



## Flavor-intensity perception: Effects of stimulus context

Lawrence E. Marks<sup>a,b,c,\*</sup>, Timothy G. Shepard<sup>a</sup>, Kelly Burger<sup>a</sup>, Emily M. Chakwin<sup>a</sup>

<sup>a</sup> John B. Pierce Laboratory, 290 Congress Avenue, New Haven, CT 06519, USA

<sup>b</sup> Division of Environmental Health Sciences, Yale School of Public Health, New Haven, CT 06520, USA

<sup>c</sup> Department of Psychology, Yale University, New Haven, CT 06510, USA

### ARTICLE INFO

#### Article history:

Received 11 May 2011

Received in revised form 30 August 2011

Accepted 31 August 2011

#### Keywords:

Flavor

Gustation

Olfaction

Psychophysics

Intensity perception

Mixture addition

Context effects

### ABSTRACT

Stimulus context affects judgments of intensity of both gustatory and olfactory flavors, and the contextual effects are modality-specific. Does context also exert separate effects on the gustatory and olfactory components of flavor mixtures? To answer this question, in each of 4 experiments, subjects rated the perceived intensity of 16 mixtures constructed by combining 4 concentrations of the gustatory flavorant sucrose with 4 concentrations of the retronasal olfactory flavorant citral. In 1 contextual condition of each experiment, concentrations of sucrose were relatively high and those of citral low; in the other condition, the relative concentrations of sucrose and citral reversed. There were 2 main results: First, consistent with earlier findings, in 5 of the 8 conditions, the ratings were consistent with linear addition of perceived sucrose and citral; departures from additivity appeared, however, in 3 conditions where the relative concentrations of citral were high. Second, changes in context produced contrast (adaptation-like changes) in perceived intensity: The contribution to perceived intensity of a given concentration of a flavorant was smaller when the contextual concentrations of that flavorant were high rather than low. A notable exception was the absence of contextual effects on the perceived intensity of near-threshold citral. These findings suggest that the contextual effects may arise separately in the gustatory and olfactory channels, prior to the integration of perceived flavor intensity.

© 2011 Elsevier Inc. All rights reserved.

### 1. Introduction

How does the overall perception of a flavorant depend on interactions among the components? Flavor stimuli typically contain large numbers of components, which can activate gustatory, somatosensory, and olfactory receptors. People are better able at detecting a weak flavorant in the mouth containing both gustatory and olfactory components compared to a flavorant containing just one [1,2]. Similarly, the perceived intensity of a flavorant containing both gustatory and olfactory components exceeds the perceived intensity of either component presented alone [3–6], and responses to gustatory-olfactory flavor mixtures are quicker than responses to either component [7]. The present study asks: How does stimulus context affect the perceived intensity of flavor mixtures that contain both gustatory and olfactory components?

Stimulus context affects perceptual judgments in virtually all sensory modalities, including the chemical senses. A given gustatory stimulus is often judged less intense in the context of higher concentrations of that stimulus, more intense in the context of lower ones — an example of *contrast* [8–10]. A series of studies showed pervasive contrast effects in taste, olfaction, and flavor perception, using a design in which the contextual concentrations of two different

stimuli shifted across sessions in a complementary fashion [11–13]. In a study of context effects in taste [11], for example, one condition presented subjects with low concentrations of sucrose and high concentrations of citric acid, while another condition presented high sucrose and low citric acid. Several concentrations of both sucrose and citric acid were common to the two conditions. This design holds the overall range of perceived taste intensity more or less constant across conditions, while measuring how the changes in context affect the judgments. The results showed stimulus-specific contrast: The common concentrations of sucrose (or citric acid) were judged less intense when the contextual concentrations of sucrose (citric acid) were high rather than low.

Contextual contrast is often attributed to relatively ‘late’ processes of comparison, judgment, and decision, for example, to a ‘relativity of judgment’ [14], consistent with evidence that contrast effects can arise in taste even when the contextual stimulus follows the test stimulus [9]. But recent research on contextual effects in several sensory systems, especially hearing, suggests that contrast can also arise, at least in part, relatively ‘early’ in perceptual processing [15]. In this regard, separate context effects appeared in judgments of the perceived intensity of a gustatory flavorant (sucrose) and an olfactory flavorant (vanillin in one experiment, orange in another) when trials presenting the two flavorants were interleaved within the same test session [13]. This outcome was surprising, given that, in each experiment, the gustatory and olfactory flavorants

\* Corresponding author at: John B. Pierce Laboratory, 290 Congress Avenue, New Haven, CT 06519, USA. Tel.: +1 203 401 6230; fax: +1 203 624 4950.

E-mail address: [marks@jbpierce.org](mailto:marks@jbpierce.org) (L.E. Marks).

were perceived to be qualitatively similar. Separate context effects did not arise with perceptually similar gustatory stimuli, such as sucrose and sucrose-NaCl mixtures [11].

If contrast reflects late processes of judgment, then similar-tasting stimuli should share contexts. The presence of gustatory-specific and olfactory-specific contrast suggests instead that context may exert its effects, at least in part, relatively early in flavor processing [13]. And if contextual effects arise relatively early in flavor processing, then context may also exert separate effects on the gustatory and olfactory components of flavor mixtures. The present experiments test the prediction that context acts separately on the gustatory and olfactory components of flavor mixtures. If (or to the extent that) gustatory and olfactory flavorants combine synthetically in perception (see Section 3.3), then evidence of distinct effects of context on the components would imply that context acts on the gustatory and olfactory flavor signals separately, before their integration.

## 2. Experiments

The 4 experiments reported here all used a common experimental method, which combined a contextual design [11–13] with a mixture-summation design [3–6]. Each experiment contained 2 contextual conditions: In condition A, 4 concentrations of sucrose (always the gustatory flavorant) were relatively high, while the 4 concentrations of citral (always the olfactory flavorant) were relatively low; in condition B, the concentrations of sucrose were lower and those of citral higher. The 16 stimuli presented within a given condition, A or B, were mixtures that represented all possible combinations of the 4 concentrations each of sucrose and citral. Table 1 lists the molar concentrations of the sucrose and citral in each condition of each of the 4 experiments.

