Chem. Senses 36: 581–587, 2011
doi:10.1093/chemse/bjr024
Advance Access publication March 25, 2011

Relationships among Taste Qualities Assessed with Response-Context Effects

Paul M. Wise[1] and Paul A.S. Breslin[1,2]

[1]Monell Chemical Senses Center, 3500 Market Street, Philadelphia, PA 19104-3308, USA and [2]Department of Nutritional Sciences, School of Environmental and Biological Sciences, Rutgers University, 96 Lipman Drive, New Brunswick, NJ, 08901-8525, USA

Correspondence to be sent to: Dr Paul M. Wise, Monell Chemical Senses Center, 3500 Market Street, Philadelphia, PA 19104-3308, USA. e-mail: pwise@monell.org

Accepted January 25, 2011

Abstract

Psychophysical judgments often depend on stimulus context. For example, sugar solutions are judged sweeter when a tasteless fruity aroma has been added. Response context also matters; adding a fruity aroma to sugar increases the rated sweetness when only sweetness is considered but not when fruitiness is judged as well. The interaction between stimulus context and response context has been explored more extensively in taste–odor mixtures than in taste–taste mixtures. To address this issue, subjects in the current study rated the sourness of citric acid mixed with quinine (bitter), sodium chloride (salty), and cyclamate (sweet) (stimulus context). In one condition, subjects rated sourness alone. In another, subjects rated both sourness and the other salient quality (bitterness, saltiness, or sweetness) (response context). Sourness ratings were most sensitive to response context for sour–salty mixtures (i.e., ratings of sourness alone exceeded ratings of sourness made simultaneously with saltiness) and least sensitive to context for the sour–sweet mixtures (sourness ratings made under the 2 conditions were essentially identical). Response-context effects for the sour–bitter mixture were nominally intermediate. The magnitudes of these context effects were related to judgments of qualitative similarity between citric acid and the other stimuli, consistent with prior findings. These types of context effects are relevant to the study of taste–taste mixture interactions and should provide insight into the perceptual similarities among the taste qualities.

Key words: gustatory, psychophysics, similarity

Introduction

Chemosensory psychophysicists often employ simple mixtures to help understand interactions among stimuli (Frank et al. 1993; Stevenson et al. 1999; Keast and Breslin 2003; Miyazawa et al. 2008). For example, many have asked how the sweetness of sucrose changes with the addition of a tasteless fruity odor or how the sourness of citric acid (CA) changes with added sucrose. Such experiments appear straightforward, but results depend, at least in part, on factors other than stimulus parameters.

For example, if subjects rate only the ''sweetness'' of a sucrose solution, ratings will increase after one adds a fruit aroma. However, if subjects rate both ''sweetness'' and ''fruitiness,'' then fruitiness ratings are positive and sweetness ratings are no different than if sucrose were presented alone (Clark and Lawless 1994). Thus, subjects may conflate multiple sensations in ratings of a target sensation. Clark and Lawless (Lawless and Clark 1992; Clark and Lawless 1994) coined the term ''halo-dumping'' to describe such conflation. The ''halo effect'' is a tendency for positive feelings to lead to more favorable ratings in general, for example, good service at a restaurant might lead to more favorable ratings of food quality. Reference to the halo effect implies a role of hedonic tone, an idea not consistent with subsequent work (Schifferstein and Verlegh 1996). Regardless, in this general framework, conflation of sensations in ratings could represent a kind of scaling bias.

Simple scaling bias alone does not account for several findings. For example, peanut odor fails to enhance rated sweetness, even when participants rate sweetness alone (Frank and Byram 1988; also see Frank et al. 1990; van der Klaauw and Frank 1996; Prescott et al. 2004; Labbe et al. 2007). Thus, sensations must be compatible in some way for conflation to occur. Furthermore, some mixture interactions are evident regardless of response alternatives, for example, the bitterness of quinine and the sweetness of sucrose are mutually suppressive, even when subjects rate multiple sensory attributes (Frank et al. 1993). Finally, instructions that focus subjects' attention on appropriate attributes of a taste–odor mixture can eliminate sweetness enhancement by an odor, even if subjects rate sweetness alone (van der Klaauw and Frank 1996).

