8.02	5.01	60.1
ace–cyc–fru	9.82	6.66	47.4	7.96	5.00	59.2
ace–cyc–glu	8.71	6.98	24.8	7.69	5.57	38.1
ace–cyc–neo	8.76	6.70	30.7	8.07	6.25	29.1
ace–cyc–sor	10.1	7.86	28.5	7.85	6.27	25.2
ace–cyc–ste	9.93	6.98	42.3	8.03	5.32	50.9
ace–fru–neo	8.76	6.12	43.1	8.10	5.92	36.8
ace–fru–sor	8.74	7.28	20.1	7.50	5.94	26.3
ace–fru–ste	8.25	6.40	28.9	7.49	4.99	50.1
ace–glu–neo	8.06	6.45	25.0	8.12	6.49	25.1
ace–glu–sor	8.65	7.61	13.7	7.64	6.51	17.4
ace–glu–ste	7.85	6.73	16.6	7.83	5.56	40.8
ace–man–neo	7.25	6.10	18.9	7.62	6.19	23.1
ace–man–sor	8.16	7.26	12.4	7.34	6.20	18.4
ace–man–ste	8.18	6.38	28.2	7.32	5.26	39.2
ace–neo–sor	8.78	7.33	19.8	8.40	7.19	16.8
ace–neo–ste	9.73	6.45	50.9	8.46	6.24	35.6
ali–ali–ali	4.40	–	–	–	–	–
ali–neo–reb	10.81	5.42	99.4	8.00	5.88	36.1
ali–neo–ste	9.83	6.14	60.1	8.02	6.20	29.4
apm–apm–apm	5.45	–	–	–	–	–
apm–cyc–neo	7.90	6.74	17.2	7.62	6.23	22.3
apm–cyc–reb	8.36	6.31	32.5	7.42	4.98	49.0
apm–cyc–sac	8.57	6.29	36.2	7.55	4.74	59.3

Table 3 Continued

apm–cyc–sor	8.55	7.90	8.2	7.38	6.25	18.1
apm–cyc–ste	9.52	7.02	35.6	7.90	5.30	49.1
apm–neo–reb	8.06	5.77	39.7	7.95	5.90	34.7
apm–neo–sor	9.23	7.37	25.2	7.90	7.17	10.2
apm–neo–ste	9.09	6.49	40.1	8.30	6.22	33.4
apm–reb–sac	8.22	5.32	54.5	7.66	4.40	74.1
apm–sac–neo	8.24	5.76	43.1	7.99	5.66	41.2
apm–sac–sor	8.49	6.91	22.9	7.49	5.68	31.9
apm–sac–ste	8.99	6.03	49.1	8.17	4.73	72.7
apm–sor–ste	8.78	7.64	14.9	7.74	6.24	24.0
cyc–cyc–cyc	8.19	–	–	–	–	–
cyc–fru–neo	7.97	7.08	12.6	8.20	6.21	32.0
cyc–fru–sor	8.64	8.23	5.0	7.71	6.23	23.8
cyc–fru–ste	8.48	7.35	15.4	7.89	5.28	49.4
cyc–glu–neo	7.00	7.40	–5.4	7.78	6.78	14.7
cyc–glu–sor	8.69	8.56	1.5	7.41	6.80	9.0
cyc–glu–ste	8.34	7.68	8.6	7.79	5.85	33.2
cyc–glu–suc	7.27	7.53	–3.5	7.41	5.92	25.2
cyc–neo–reb	7.79	6.69	16.4	7.82	6.20	26.1
cyc–neo–sac	8.80	6.67	31.9	7.81	5.97	30.8
cyc–neo–sor	8.16	8.28	–1.4	7.87	7.48	5.2
cyc–neo–ste	8.77	7.40	18.5	8.12	6.53	24.3
cyc–neo–suc	8.88	7.25	22.5	7.69	6.60	16.5
cyc–neo–tha	7.10	6.77	4.9	8.29	7.28	13.9
cyc–reb–sac	8.62	6.23	38.4	7.52	4.71	59.7
cyc–reb–suc	8.51	6.81	25.0	7.28	5.35	36.1
cyc–sac–sor	8.91	7.83	13.8	7.45	5.98	24.6
cyc–sac–ste	9.30	6.95	33.8	7.98	5.04	58.3
cyc–sor–ste	9.83	8.56	14.8	7.70	6.55	17.6
cyc–sor–suc	9.78	8.40	16.4	7.40	6.62	11.8
cyc–ste–suc	9.30	7.52	23.7	7.70	5.67	35.8
cyc–ste–tha	7.76	7.05	10.1	7.58	6.35	19.4
fru–fru–fru	6.45	–	–	–	–	–
fru–neo–ste	10.02	6.82	46.9	8.25	6.20	33.1
fru–sor–ste	7.98	7.98	0.0	7.44	6.22	19.6
glu–glu–glu	7.43	–	–	–	–	–
glu–neo–sor	7.94	8.03	–1.1	8.16	7.72	5.7
glu–neo–ste	9.04	7.15	26.4	8.44	6.77	24.7
glu–neo–suc	8.55	6.99	22.3	8.22	6.84	20.2
glu–sor–ste	8.13	8.30	–2.0	7.74	6.79	14.0
glu–sor–suc	8.65	8.15	6.1	7.66	6.86	11.7
glu–ste–suc	8.01	7.27	10.2	7.97	5.91	34.9
man–man–man	6.38	–	–	–	–	–
man–neo–sac	7.43	6.07	22.4	7.68	5.90	30.2
man–neo–sor	8.02	7.68	4.4	7.74	7.41	4.5
man–neo–ste	8.20	6.80	20.6	7.80	6.47	20.6
man–sac–sor	7.94	7.22	10.0	7.25	5.92	22.5
man–sac–ste	7.98	6.34	25.9	7.59	4.97	52.7
man–sor–ste	8.10	7.95	1.9	7.31	6.48	12.8
neo–neo–neo	6.59	–	–	–	–	–
neo–reb–sac	9.19	5.70	61.2	8.32	5.63	47.8
neo–reb–suc	8.75	6.28	39.3	8.21	6.27	30.9
neo–sac–sor	8.13	7.29	11.5	8.24	6.90	19.4
neo–sac–ste	9.07	6.41	41.5	8.66	5.96	45.3
neo–sor–ste	9.42	8.02	17.5	8.45	7.47	13.1
neo–sor–suc	8.80	7.87	11.8	8.32	7.54	10.3
neo–ste–suc	9.29	6.99	32.9	8.51	6.59	29.1
neo–ste–tha	9.83	6.51	51.0	8.92	7.27	22.7
reb–reb–reb	5.28	–	–	–	–	–
sac–sac–sac	5.23	–	–	–	–	–