Experiments 1 and 2 examined flavor-intensity summation using stimulus concentrations chosen to lie moderately above absolute threshold. Experiment 1 served as an initial test of how the concentrations of sucrose and citral used in the mixtures affect perceived flavor intensity; Experiment 2 reprised the paradigm of Experiment 1, but lowered the highest concentration of sucrose in order to increase the overlap of the sucrose concentrations in the two conditions. Experiments 3 and 4 used lower concentrations, nearer threshold.

**Table 1**  
Molar concentrations of sucrose and citral used the experiments.

Condition A		Condition B	
Sucrose	Citral	Sucrose	Citral
<i>Experiment 1</i>			
0.000	0.000	0.000	0.000
0.049	0.00020	0.021	0.00066
0.066	0.00066	0.031	0.00099
0.097	0.00099	0.049	0.0013
<i>Experiment 2</i>			
0.000	0.000	0.000	0.000
0.031	0.00033	0.021	0.00066
0.049	0.00066	0.031	0.00099
0.066	0.00099	0.049	0.0013
<i>Experiment 3</i>			
0.000	0.000	0.000	0.000
0.005	0.0000039	0.00158	0.0000013
0.0158	0.0000013	0.005	0.0000039
0.05	0.0000039	0.0158	0.000013
<i>Experiment 4</i>			
0.000	0.000	0.000	0.000
0.0158	0.0000013	0.0097	0.0000026
0.032	0.0000026	0.0158	0.0000053
0.050	0.0000053	0.032	0.000013

These experiments were motivated both by earlier findings indicating linear addition of the sensory effects of gustatory and olfactory flavorants at absolute threshold [2] as well as above threshold [3–6], and by a suggestion of Norman H. Anderson. Because the concentrations of the lowest non-zero concentrations of sucrose in Experiment 3 were poorly differentiated, Experiment 4 repeated Experiment 3 but with greater spread among the sucrose concentrations.

### 2.1. Materials and method

#### 2.1.1. Subjects

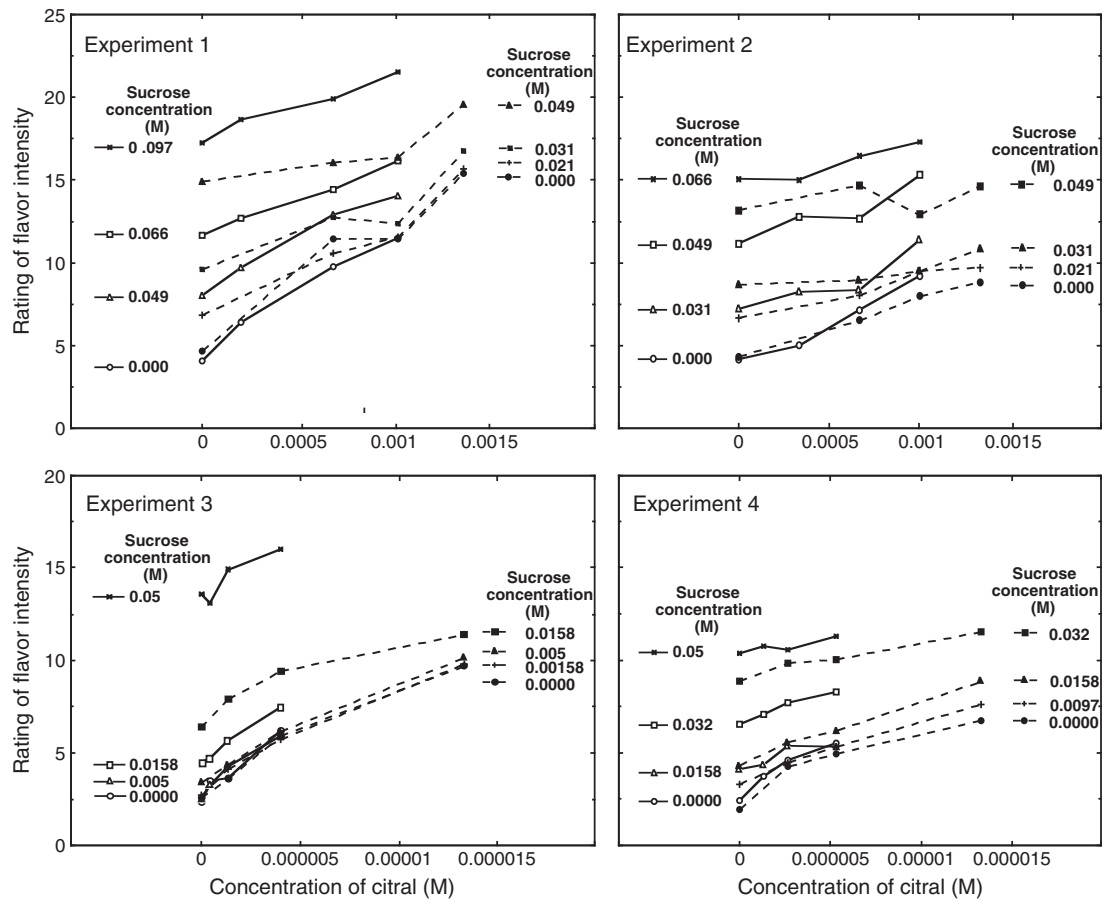
Each of the 4 experiments tested 16 subjects: Experiment 1 tested 5 men and 11 women, aged 18–32 years (mean  $26.3 \pm 3.5$  [sd]); Experiment 2 tested 4 men and 12 women, aged 18–32 (mean  $25.6 \pm 3.8$ ), 3 of whom had participated in Experiment 1. Experiment 3 tested 4 men and 12 women, aged 18 to 32 (mean  $24.4 \pm 4.0$ ), and Experiment 4 tested 2 men and 14 women, aged 18 to 33 (mean  $24.9 \pm 4.2$ ). None of the subjects in either Experiment 3 or Experiment 4 participated in any other experiment. All subjects were non-smokers who were paid to participate, and most were students at Yale University, the others being employees of Yale or affiliated institutions, or members of the New Haven community at large. None of the subjects reported any impairment to flavor perception due to allergies or head colds at the beginning of an experimental session. Subjects were instructed not to eat or drink anything except water for one hour prior to the experiment. The experiments were conducted in accord with the Declaration of Helsinki; all of the subjects gave informed consent in accord with protocols approved by institutional review committees at Yale University.