A multistage model of mixture processing can accommodate the findings outlined above (van der Klaauw and Frank 1996; Frank 2003). Interactions that are insensitive to response alternatives (like mutual suppression of sweet and bitter) may arise at an early stage of processing. At later stages, neural signals give rise to subjective sensations (internal representations), which, in turn, result in an implicit response. At this stage, the concept of sweetness can expand to include portions of compatible sensations like fruitiness, but this flexibility has limits such that noncompatible sensations like "peanut" will not be included. In this framework, asking subjects to rate only one sensory attribute encourages them to attend to the sensation as a whole (a synthetic approach), expanding the boundary of the concept associated with the rated attribute. Whereas, multiple appropriate response alternatives encourage subjects to attend to component sensations (an analytic approach), narrowing conceptual boundaries.

What factors predict whether conflation will occur? Congruence, that is, the degree to which a combination of sensations is judged to be familiar, common, or harmonious seems like a natural candidate, but rated congruence is a poor predictor of conflation (Murphy and Cain 1980; Schifferstein and Verlegh 1996). Rather, qualitative similarity seems to be the best predictor (Frank et al. 1993; Schifferstein and Verlegh 1996). Indeed, the degree to which an odor will enhance the rated sweetness of a sucrose solution depends on the degree to which the tasteless odor itself is rated as "sweet smelling" (Stevenson et al. 1999; Valentin et al. 2006). Learning plays a role in perception of qualitative similarity because unfamiliar odors presented with a sucrose solution come to be perceived as sweet smelling, even after single pairing (Stevenson et al. 1995; Prescott and Murphy 2009; also see Labbe and Martin 2009). Acquisition of taste descriptors by odors is facilitated by a synthetic perceptual approach during learning (Prescott and Murphy 2009). Thus, attention plays a key role in the development of qualitative similarity between stimuli, as well as in one's performance in these psychophysical tasks.

Conflation of sensations in taste–taste mixtures has not been explored as extensively as in taste–odor mixtures. This issue has potential relevance for the literature on taste–taste interactions (reviewed in Keast and Breslin 2003). If some mixture effects are sensitive to response context (the number of appropriate response alternatives provided), then we can infer that such effects occur at relatively late stages of processing. In addition, if conflation of different taste qualities depends on similarity (as taste–odor conflation does), then conflation might serve as an indirect measure of perceptual similarity that can complement direct ratings of similarity (see General discussion).

The current experiments explored conflation of sourness with other basic taste sensations. In Experiment 1, participants rated the intensity of sourness for CA in binary mixtures with sodium chloride (salty), quinine hydrochloride (bitter), and sodium cyclamate (sweet). Under one condition, participants rated sourness alone. Under another condition, participants rated sourness with another quality (saltiness, bitterness, or sweetness, depending on the second component of the binary mixture). To explore possible drivers of sensory conflation, additional experiments determined the qualitative similarity (Experiment 2) and congruency (Experiment 3) between CA and the other 3 basic taste exemplars.

Experiment 1

Materials and methods

Taste materials

Filtered deionized water was used to dilute 4 chemicals: 1) cyclohexanesulfamic acid (Cycl) series: 6.67, 20, and 60 mM (sweet), 2) CA monohydrate series: 1.67, 5, and 15 mM (sour), 3) quinine hydrochloride (QHCl) series at 0.05, 0.25, and 0.60 mM (bitter), and 4) sodium chloride (NaCl) series: 130, 280, and 500 mM (salty). These concentrations were selected (based on preliminary studies) to provide wide (and comparable) ranges of perceived intensity. Single-compound solutions were used for screening (see Participants and screening). Three sets of 2-compound mixtures were used for testing: 1) each concentration of CA paired with each concentration of NaCl (9 sour–salty solutions), 2) CA paired with QHCl (9 sour–bitter solutions), and 3) CA paired with Cycl (9 sour–sweet solutions). All were presented in 10 mL aliquots, at room temperature.

Participants and screening

Sixteen healthy nonsmokers (7 female, aged 18–55) participated. Participants provided written informed consent using forms approved by the Office of Regulatory Affairs at the University of Pennsylvania before testing. Participants demonstrated adequate quality perception by correctly sorting taste solutions by quality, that is, sweet, sour, salty, and bitter. Participants demonstrated adequate intensity perception by rating the intensity of all 3 concentrations of each compound. Participants rated intensity by marking a 117-mm printed general labeled magnitude scales (Bartoshuk et al. 2003). The scale included the following descriptors: "Barely Detectable" (1.7 mm), "Weak" (7.9 mm), "Moderate" (21.6 mm), "Strong" (41.9 mm), "Very Strong" (62.2 mm), and "Strongest Imaginable Sensation of Any Kind" (117 mm). All intensity ratings increased with concentrations.