Table 3 Continued

sor–sor–sor	10.06	–	–	–	–	–
sor–ste–suc	8.73	8.15	7.1	7.89	6.61	19.4
ste–ste–ste	7.42	–	–	–	–	–
suc–suc–suc	6.96	–	–	–	–	–
tha–tha–tha	5.53	–	–	–	–	–

[a](Schiffman *et al.*, 1995).

mean responses of the dyads from the average of their self-mixtures.

The following is an example of how the values in Table 3 were calculated. The triad 'ace–apm–sor' consists of acesulfame-K, aspartame and sorbitol. The first value in the corresponding row of Table 3—8.96—is the mean perceived sweetness of this triadic mixture. The second value—6.95—is the average of the mean perceived sweetness of the three associated self-mixtures. The acesulfame-K self-mixture is 5.33, for aspartame it is 5.45 and for sorbitol it is 10.06. The third value—28.9%—is the percentage difference between the self-mixtures' average and the mean response for the triad. This was calculated by subtracting 6.95 from 8.96 (2.01), then dividing this by 6.95, and multiplying the result by 100 to give the percentage. The fourth value—7.70—is the average of the mean responses of the associated dyads [from Schiffman *et al.* (1995)]. The mean response of the dyadic mixture ace–apm is 7.86, for ace–sor it is 8.01 and for apm–sor it is 7.22. The fifth value—5.96—is the average of the mean responses of the associated dyadic self-mixtures. The acesulfame-K dyadic self-mixture's mean response is 4.75, for aspartame it is 4.70 and for sorbitol it is 8.43. The sixth value—29.2%—is the percentage difference between the self-mixtures' average and the average of the mean responses for the dyadic mixtures. This was calculated by subtracting 5.96 from 7.70 (1.74), then dividing this by 5.96, and multiplying the result by 100 to give the percentage.

Results from other taste factors including temporal aspects, will be dealt with in a future paper.

Discussion

No clear trends to predict which triads are synergistic were found, although the presence of a bulk sweetener (e.g. fructose, glucose) tended to reduce synergism. This conclusion is consistent with previous reports on synergism and taste modulation of sweeteners (Portmann and Kilcast, 1996; Hutteau *et al.*, 1998; Birch, 1999). While the majority of sweetener triads tested in the present study were found to be synergistic, it appears that a greater degree of synergism may be reached using binary combinations of sweeteners. When comparing the percentage increase in sweetness intensity ratings of dyads with that of their constituent self-mixtures, and triads with that of their constituent self-mixtures, it was found that the percentage increase of the majority of the triads is about the same or lower than that of the dyads. In 53 cases, the dyads had a greater degree of synergy than their associated triads, and in only 25 cases was the reverse true. It is possible that the greatest benefit from the synergism of sweeteners is derived from the simple combination of two sweeteners and not multiple sweeteners.

Further research is required fully to understand the chemical and biochemical mechanisms that produce synergy among specific sweeteners. This will involve a more complete understanding of transduction of sweet taste at the receptor level, the state of sweeteners in aqueous solution and quantitative structure–activity studies using molecular graphics and molecular dynamics simulations (Birch, 1996).

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