#### 2.1.2. Materials

The gustatory flavorant was sucrose (J.T. Baker, CAS# 57-50-1 C12H22O11) and the olfactory flavorant was citral (International Flavors and Fragrances, CAS# 5392-40-5, chemical characterization: 3,7-dimethyl-2,6 octadienal, mixture of cis- and trans-isomers). Each condition, A and B, of each experiment used 16 stimuli, created by combining each of 4 concentrations of sucrose, including zero, with each of 4 concentrations of citral, including zero, all dissolved in deionized water. Either 6 of the 16 stimuli (in Experiment 1) or 9 of the 16 (in Experiments 2–4) were common to the two conditions. All stimuli, as well as water rinses, were presented at room temperature, approximately 21 °C.

#### 2.1.3. Method

Each flavorant was sampled by a sip method. Subjects thoroughly rinsed their mouth with deionized water before each stimulus. On each trial, the subjects received 5 ml of solution in a 30 ml disposable cup. Subjects were instructed to sip the stimulus, hold it in their mouth for 3 s, and expectorate. Subjects rated flavor intensity on a modified labeled magnitude scale (LMS). The LMS, commonly used in human chemosensory research, is a graphic scale containing descriptive adjectives. The spacing of the descriptors on the numerical scale is based on magnitude estimates given to the descriptors themselves [16,17]. A brief training session with the LMS informed the subjects to apply a number between 0 (just below “barely detectable”) and 100 (“strongest imaginable”) to the perceived intensity of each stimulus. After the presentation of each stimulus, the subject reported the number aloud to the experimenter, who recorded the response. Although the LMS is typically presented to subjects as a line without numbers [16], earlier studies of sucrose-citral intensity perception [e.g., 3,4,6] used numerical magnitude-estimation scales; to increase the similarity of the present method to the magnitude-estimation method used in earlier studies, our modified LMS included the numerical scale: numbers from 0 to 100 in equal steps of 5 [see 16, Fig. 1, p. 687].



**Fig. 1.** Average normalized ratings of flavor intensity given to the 16 sucrose-citral mixtures in condition A (data points connected by solid lines) and the 16 mixtures in condition B (data points connected by dashed lines), plotted against the concentration of citral, separately for each concentration of sucrose in each condition. The concentrations of sucrose in condition A are indicated on the left and those in condition B on the right. Ratings obtained in each Experiment, 1–4, appear in a separate panel of the figure.

Subjects judged the stimuli in conditions A and B in different sessions, held on separate days. Order of conditions was counterbalanced across subjects, half of the subjects beginning with A and half with B. Each session contained 5 blocks of 16 trials (80 in all), each of the 16 possible stimuli presented once in each block in a random order that varied from block to block and subject to subject. Approximately 20 s separated successive trials.

#### 2.1.4. Data analysis

Responses from each subject to each stimulus in each condition of each experiment were first averaged arithmetically across the 5 replicates. The resulting averages were then normalized, as described below, before being averaged arithmetically across subjects and subjected to analysis of variance.

Analysis of variance (ANOVA) was used for statistical evaluation (SPSS, version 17.0). In the first analyses, separate repeated-measures ANOVAs were applied to the data obtained in conditions A and B of each experiment, each ANOVA using the 2 within-subjects variables of sucrose concentration and citral concentration. Besides anticipating reliable effects of the main variables, an additive model predicts that there should be no reliable interaction between sucrose and citral. Note, however, that the ability of ANOVA to detect a departure from additivity depends on the size of the deviations from additivity, the size of the interaction's error term, and the size of within-subject covariances (non-sphericity). Consequently, it is important to take precautions against artificially inflating the error term and/or non-sphericity.

ANOVA equates the overall means across subjects (removes main effects of subjects) by adding a constant to each subject's scores. It is also possible to equate the subject means by multiplying each subject's scores by a constant; multiplicative transformation is often appropriate with LMS ratings [e.g., 17]. Relative to additive transformation, multiplicative transformation may reduce error terms and/or departures from sphericity. For this reason, we computed ANOVAs both on the original data (additive transformation) and on data normalized by multiplicative transformation. Where non-sphericity was present in the final analyses, as assessed by the method of Huynh and Feldt [18], we report corrected values of *p*.

Multiplicative normalization was accomplished separately in each condition of each experiment as follows: First, we calculated, for each subject, *i*, the average rating,  $M_i$ , given to all 16 stimuli. Second, we calculated the grand average,  $M$ , across all 16 subjects, of the values of  $M_i$ . Finally, for each subject, we multiplied the mean rating to each of the 16 stimuli by that subject's ratio  $M_i/M$ . This procedure maintains, for each subject, all of the ratios among the original 16 means, while making each normalized subject mean identical to the grand mean  $M$ .

We then analyzed the effects of context in two ways. First, following the initial 2-way ANOVAs, we ran a repeated-measures 3-way ANOVA on the results of each experiment. Each 3-way ANOVA used only ratings given to the stimuli common to conditions A and B, testing the variables of condition, sucrose concentration, and citral concentration. Significant interactions of condition with sucrose and/or citral concentration indicate modality-specific effects of context, while significant main effects of condition indicate overall effects of

context on perceived flavor intensity. A main effect of condition could reflect a non-specific change in perceived intensity, but it also could reflect unequal, modality-specific effects of context on sucrose and citral.