Procedure

Participants did not eat or drink (except water) for at least 45 minutes prior to each test session. Participants wore nose clips to pinch their nostrils shut to prevent odors during testing. To taste a sample, participants took the entire 10 mL aliquot into the mouth and held it for at least 5 s before making intensity ratings and finally expectorating. Between samples, participants rinsed thoroughly with deionized water. At least 1 min elapsed between the last rinsing and the next sample.

Over 12 sessions, participants rated 1) the sourness or both the sourness and saltiness of sour–salty solutions, 2) the sourness or both the sourness and bitterness of sour–bitter solutions, and 3) the sourness or both the sourness and sweetness of sour–sweet solutions. Half the participants were randomly assigned to make all ratings using single scales (one quality) first, whereas the other half made ratings using both qualities simultaneously first. Apart from this constraint, participants evaluated the stimuli in blocked random order.

Data analysis

We pooled the data from the 2 counterbalanced groups prior to further analysis; initial analyses revealed no significant differences when single qualities were rated first and when 2 qualities were rated first. We next calculated the response-context effect (RCE) ratio for each subject. In each RCE ratio, the numerator was the rated sourness for a particular mixture made when subjects rated sourness alone, and the denominator was rated sourness for the same mixture when subjects rated both sourness and another quality. Ratios were log-transformed to compare ratios below 1.0 with those above 1.0. Values of zero (log 1.0) indicate no difference between single and multiscale ratings (no effect of scale number and no conflation of other taste quality with sourness). Values greater than zero indicate some degree of conflation. Log-transformed ratios were analyzed by repeated measures analysis of variance (ANOVA). Post hoc contrasts (with Bonferroni corrections) were used to examine effects in more detail.

Results and discussion

Response-context effects

RCE ratios were submitted to a 3-way ANOVA: mixture (sour–salty, sour–bitter, sour–sweet) × CA concentration × additive (NaCl, QHCl, or Cycl) concentration. The effect of CA concentration reached significance, $F_{2,30} = 5.36$, $P = 0.01$, $\eta_p^2 = 0.26$. RCE ratios decreased as CA concentration increased. The effect of additive compound concentration also reached significance, $F_{2,30} = 10.58$, $P < 0.001$, $\eta_p^2 = 0.41$. RCEs increased with additive concentration. Thus, the relative concentration of the mixture components proved important (concentration effects will be discussed in more detail later in this subsection). The effect of mixture approached significance, $F_{2,30} = 3.02$, $P = 0.06$, $\eta_p^2 = 0.17$. RCE ratios were largest for the sour–salty mixtures and lowest for the sour–sweet mixtures.

The fact that ratios were somewhat variable across trials suggested that averaging ratings would be beneficial to the analyses. Ratings of sourness were averaged across the 9 mixtures in each stimulus matrix before ratios were computed (to generate a single scale number ratio for each participant for each of the mixture sets). A single factor repeated measures ANOVA showed that scale number ratios differed across the 3 stimulus matrixes, $F_{2,30} = 4.06$, $P < 0.03$, $\eta_p^2 = 0.21$ (Figure 1). Contrasts showed that ratios for sour–salty solutions exceeded those for sour–sweet solutions. Ratios for sour–bitter solutions appeared intermediate but did not differ significantly from the other 2 mixtures. These results suggest that sour tastes are more likely to be conflated with salty tastes than with sweet tastes and that sour tastes might be more likely to be conflated with bitter tastes than with sweet tastes.