The second analysis of contextual effects used standard functional-measurement procedures [19] to estimate the flavor intensity associated with each concentration of sucrose and citral in each condition of each experiment. To accomplish this, we calculated marginal means from each  $4 \times 4$  matrix of mean ratings. In a given condition, the average rating at a given concentration of sucrose across concentrations of citral gives the marginal mean for that level of sucrose, while the average rating at a given concentration of citral across concentrations of sucrose gives the marginal mean for that level of citral. Thus, using condition A as an example, the marginal means for each concentration,  $j$ , of sucrose,  $S$ , in condition A,  $MA_{S,j}$ , is defined by

$$MA_{S,i} = IA_{S,j} + MA_C \quad (1)$$

where  $IA_{S,i}$  is the perceived intensity of sucrose at concentration  $j$  and  $MA_C$  is the average perceived intensity of citral,  $C$ , across the 4 citral concentrations. By analogy, averaging the ratings across all 4 concentrations of sucrose, separately for each concentration,  $k$ , of citral, gives marginal means for citral in condition A,  $MA_{C,k}$

$$MA_{C,k} = IA_{C,k} + MA_S \quad (2)$$

where  $IA_{C,k}$  is the underlying perceived intensity of citral at concentration  $k$  and  $MA_S$  is the average perceived intensity of sucrose across all 4 sucrose concentrations. Finally, we define the perceptual values of  $IA_{S,j}$  and  $IA_{C,k}$  as zero when the concentrations of sucrose and citral are zero. By subtracting from each of the 4 values of  $MA_{S,j}$  the value when sucrose concentration is zero, and from each value of  $MA_{C,k}$  the value when citral concentration is zero, we derive the contribution to overall flavor intensity of each concentration of sucrose and citral, starting at zero when concentration is zero – assuming that the flavor system combines additively the perceived intensity of sucrose and citral. Analogous computations apply to measures in condition B.

## 2.2. Results

Results of the initial ANOVAs showed that, compared to original (non-normalized) ratings, across the 4 experiments, multiplicatively normalized ratings gave smaller ratios of error variance to total variance in 8 of 8 cases,  $t(1,7) = 5.66$ ,  $p = 0.0008$ , and gave greater sphericity in 21 of 24 cases,  $t(1,23) = 2.80$  ( $p = .01$ ). Consequently, all of the results reported below are based on multiplicatively normalized ratings.

### 2.2.1. Effect of concentration on flavor intensity

The arithmetic means of the normalized ratings of flavor intensity from Experiments 1–4 appear in the 4 panels of Fig. 1. As Fig. 1 shows, the ratings increase with increasing concentration of both sucrose and citral in both conditions of all 4 experiments, and these effects of concentration are robust: For sucrose, in conditions A and B, respectively,  $F(3,45) = 18.82$  and  $18.36$  (Experiment 1),  $45.29$  and  $9.51$  (Experiment 2),  $77.00$  and  $28.02$  (Experiment 3), and  $82.86$  and  $38.73$  (Experiment 4), all values of  $p \leq .001$ . For citral,  $F(3,45) = 12.73$  and  $11.30$  (both values of  $p = .001$ ) (Experiment 1),  $15.60$  and  $27.52$  (both values of  $p < .001$ ) (Experiment 2),  $17.91$  and  $25.09$  (both values of  $p < .001$ ) (Experiment 3), and  $13.12$  and  $55.03$  (both values of  $p < .001$ ) (Experiment 4).

### 2.2.2. Addition of flavor intensity

To visual inspection, the 4 functions obtained in condition A of each experiment appear reasonably parallel, a hallmark of linear

addition of perceived intensity. But the functions in condition B tend to converge at high levels of perceived intensity, suggesting possible departures from linear addition. With factorial designs, departures from parallelism (additivity) appear statistically as significant interactions between the main variables, here, between effects of sucrose concentration and citral concentration. The 2-way ANOVAs showed the sucrose  $\times$  citral interaction was not significant in condition A of all Experiments, 1–4:  $F(9,135) = 1.22$  ( $p = .31$ ),  $1.56$  ( $p = .17$ ),  $0.891$  ( $p = .48$ ), and  $1.43$  ( $p = .24$ ), respectively. The interaction in condition B, however, was significant in Experiment 1,  $F(9,135) = 4.50$  ( $p < .001$ ), approached significance in Experiment 2,  $F(9,135) = 2.29$  ( $p = .059$ ), and was significant in Experiments 3 and 4,  $F(9,135) = 2.20$  ( $p = .026$ ) and  $2.39$  ( $p = .023$ ), respectively. The significant interactions indicate some departures from linear addition in the B conditions.

### 2.2.3. Effects of stimulus context

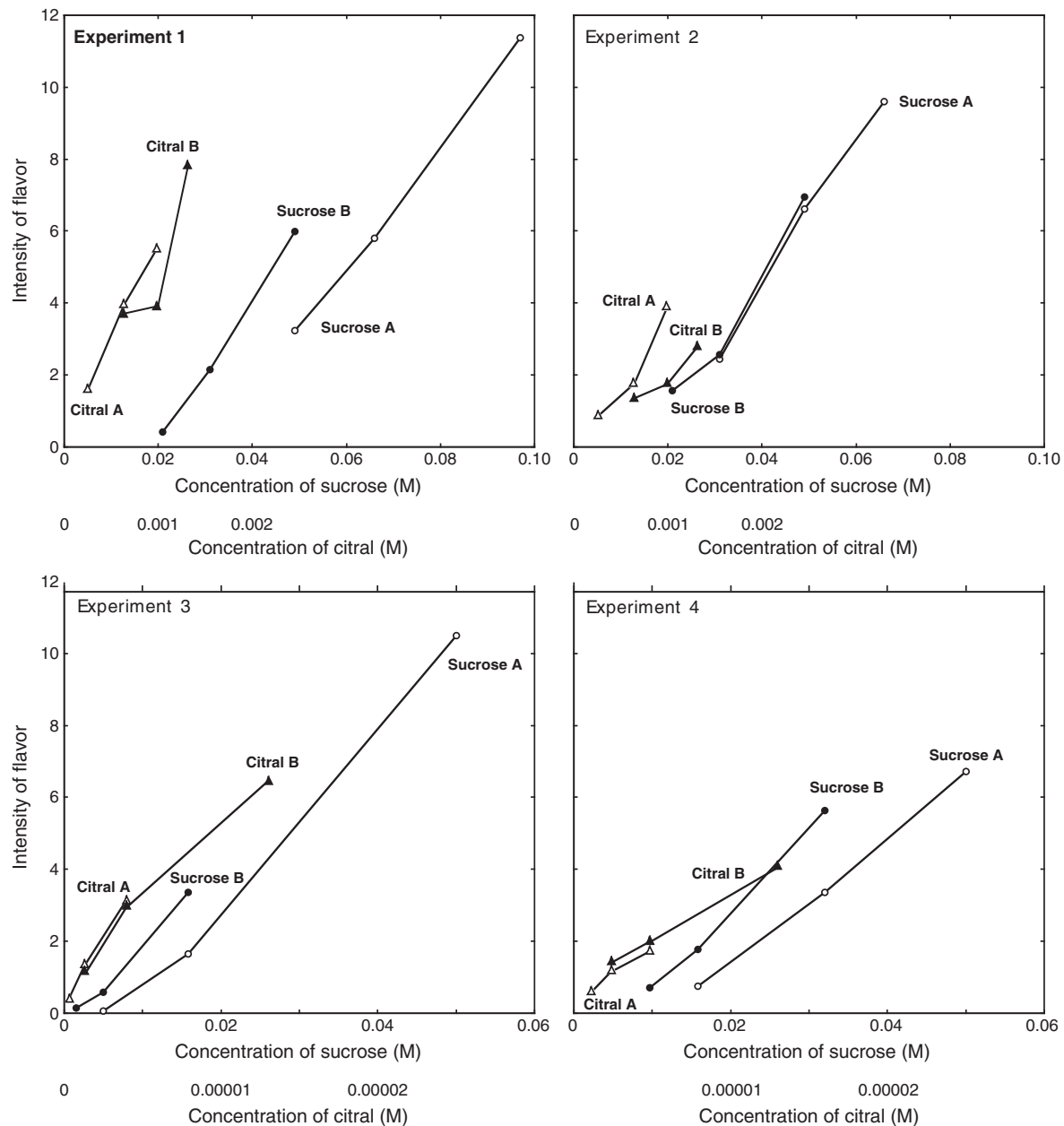
In each experiment, either 6 of the 16 stimuli (Experiment 1) or 9 of the 16 (Experiments 2–4) were common to the 2 conditions, A and B (see Table 1). Differences between conditions reflect effects of context, and the 3-way ANOVAs provide pertinent statistical evidence.

First, the average rating may be smaller in one condition than the other, leading to a main effect of contextual condition. A main effect of condition could reflect a non-specific, context-induced reduction of the perceived intensity of both sucrose and citral. Alternatively, it could mean that context affects sucrose more than citral or citral more than sucrose. The average rating was numerically smaller in condition A than B in 3 of the 4 experiments, the difference approaching significance in Experiment 1,  $F(1,15) = 3.40$  ( $p = .085$ ) and Experiment 3,  $F(2,30) = 3.37$  ( $p = .086$ ), and being significant in Experiment 4 ( $F(2,30) = 8.10$  ( $p = .012$ )). The difference was small and not significant in Experiment 2,  $F(2,30) = 0.003$  ( $p = .96$ ).

Second, the effects of context may be specific to sucrose and/or citral but depend on concentration. These effects reveal themselves as interactions of condition with sucrose, citral, and/or both. All 4 experiments revealed interactions, albeit variable ones. In Experiment 1, increasing sucrose concentration from zero increased the ratings to a much greater extent in condition B than A, mainly when citral concentration was zero, the interaction of condition  $\times$  sucrose  $\times$  citral being significant,  $F(2,30) = 6.34$  ( $p = .005$ ). Ratings were greater overall at the non-zero concentration of sucrose in condition B, the interaction of condition  $\times$  sucrose approaching significance,  $F(1,15) = 3.87$  ( $p = .068$ ). The condition  $\times$  citral interaction was not significant,  $F(2,30) = 2.40$  ( $p = .11$ ). In Experiment 2, however, the ratings increased more uniformly with citral concentration in condition A than B, the condition  $\times$  citral interaction being significant,  $F(2,30) = 12.35$  ( $p < .001$ ). This differential effect of condition and citral was somewhat stronger at the lower sucrose concentrations, the 3-way interaction of condition  $\times$  sucrose  $\times$  citral approaching significance  $F(4,60) = 2.18$  ( $p = .082$ ). The condition  $\times$  sucrose interaction was not significant,  $F(2,30) = .90$  ( $p = .42$ ).

The results of Experiments 3 and 4 were more cohesive: The ratings showed larger increases with sucrose concentration in condition B compared to A in both experiments, the condition  $\times$  sucrose interaction being significant in each:  $F(2,30) = 13.10$  ( $p < .001$ ) in Experiment 3 and  $8.95$  ( $p = .002$ ) in Experiment 4. Neither Experiment 3 nor 4 had a significant condition  $\times$  citral interaction,  $F(2,30) = 0.24$  ( $p = .79$ ) and  $.003$  ( $p = .996$ ), respectively, nor a significant 3-way interaction,  $F(4,60) = 0.45$  ( $p = .75$ ) and  $0.60$  ( $p = .57$ ), respectively.

The pattern of contextual effects becomes clearer in the results of the functional-measurement analyses. Fig. 2 shows the derived measures of flavor intensity of sucrose and citral as functions of flavorant concentration, separately for the two contextual conditions in each Experiment, 1–4. In general, the effects of context are consistent with modality-specific contrast: In Experiment 1,



**Fig. 2.** Perceived intensity of each flavorant, sucrose (circles) and citral (triangles), plotted as a function of stimulus concentration in each contextual condition, A (open symbols) and B (filled symbols). The values are derived from the marginal means of each matrix of ratings in Fig. 2, with perceived flavor intensity set to zero when stimulus concentration is zero. Ratings obtained in each Experiment, 1–4, appear in a separate panel of the figure.

for example, the perceived intensity of sucrose at the single common non-zero concentration is smaller in condition A than condition B (sucrose context greater in A than B), whereas the perceived intensity of citral at each of the two common non-zero concentrations is smaller in condition B (citral context greater in B). In Experiment 1, shifting the contextual concentrations of sucrose had a greater effect on the perceived intensity of sucrose than shifting the concentrations of citral had on the perceived intensity of citral.