To help illustrate the concentration effects outlined in the first paragraph of this subsection, Figure 2 shows ratings of sourness intensity (rather than RCE ratios) for all mixtures. Focusing on the first column of figures, for the lowest added concentration of NaCl, sourness rated alone was comparable to sourness rated along with saltiness. However, for higher concentrations of added NaCl, sourness ratings were higher when subjects rated sourness alone. A similar, but weaker, trend was apparent for the sour–bitter mixtures). This trend corresponds to the main effect of additive compound for

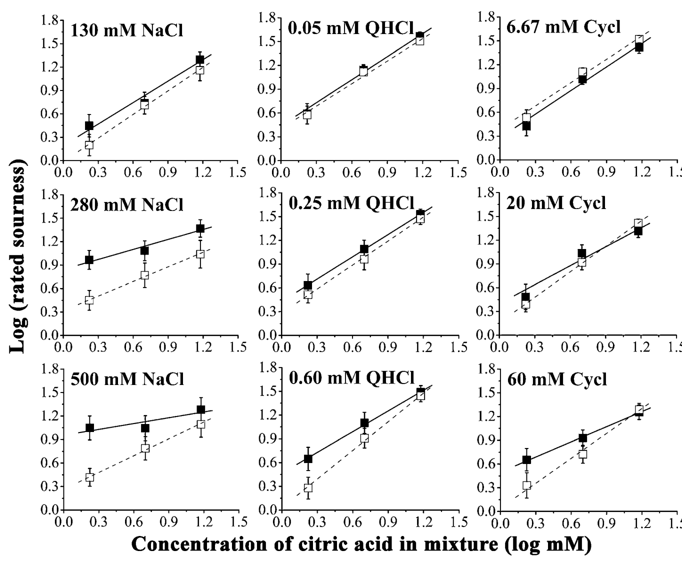

Figure 1 *y* Axis: log-rated sourness of CA for all mixtures. *x* Axis: concentration of (CA) in the mixtures (log mM). Filled symbols represent ratings of sourness alone. Open symbols represent ratings of sourness made simultaneously with ratings of the other salient quality (saltiness, bitterness, or sweetness, depending on what compound was mixed with CA). Error bars: ±standard error of the mean.

Figure 2 *y* Axis: average ratio of ratings made using only one quality scale per trial (e.g., rating only sourness) to ratings made using more than one quality scale (e.g., rating sourness and saltiness simultaneously each trial). The ratio is log-transformed such that 0.0 (dotted horizontal line) indicates no difference between the 2 rating conditions. *x* Axis: 3 different taste mixtures that all share sour ("Sr.") components but differ in which other quality is paired with sourness. Error bars: ±standard error of the mean.

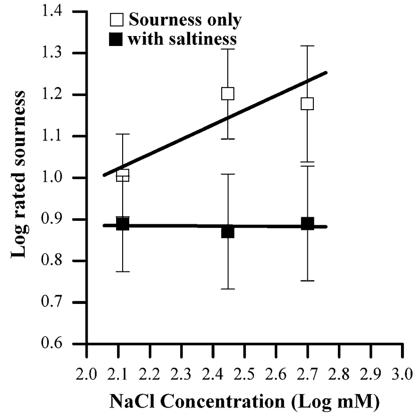

Figure 3 *y* Axis: log-rated sourness, averaged across CA concentration. *x* Axis: concentration of NaCl mixed with CA (log mM). Filled symbols represent ratings of sourness alone. Open symbols represent ratings of sourness made simultaneously with ratings of saltiness. Error bars: ±standard error of the mean.

RCE ratios (see above, beginning of this section). In addition, as most clearly seen for 500 mM added NaCl, the difference between rating conditions was less for higher concentrations of CA. This trend corresponds to the main effect of CA concentration for RCE ratios.

These concentration effects are consistent with the general framework of the mixture-processing model of van der Klaauw and Frank (1996). For example, we might expect the portion of NaCl sensation that is conflated with sourness to become stronger as the overall sensation of NaCl increases (main effect of the additive). Furthermore, for a given additive, we might expect a stronger impact on a stimulus that was only weakly sour than on a stimulus that was already strongly sour.

How RCEs might influence conclusions in mixture interaction studies

A separate analysis determined whether RCE differences among stimulus mixtures would affect conclusions regarding mixture interactions. To answer this, ratings of sourness (averaged across CA concentrations) for each mixture were submitted to a 2-way repeated measures ANOVA: scale condition (sourness ratings made alone vs. made simultaneously with another quality) × additive concentration (concentration of NaCl, QHCl, or Cycl, depending on the mixture). For the sour–salty mixtures, the effect of scaling condition reached significance, $F_{1,15} = 4.71$, $P < 0.05$, $\eta_p^2 = 0.24$. Consistent with the relatively large RCE ratios for sour–salty mixtures, sourness ratings were higher when participants rated sourness alone. In addition, the interaction between scale condition and NaCl concentration was significant, $F_{1,15} = 4.57$, $P < 0.02$, $\eta_p^2 = 0.23$. Rated sourness increased with NaCl concentration when participants rated sourness alone but not when participants also rated saltiness (Figure 3). Thus, in the case of sour–salty mixtures, a slight difference in methods led to qualitatively different conclusions regarding mixture interactions.

In contrast, for the sour–sweet mixtures, the effect of scaling condition and the interaction failed to reach significance. There was, however, a main effect of Cycl concentration, $F_{2,30} = 8.65$, $P < 0.01$, $\eta_p^2 = 0.37$. Consistent with past findings of suppression of sourness by sweetness (Keast and Breslin 2003), rated sourness decreased as Cycl concentration increased, regardless of scaling condition. Neither the main effects nor the interaction reached significance for the sour–bitter mixtures. These data provide an example of a mixture effect that seems dependent on response context (sour–salty mixtures) and another mixture that seems insensitive to response context (sour–sweet mixtures). Differences of this nature may prove important in the interpretation of interactions in taste–taste mixtures as they may imply interactions at different levels of perceptual processing (Frank et al. 1993).

Experiment 2

Purpose

To determine whether the above results were related to qualitative similarities among stimuli, we tested the qualities elicited by NaCl (salty), QHCl (bitter), and Cycl (sweet) for their resemblance the taste quality of CA. Participants directly ranked NaCl, QHCl, and NaCycl solutions with respect to their qualitative similarity to CA.

Materials and methods

Twenty-five healthy nonsmokers (14 female, aged 18–29), ranked the tastes of NaCl, QHCl, and Cycl with respect to their similarity to the taste of CA. During each trial, participants received 4 taste cups: a "standard," which contained CA, and 3 "comparisons" which contained the other 3 compounds (in random order). Participants ranked the 3 comparison cups with respect to their qualitative similarity to the standard. Participants ranked the stimuli at high, medium, and low concentrations (the same concentrations used in Experiment 1) twice, in separate sessions. Participants assigned the taste most similar to that of CA a rank of 1 and the taste least similar to CA a rank of 3. Ranks were averaged across the 2 replicate sessions for each participant. Averaged similarity ranks for QHCl, NaCl, and Cycl were submitted to a 3 × 3 (taste quality × concentration) repeated-measures ANOVA.

Results and discussion

The overall effect of taste quality on ratings of similarity was significant, $F_{2,48} = 5.04$, $P = 0.01$; $\eta_p^2 = 0.17$. Mean (±standard error of the mean) similarity rankings to the sour standard were 1.68 (0.08) for NaCl, 2.11 (0.12) for QHCl, and 2.33 (0.11) for Cycl. Post hoc analysis (Bonferroni corrected) revealed that salt solutions were more similar to acid solutions than were the cyclamate solutions but that the intermediate CA–quinine solutions did not differ from the other 2 sets of comparisons. The effect of concentration and the interaction of quality and concentration failed to reach significance ($P >$ 0.30). These results suggest that salty stimuli are most qualitatively similar to sour solutions, sweet solutions are least similar, and that bitter solutions may again be intermediate between the 2. These results directly reflect the pattern seen for RCE ratios in Experiment 1 observed simply by varying the rating context, which supports the idea that qualitative similarity is related to and may drive RCE effects with taste stimuli.

Note that we did not evaluate pleasantness. When subjects are asked to rate the similarity of distinct odors, for example, hedonic tone seems to account for a large portion of the variance, perhaps because pleasantness is a salient basis for comparison (reviewed in Wise et al. 2000). Thus, hedonic tone could potentially play a role in the correlation between RCE ratios and ratings of similarity in the current experiments. Whereas we cannot eliminate this possibility, we note that the degree of taste enhancement by odors is predicted by ratings of qualitative similarity but not by ratings of pleasantness (Schifferstein and Verlegh 1996).

Experiment 3

Purpose

In Experiment 3, participants rated how well various taste qualities "go together" and how frequently they experienced various combinations of tastes in foods or beverages. These assessments are similar to some ratings of congruency in previous work (Schifferstein and Verlegh 1996).