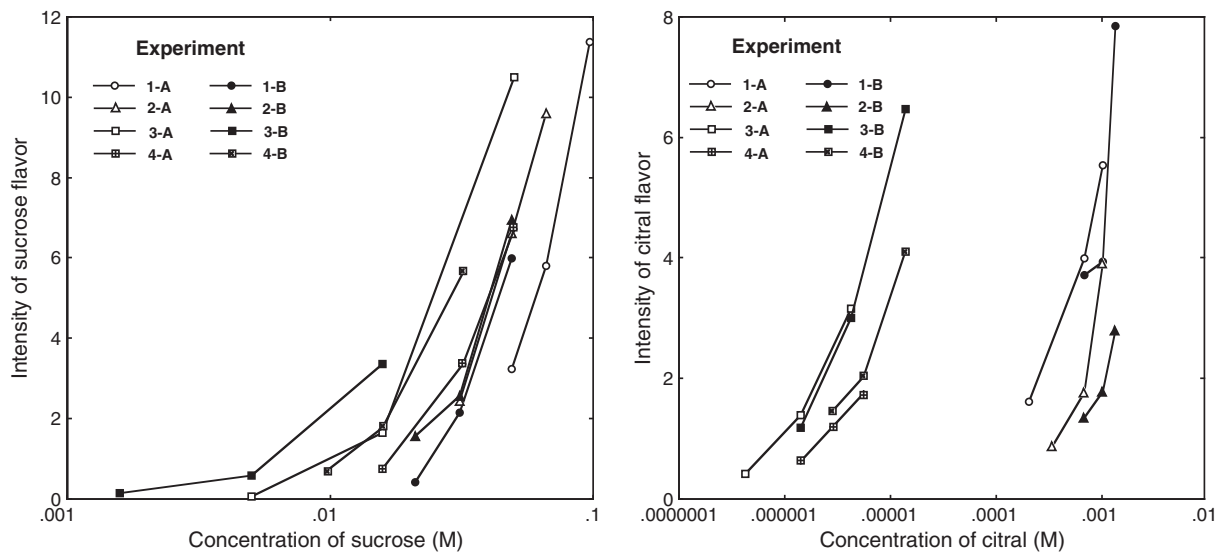
Relative to Experiment 1, Experiment 2 lowered the highest concentration of sucrose in condition A so that 2 sucrose concentrations were common to the 2 contextual conditions. Citral in Experiment 2 shows contrast similar to that of Experiment 1. Surprisingly, sucrose in Experiment 2 shows little effect of context. In Experiments 3 and 4, however, it is citral that shows little effect of context: a slight contrast effect Experiment 3 and a slight assimilation in Experiment 4. Sucrose, on the other hand shows clear and substantial contrast in

both Experiments 3 and 4, even though the concentrations of sucrose are similar to those used in Experiment 2. The absence of an effect of context on sucrose in Experiment 2 may be spurious.

#### 2.2.4. Effects of stimulus context across experiments

A striking feature of the results shown in Fig. 2, besides the effects of context within each experiment, is how little the perceived intensity of the citral component changed when the concentrations of citral were lowered substantially across experiments, from the moderate levels in Experiments 1 and 2 to the 100-fold lower levels in Experiments 3 and 4. Fig. 3 replots the data of Fig. 2 separately for sucrose and citral in order to show how context affected perceived intensity across all of the conditions of all 4 experiments. In Fig. 3, the scale of concentrations is logarithmic to accommodate the 2-order-of-magnitude difference between the concentrations of citral in Experiments 1 and 2 versus 3 and 4.





**Fig. 3.** Flavor intensity of sucrose (left panel) and citral (right panel), from all 4 experiments, replotted from Fig. 3. Each function is labeled by number plus letter to indicate the Experiment (1, 2, 3, or 4) and the condition (A or B).

Viewed across all 8 conditions, it is clear that stimulus context exerted strong effects on both flavorants. But the functions for sucrose and for citral show distinctly different patterns: As the range of concentrations of the sucrose component increases, the function relating perceived flavor intensity to sucrose concentration shifts downward (Fig. 3, left panel). Thus, the function for condition 3-B (lowest concentrations) lies above those for conditions 3-A and 4-B (higher concentrations), which in turn lie above those for conditions 1-B, 2-A, 2-B, and 4-B (still higher concentrations), which lie above the function for condition 1-A (highest concentrations). Despite some overlap among the functions, the general trend is clear and systematic.

The results for citral are more complicated, forming 2 distinct clusters. In Experiments 1 and 2, where the concentrations of citral were well above threshold, shifting context within each experiment produced a modest contrast effect in perceived citral intensity. But in Experiments 3 and 4, where all of the citral concentrations were low, shifting context had no systematic effect on perceived citral intensity. That is, in the vicinity of citral's absolute threshold, contextual effects on citral were essentially absent. Lowering the overall citral concentrations from the higher levels in Experiments 1 and 2 to the near-threshold levels in 3 and 4, however, had a dramatic effect: Citral contributed about as much to flavor intensity when its concentrations were barely above threshold as it did when its concentrations were more than 100-fold greater.

### 3. Discussion

The results are broadly in line with the two main expectations. First, the ratings of overall perceived intensity of the flavor mixtures show approximate additivity of the gustatory (sucrose) and olfactory (citral) components (see Section 3.1). Second, and more important, the contribution of each component to overall flavor intensity depends on the context of flavorant concentrations, consistent with a process of modality-specific contrast (see Section 3.2).

#### 3.1. Gustatory-olfactory flavor addition

Several previous studies gave results consistent with linear addition of gustatory and olfactory flavor intensity [3–6], although not all did [20]. Curiously, in 3 of the present experiments, the results obtained in condition B deviate significantly from strict linear addition. It may

be tempting to attribute the deviations to the greater concentrations of citral in condition B versus condition A in each experiment. But this cannot be the whole explanation, given that the concentrations of citral were even greater in condition A of Experiments 1 and 2 (where the results were consistent with additivity) than they were in condition B of both Experiments 3 and 4 (where the results showed significant departures from additivity).

#### 3.2. Effects of context on gustatory and olfactory flavor intensity

Regardless of whether the integration of gustatory and olfactory flavor intensity is always (or ever) fully additive, the present results show clearly that stimulus context can exert separate effects on the components. Context effects, when they occur, are consistent with a process of modality-specific contrast, in that the perceived intensity of sucrose (or citral) at a given concentration is weaker when the contextual concentrations of sucrose (citral) are high, stronger when the contextual concentrations are low. Note, however, that in the present design, when the context of sucrose is high, the context of citral is low, and vice versa. So, for example, a given concentration of sucrose is perceived as stronger when the contextual concentrations of citral are high rather than low. Might the contextual effects observed here represent cross-modality assimilation, rather than same-modality contrast?