Materials and methods

Eighteen healthy nonsmokers (9 female, aged 18–36) marked 18 cm horizontal line scales in response to 6 questions. Questions 1–3 were worded as: "How frequently have you experienced sour and (salty/bitter/sweet) tastes together in foods and drinks?" The label "never" anchored the left end of scales at 0.0 cm and "very frequently" anchored the right at 18.0 cm. Questions 4–6 were worded as: "How harmonious do you think sour and (salty/bitter/sweet) tastes are (how well do they go together)?" "Not harmonious at all" and "very harmonious" anchored the scales. Participants responded to the 6 questions in random order. At the beginning of the session, participants tasted 5.0 mM CA as an exemplar of sourness, 280.0 mM NaCl as an exemplar of saltiness, 0.25 mM QHCl as an exemplar of bitterness, and 20.0 mM Cycl as an exemplar of sweetness.

Results and discussion

On average (±standard error), participants reported more frequent pairing of sour and sweet tastes (12.2 ± 0.8) (such as in lemonade) than of sour and salty (7.2 ± 1.2) (such as in many soups) or sour and bitter tastes (5.9 ± 1.1) (such as in grapefruit). Differences reached significance, $F_{2,32} = 14.06$, $P < 0.001$; $\eta_p^2 = 0.47$. Contrasts (Bonferroni corrected) revealed significant differences between sweet and salty pairings with sourness and between sweet and bitter pairings but not between salty and bitter pairings. Participants also reported greater harmony between sour and sweet (12.6 ± 1.2) than between sour and salty (7.1 ± 1.5) or sour and bitter (7.2 ± 1.3). Differences reached significance, $F_{2,32} = 6.34$, $P <$ 0.01; $\eta_p^2 = 0.28$. Contrasts revealed significant differences between the sweet and salty pairings with sour and between sweet and bitter pairings but not between salty and bitter pairings. That participants judged the sweet and sour taste qualities to "go together" more naturally and to be experienced together more frequently makes sense, given that the combination of these 2 taste stimuli is ubiquitous in common ripe fruits. Importantly, this pattern of results is qualitatively different from the magnitude of RCE ratios (Experiment 1) and judged qualitative similarity (Experiment 2). Thus, RCE ratios (the degree of conflation) correlate with qualitative similarity rather than congruency, a conclusion consistent with past results (Murphy and Cain 1980; Schifferstein and Verlegh 1996; Frank et al. 1993).

Of course, ratings of how frequently tastes have been experienced together depend on recall, which may not be entirely accurate. Regardless, the results are consistent with the conclusion that the degree of conflation is correlated with perceived similarity of stimuli.

General discussion

Experiment 1 revealed larger RCE ratios for sour–salty taste mixtures than for sour–sweet mixtures. Thus, under the conditions of Experiment 1, saltiness was most likely to be conflated with sourness and sweetness least likely. Experiments 2 and 3 provided some additional insight, suggesting that the magnitude of RCEs is predicted by qualitative similarity rather than by congruence or recalled frequency of pairings in foods. This conclusion is consistent with past findings in comparable studies (Murphy and Cain 1980; Frank et al. 1993; Schifferstein and Verlegh 1996).

This work provides further evidence of RCEs for taste–taste interactions and strengthens the conclusion that response context is an important factor in psychophysical evaluations of taste–taste mixtures. Thus far, results are consistent with the multistage model of mixture processing of van der Klaauw and Frank (1996): Sour and salty sensations may be perceptually similar enough that the concept of sourness can expand to include portions of salty sensation but that sour and sweet sensations are different enough that small differences in methodology cannot expand the concept of sourness to include portions of sweet sensations. We will discuss "similarity" below (see section "A possible tool to probe the nature of perceptual similarity").

Regarding the particularly large RCE ratios for sour–salty solutions, NaCl has a slight sour side taste that could potentially impact interactions. However, any contribution of this side taste to sourness would presumably occur under both scaling conditions. It is also perhaps surprising that we failed to observe larger RCE ratios for sour–bitter mixtures because subjects "confuse" or, more likely, mislabel these 2 taste qualities according to several authors (e.g., McAuliffe and Meiselman 1974). This could result in strong conflation of sour and bitter sensations in ratings of sourness. In the current experiments, sour–bitter mislabeling (or confusion) may have been ameliorated by instructions and training that associated the concepts of sweet, sour, salty, and bitter to particular moduli (McAuliffe and Meiselman 1974; O'Mahony et al. 1979).