Two lines of evidence imply that the contextual effects represent same-modality contrast. First, attempts to find assimilation effects in judgments of taste intensity have been unsuccessful [21], probably because assimilation dissipates quickly relative to the interstimulus intervals of 20–30 s typically used in taste and flavor research [21,22]. Second, when assimilation is found, in other sensory systems, it is not modality-specific [23]. In the present design, the concentrations of sucrose and citral in each condition are complementary (concentrations of one flavorant low, the other high), so the net effect of non-specific assimilation would be nil. Assimilation cannot easily explain, for example, the effects of context on sucrose but not on citral in Experiments 3 and 4.

The pattern of contextual effects observed here is broadly consistent with patterns previously reported when gustatory and olfactory flavorants were presented alone (that is, unmixed) [11–13], and with findings in hearing and vision [15,24–26]. These findings suggest that the contextual effects result from a stimulus-specific, adaptation-like process [24–27]: the more intense the contextual stimuli, the

greater the contrast (in hearing, the effect has come to be called ‘induced loudness reduction’ [27]). In hearing and vision, weak stimuli do not show these effects [25,26]. Strong contextual stimuli reduce the perceived intensity of weaker stimuli, but weak contextual stimuli have little or no effect on the perceived intensity of stronger ones.

The present results suggest a similar principle may apply to the perceived flavor intensity of sucrose: the greater the contextual concentrations of sucrose used in the mixtures, the smaller the perceived intensity contributed by a given sucrose concentration. There is no clear evidence here for a lower limit on the sucrose concentrations capable of producing contextual effects.

The effects of context on citral, however, are more complex and may reflect the concatenation of several processes. Consider first the effects of context within each experiment. In both Experiments 1 and 2, increasing the contextual concentrations of citral led to a reduction in perceived citral intensity – contrast, like that observed with sucrose. But the contrast effects in citral disappeared in Experiments 3 and 4, where the citral concentrations were much lower. This outcome resembles findings in hearing and vision [15,24–26] and is consistent with an adaptation-like contextual process in olfactory flavor perception that operates when the stimulus concentrations lie well above absolute threshold, but not when they lie near threshold.

Superimposed on the effect of citral context within experiments is the much greater effect across experiments. Lowering the citral concentrations across experiments more than 100-fold left the range of perceived citral intensities virtually unchanged. None of the present findings speaks to the mechanism responsible for the perceptual constancy of citral – for example, whether the mechanism is sensory-perceptual, involving changes in the underlying neural representations of flavor intensity, or decisional, involving changes in response criteria.

### 3.3. Synthetic versus analytic processes

Mix a tone of 1000 Hz with an equally loud band of noise and you hear a tone and noise. Mix a yellow light with an equally bright red and you see orange. Mix sucrose with equally strong citral and you perceive a flavor like lemonade. Are sucrose and citral perceptually separable, like tone and noise? Or do sucrose and citral blend into a unitary flavor having sweet and lemon ‘notes,’ much as the color orange has a phenomenal similarity to red and yellow? Auditory frequency perception and visual color perception often serve as prototypes for analytic and synthetic processing, respectively [28]. Flavor perception may fall somewhere between, as the components of a complex flavor can be difficult to separate fully [3,29–31].

As mentioned earlier, the synthetic versus analytic character of flavor processing is pertinent to identifying where stimulus-context effects arise. Is flavor perception the outcome of a synthetic process that precludes access to the original components? If so, then the results of the present experiments support the view that the context effects, specific to the gustatory and olfactory signals, arise prior to their synthesis. Alternatively, flavor perception may reflect a process of fusion rather than synthesis, fusion allowing access to the components [32]. If so, then the present contextual effects could arise after the gustatory and olfactory signals fuse.

To be analytic, processing requires both perceptual and decisional separability. That is, the judgment given to any one component must be independent of the perception and the judgment of other components [cf. 33]. But decisional separability often fails: Adding a strawberry or lemon flavorant to sucrose can enhance its sweetness [21,34]. Enhancement occurs largely when subjects are not provided an opportunity to judge, for instance, the strawberry flavor. Lacking the opportunity to judge strawberry, subjects may combine a portion of the strawberry flavor into the judgment of sweetness. Indeed,

enhancement often diminishes or disappears when subjects are given the opportunity to judge additional flavor attributes [35,36]. Further, olfactory enhancement of sweetness is observed when subjects are encouraged, by instructions, to adopt a “synthetic” strategy, but disappears when subjects are encouraged to adopt an “analytic” strategy [37]. Allowing subjects to judge the multiple attributes of a flavor may enable the subjects to respond more analytically, thereby increasing decisional separability.

Given the strong tendency to localize orally presented olfactory flavors in the mouth [3,29], and given the perceptual similarity or congruence of some gustatory and olfactory flavors [4,34,36], the perceptual boundary between, say, the sweet and fruit qualities of a flavor may be indistinct. Results of several studies imply that the response boundaries around a gustatory quality such as sweetness may expand or contract depending on the response scales available [35,36]. By this account, the enhancement observed in ratings of intensity reflects decisional interactions – although there may be conditions in which perceptual enhancement takes place as well. To the extent that gustatory and olfactory flavorants combine synthetically, that is, to the extent that, once the signals combine, the components are no longer perceptually and/or decisionally separable, the present findings suggest that stimulus context affects the processing of intensity in the gustatory and olfactory signals before they combine.

### 3.4. Conclusions

The perceived intensity of flavor mixtures of sucrose and citral depends not only on the concentrations of the components in the mixture being tasted, but also on the stimulus context. The contextual effects consist of *contrast* (adaptation-like effects): A given concentration of sucrose (or citral) can contribute less to overall perceived flavor intensity when the contextual concentrations of sucrose (or citral) are high rather than low. To the extent that the gustatory and olfactory components of mixtures combine synthetically and the mixtures are roughly additive, the presence of separate contextual effects on sucrose and citral is consistent with the hypothesis that shifts in stimulus context modulate the effective strength of each flavorant prior to the integration of the neural signals for gustatory and olfactory intensity. By this token, these contextual effects may be “local” rather than (or perhaps in addition to also being) “global.” That is, context may operate separately on the signals produced by each flavorant, before the signals combine, and not (just) on flavor intensity as a whole.

### Acknowledgments

This work was supported by grant R01 DC009021-03 from the National Institute on Deafness and Other Communication Disorders, NIH, USA, to LEM. We thank International Flavors and Fragrances for providing the citral, and we especially thank Norman H. Anderson for the suggestion that led us to Experiments 3 and 4.

### References

- [1] Delwiche JF, Heffelfinger AL. Cross-modal additivity of taste and smell. *J Sens Stud* 2005;20:512–25.
- [2] Marks LE, Elgart BZ, Burger K, Chakwin EM. Human flavor perception: application of information integration theory. *Teor Model* 2007;12:121–32.
- [3] Murphy C, Cain WS, Bartoshuk LM. Mutual action of taste and olfaction. *Sens Proc* 1977;1:204–11.
- [4] Murphy C, Cain WS. Taste and olfaction: independence vs. interaction. *Physiol Behav* 1980;24:601–5.
- [5] McBride RL. Integration psychophysics: the use of functional measurement in the study of mixtures. *Chem Senses* 1993;18:83–92.
- [6] Cerf-Ducastel B, Murphy C. Validation of a stimulation protocol suited to the investigation of odor-taste interactions with fMRI. *Physiol Behav* 2004;81:389–96.

- [7] Veldhuizen MG, Shepard TG, Wang M-F, Marks LE. Coactivation of gustatory and olfactory signals in flavor perception. *Chem Senses* 2010;35:121–33.
- [8] Schifferstein HN, Oudejans IM. Determinants of cumulative successive contrast in saltiness intensity judgments. *Percept Psychophys* 1996;5:713–24.
- [9] Lawless HT, Horne J, Spiers W. Contrast and range effects for category, magnitude and labeled magnitude scales in judgements of sweetness intensity. *Chem Senses* 2000;25:85–92.
- [10] Diamond J, Lawless HT. Context effects and reference standards with magnitude estimation and the labeled magnitude scale. *J Sens Stud* 2001;16:1–10.
- [11] Rankin KM, Marks LE. Differential context effects in taste perception. *Chem Senses* 1991;16:617–29.
- [12] Rankin KM, Marks LE. Effects of context on sweet and bitter tastes: unrelated to sensitivity to PROP (6-*n*-propylthiouracil). *Percept Psychophys* 1992;52:479–86.
- [13] Rankin KM, Marks LE. Chemosensory context effects: role of perceived similarity and neural commonality. *Chem Senses* 2000;25:747–59.
- [14] Stevens SS. Adaptation level vs. the relativity of judgment. *Am J Psychol* 1958;71:633–46.
- [15] Marks LE, Arieh Y. Differential effects of stimulus context in sensory processing. *Eur Rev Appl Psychol* 2006;56:213–21.
- [16] Green BG, Shaffer GS, Gilmore MM. Derivation and evaluation of a semantic scale of oral sensation magnitude with apparent ratio properties. *Chem Senses* 1993;18:683–702.
- [17] Green BG, Dalton P, Cowart B, Shaffer G, Rankin K, Higgins J. Evaluating the "Labeled Magnitude Scale" for measuring sensations of taste and smell. *Chem Senses* 1996;21:323–34.
- [18] Huynh H, Feldt LS. Estimation of the Box correction for degrees of freedom for sample data in randomized block and split designs. *J Educ Stat* 1976;1:69–82.
- [19] Anderson NH. *Methods of information integration theory*. New York: Academic Press; 1982.
- [20] Hornung DE, Enns MP. The contributions of smell and taste to overall intensity: a model. *Percept Psychophys* 1986;39:385–91.
- [21] Schifferstein HN, Verlegh PW. The role of congruency and pleasantness in odor-induced taste enhancement. *Acta Psych* 1996;94:97–105.
- [22] DeCarlo LT. Intertrial interval and sequential effects in magnitude scaling. *J Exp Psychol* 1992;18:1080–8.
- [23] Ward LM. Mixed-modality psychophysical scaling: inter- and intramodality sequential dependencies as a function of lag. *Percept Psychophys* 1985;38:512–22.
- [24] Marks LE. "Recalibrating" the auditory system: the perception of loudness. *J Exp Psychol Hum Percept Perform* 1994;20:382–96.
- [25] Arieh Y, Marks LE. Context effects in visual length perception: role of ocular, retinal, and spatial location. *Percept Psychophys* 2002;64:478–92.
- [26] Mapes-Riordan D, Yost WA. Loudness recalibration as a function of level. *J Acoust Soc Am* 1996;106:3506–11.
- [27] Scharf B, Buus S, Nieder B. Loudness enhancement: induced loudness reduction in disguise? *J Acoust Soc Am* 2002;112:807–10.
- [28] Erickson RP. Stimulus coding in topographic and non-topographic afferent modalities: on the significance of the activity of individual sensory neurons. *Psychol Rev* 1968;75:447–65.
- [29] Rozin P. 'Taste-smell confusions' and the duality of the olfactory sense. *Percept Psychophys* 1982;31:397–401.
- [30] Small DM, Prescott J. Odor/taste integration and the perception of flavor. *Exp Brain Res* 2005;166:345–57.
- [31] White TL, Prescott J. Chemosensory cross-modal Stroop effects: congruent odors facilitate taste identification. *Chem Senses* 2007;32:337–41.
- [32] McBurney DH. Taste, smell, and flavor terminology: taking the confusion out of fusion. In: Meiselman HL, Rivlin RS, editors. *Clinical Measurement of Taste and Smell*. New York: Macmillan; 1986. p. 117–25.
- [33] Ashby G, Townsend J. Varieties of perceptual independence. *Psychol Rev* 1986;93:154–79.
- [34] Frank RA, Byram J. Taste-smell interactions are tastant and odorant dependent. *Chem Senses* 1988;13:445–55.
- [35] Clark CC, Lawless HG. Limiting response alternatives in time-intensity scaling: an examination of the halo-dumping effect. *Chem Senses* 1994;19:583–94.
- [36] Frank RA, van der Klaauw NJ, Schifferstein HN. Both perceptual and conceptual factors influence taste-odor and taste-taste interactions. *Percept Psychophys* 1993;54:343–54.
- [37] Prescott J, Johnstone V, Francis J. Odor-taste interactions: effects of attentional strategies during exposure. *Chem Senses* 2006;29:331–40.