Implications for studies of taste mixture interactions

Simple mixtures are commonly used to evaluate taste–taste interactions (reviewed in Keast and Breslin 2003). A key question is how one mixture component affects the taste of others, for example, the extent to which added salt suppresses bitter taste (Breslin and Beauchamp 1995). Such work has clear importance for formulation of foods and beverages. In addition, perceptual interactions, including enhancement and suppression of the perceived magnitudes of qualities, have been used to gain insights into mechanisms of perception (Keast and Breslin 2003). The current result for sour–salty solutions, increasing sourness with increasing concentrations of added salt when subjects rated sourness alone but not when subjects also rated saltiness, shows that differences in response context can lead to qualitatively different conclusions regarding mixture interactions. In contrast, sourness decreased with increasing concentrations of added cyclamate, regardless of response context. The results are broadly consistent with some previous work on bitter mixtures (Frank et al. 1993; Breslin and Beauchamp 1997). Thus, response context should be considered when interpreting results on taste–taste interactions. We do not suggest that effects that are sensitive to response context are invalid, but differences in sensitivity to response context could imply interactions that occur at different levels of perceptual processing.

A possible tool to probe the nature of perceptual similarity

Sensory stimuli give rise to perceived qualities, internal representations that are correlated with physical properties of stimuli. That there are orderly relationships among these internal representations can be inferred from the judgments subjects make (Bimler et al. 2004). Inferred similarity among sensations, however, can depend on the psychophysical task. For example, multidimensional scaling analysis of ratings of color similarity yields a somewhat different representation of color space than does color-matching (reviewed in Kuehni 2003). The demands of different psychophysical tasks may cause people to reorder or transform internal representations in different ways or may access representations at different levels of sensory processing.

An odor may be called sweet smelling and be rated as qualitatively similar to the taste of sucrose. Does this mean that the 2 stimuli give rise to similar internal representations or even tastes? Performance in a side-by-side discrimination task may provide the most objective answer (Wise and Cain 2000; Wise et al. 2000), but basic taste qualities are perfectly discriminable to normal subjects. Performance in various other tasks can provide useful insights. For example, sweet odors selectively enhance response times for sweet tastes (White and Prescott 2007) and sweet odors are confused with sweet tastes in memory (Stevenson and Oaten 2010), but sweet odors and sweet tastes do not provide equivalent context with respect to intensity judgments (Rankin and Marks 2000; Stevenson and Mahmut 2010). We can infer that internal representations of sweet tastes and sweet smells are similar at some levels of processing (or for some purposes) but at other levels of processing they are not.

The current work shows that RCE ratios for sourness ratings are correlated with judgments of qualitative similarity. The exact meaning of this finding with respect to internal representations of taste quality is not yet clear. The results suggest that RCEs should prove useful in probing the relationships among internal representations associated with distinct taste qualities.

Limitations

The relatively simple model system in the current work, which focused on CA paired with only 3 other stimuli, differs markedly from the rich context of foods and beverages that involve virtually all of our sensory modalities. More work, using a wider array of chemosensory stimuli, is clearly needed. In particular, future studies should expand the array of taste–taste mixtures to include more binary mixtures of various qualities, as well has more complex mixtures. The current work on sourness highlights how slight differences in methods can influence even seemingly simple qualitative ratings with important implications for experimental outcomes and, furthermore, that the experimental manipulations of response context may be useful as a tool to help establish how taste quality is represented at different levels of processing.

Funding

This work was supported in part by the National Institute on Deafness and Other Communication Disorders (NIH T32 DC00014, NIH DC02995 PASB).

Acknowledgement

We thank Ms Anilet Tharp for excellent technical assistance.

References

Bartoshuk LM, Duffy VB, Fast K, Green BG, Prutkin J, Snyder DJ. 2003. Labeled scales (e.g., category, Likert, and VAS) and invalid across-group comparisons: what we have learned from genetic variation in taste. Food Qual Pref. 14:125–138.

Bimler D, Kirkland J, Pichler S. 2004. Escher in color space: individual-differences multidimensional scaling of color dissimilarities collected with a gestalt formation task. Behav Res Methods Instrum Comput. 36: 69–76.

Breslin PAS, Beauchamp GK. 1995. Suppression of bitterness by sodium: variation among bitter taste stimuli. Chem Senses. 20:609–623.

Breslin PAS, Beauchamp GK. 1997. Salt enhances flavour by suppressing bitterness. Nature. 387:563.

Clark CC, Lawless HT. 1994. Limiting response alternatives in time–intensity scaling: an examination of the halo-dumping effect. Chem Senses. 19:583–594.

Frank RA. 2003. Response context affects judgments of flavor components in foods and beverages. Food Qual Pref. 14:139–145.

Frank RA, Byram J. 1988. Taste–smell interactions are tastant and odorant dependent. Chem Senses. 13:445–455.

Frank RA, van der Klaauw NJ, Schifferstein HNJ. 1993. Both perceptual and conceptual factors influence taste–odor and taste–taste interactions. Percept Psychophys. 54:343–354.

Frank RA, Wessel N, Shaffer G. 1990. The enhancement of sweetness by strawberry odor is instruction-dependent. Chem Senses. 15:576.

Keast RSJ, Breslin PAS. 2003. An overview of binary taste–taste interactions. Food Qual Pref. 14:111–124.

Kuehni RG. 2003. Color space and its divisions: color order from antiquity to the present. Hoboken (NJ): Wiley and Sons.

Labbe D, Martin N. 2009. Impact of novel olfactory stimuli at supra and subthreshold concentrations on the perceived sweetness of sucrose after associative learning. Chem Senses. 34:645–651.

Labbe D, Rytz C, Morgenegg S, Ali S, Martin N. 2007. Subthreshold olfactory stimulation can enhance sweetness. Chem Senses. 32:205–214.

Lawless HT, Clark CC. 1992. Psychological biases in time intensity scaling. Food Technol. 46:81–90.

McAuliffe WK, Meiselman HL. 1974. The roles of practice and correction in the categorization of sour and bitter taste qualities. Percept Psychophys. 16:242–244.

Miyazawa T, Gallager M, Preti G, Wise PM. 2008. The impact of sub-threshold carboxylic acids on the odor intensity of supra-threshold flavor compounds. Chemosensory Percep. 3:163–167.

Murphy C, Cain WS. 1980. Taste and olfaction: independence vs interaction. Physiol Behav. 24:601–605.

O'Mahony M, Goldenberg M, Stedmon J, Alford J. 1979. Confusion in the use of the taste adjectives 'sour' and 'bitter'. Chem Senses. 4:301–318.

Prescott J, Johnstone V, Francis J. 2004. Odor–taste interactions: effects of attentional strategies during exposure. Chem Senses. 29:331–340.

Prescott J, Murphy SA. 2009. Inhibition of evaluative and perceptual odour–taste learning by attention to the stimulus elements. Q J Exp Psychol. 62:2133–2140.

Rankin KM, Marks LE. 2000. Chemosensory context effects: role of perceived similarity and neural commonality. Chem Senses. 25:747–759.

Schifferstein HNJ, Verlegh PWJ. 1996. The role of congruency and pleasantness in odor-induced taste enhancement. Acta Psychol. 94:87–105.

Stevenson RJ, Mahmut M. 2010. Differential context effects between sweet tastes and smells. Atten Percept Psychophys. 72:2304–2313.

Stevenson RJ, Oaten MJ. 2010. Sweet odours and sweet tastes are conflated in memory. Acta Psychol. 134:105–109.

Stevenson RJ, Prescott J, Boakes RA. 1995. The acquisition of taste properties by odors. Learn Motiv. 26:1–23.

Stevenson RJ, Prescott J, Boakes RA. 1999. Confusing tastes and smells: how odors can influence the perception of sweet and sour tastes. Chem Senses. 24:627–635.

Valentin D, Chrea C, Nguyen DH. 2006. Taste-odour interaction in sweet taste perception. In: Spillane WJ, editor. Optimising sweet taste in foods. Cambridge (UK): Woodhead Publishing Ltd. p. 66–84.

van der Klaauw NJ, Frank RA. 1996. Scaling component intensities of complex stimuli: the influence of response alternatives. Environ Int. 22:21–31.

White TL, Prescott J. 2007. Cross-modal stroop effects: congruent odors facilitate taste identification. Chem Senses. 32:337–341.

Wise PM, Olsson M, Cain WS. 2000. Quantification of odor quality. Chem Senses. 25:429–443.

Wise PM, Cain WS. 2000. Latency and accuracy of discriminations of quality between binary mixtures and their components. Chem Senses. 25: 247–265.