The merging of the senses: integration of subthreshold taste and smell

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Central neural integration of sensory input from different modalities is a prerequisite for many types of perception and behavior. One of the best examples of such an integrative process may be flavor perception, whereby activation in two peripherally distinct neural systems, olfaction and gustation, combines to give rise to a unified oral sensation. Here we used a psychophysical method to show cross-modal summation of subthreshold concentrations of selected gustatory and olfactory stimuli, thus demonstrating that central neural integration of taste and smell inputs generates a representation of flavor perception.

Central integration of multisensory cues (for instance, visual and auditory) is inferred from studies finding that detectability and reaction times are better with multiple rather than single sensory inputs[1]. Such observations are thought to reflect true integration of multisensory information at the neural level; this interpretation is supported by multisensory neurons, found in the superior colliculi of cats and primates, that integrate cues from three sensory modalities, vision, audition and somatosensation[2,3]. As for the chemical senses, animal studies reveal central neurons uniquely responsive to combinations of odors and tastes. Psychophysical studies of subthreshold odor or taste stimuli, however, reveal only within-modality additivity[4,5]. Intermodal integration of taste and odor into a flavor perception is found only at suprathreshold levels, suggesting an attentional component in flavor-perception integration[6].

Here we tested five males and five females (22–33 years old) to investigate whether an odor and a taste stimulus, which were individually below their respective detection thresholds, could be detected when simultaneously presented (as occurs while eating). Saccharin and benzaldehyde were chosen as taste and odor stimuli for three reasons. First, saccharin is not volatile and therefore does not provide any retronasal augmentation of odor. (Saccharin thresholds with and without retronasal olfaction did not differ, 0.021 mM versus 0.024 mM.) Second, benzaldehyde cannot be tasted at the concentration used here. Third, saccharin and benzaldehyde share flavor congruency: foods smelling of cherry and almond are more likely to be associated with sweet taste than with salty, sour, bitter or savoury (the taste of L-glutamic acid monosodium salt or MSG).

Each of the three experiments we report consisted of five sessions. At each session, we first measured our subjects' nasal detection thresholds for benzaldehyde and their oral detection thresholds for saccharin (or MSG) separately. Thresholds for each were obtained in counterbalanced order using a two-alternative, forced-choice, modified-staircase method for stimulus presentation[7]. After a 15-minute break, we then obtained a second orthonasal detection threshold for benzaldehyde while the subject held 10 ml of a subthreshold saccharin, water or MSG solution in the mouth.

To claim additivity for within-modality stimuli (for instance, taste only or smell only), one must demonstrate that a mixture of n stimuli is detectable when each stimulus in the mixture is present at $1/n$ of its individual threshold concentration. Thus, complete additivity for a within-modality taste mixture would occur if a binary mixture (for example, citric acid and glucose) were detectable when its constituents were each at half of their individual thresholds, or if a trinary mixture (for example, citric acid, glucose and quinine) were detectable when its constituents were each at one-third their respective individual thresholds[4]. Here we examined the additivity of two cross-modal stimuli; thus, we yoked the dilution series of benzaldehyde and saccharin (or MSG) such that each pair contained stimuli at the same fraction of their respective threshold concentrations. Because additivity requires that both stimuli be detectable at 50% of their respective thresholds when presented simultaneously[4,5], this method of yoking stimuli allowed us to simply determine whether cross-modal integration of odors and tastes was additive.

We measured thresholds for benzaldehyde, saccharin and MSG in the single and summation conditions and recorded them in terms of molarities (**Table 1**). The data of primary interest were the differences in the lowest detectable concentration of benzaldehyde from the first (single) to the second (summation) threshold test. Sensitivity to benzaldehyde was significantly increased by the presence of a subthreshold concentration of saccharin in the mouth. On average, benzaldehyde thresholds with saccharin in the mouth were 28% lower than the thresholds obtained alone, demonstrating summation, but not complete additivity, as found for within-modality mixtures of odors or tastes (**Fig. 1**)[4,5]. The effect was both significant ($p = 0.0\,1$) and reliable: 9 of the 10 subjects showed markedly

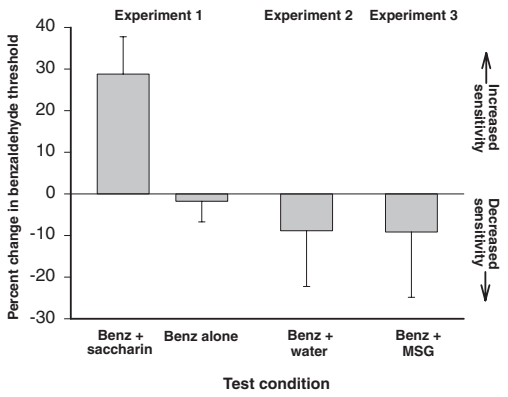

Fig. 1. Median percent change from baseline benzaldehyde threshold in experiments 1–3. On each summation trial, subjects first placed 10 ml of the oral stimulus in their mouths, then sniffed through both nares from two bottles that contained either benzaldehyde solution in one bottle and diluent only in the second bottle (stimulus pair), or diluent in both bottles (blank pair). Subjects then rinsed their mouths with deionized water. Next, subjects tasted the same oral stimulus while sniffing from the second set of two bottles. After rinsing their mouths, they indicated which set of two bottles contained the odorant (benzaldehyde). Negative numbers represent decreases in sensitivity; positive numbers represent increases. Single sample t-tests on the median change in each condition revealed that only the threshold change obtained when saccharin was in the mouth differed significantly from zero (saccharin, $p = 0.01$; nothing, $p = 0.71$; water, $p = 0.52$; MSG, $p = 0.57$). The two bars on the left depict the results from experiment 1, showing the significant change from baseline in benzaldehyde threshold with saccharin as the oral stimulus versus with nothing in the mouth (paired directional t-test, $t_{18} = 2.66$, $p = 0.001$). The changes from baseline in benzaldehyde threshold when water was the oral stimulus (experiment 2) and when MSG was the oral stimulus (experiment 3) were significantly different from the decreased threshold obtained with saccharin in the mouth (directional t-tests with Bonferroni corrections for multiple comparisons, $t_{18} = 3.52$, $p = 0.006$; $t_{18} = 2.10$, $p = 0.04$).

Table 1. Average detection thresholds for odor and taste stimuli, singly and in combination.

	Condition 1			Condition 2			Condition 3			Condition 4		
	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3	Stage 1	Stage 2	Stage 3
	Benz	Sac	Benz + Sac	Benz	Sac	Benz	Benz	Sac	Benz+ H_20	Benz	MSG	Benz + MSG
Grand mean	0.071	0.026	0.049	0.103	0.018	0.115	0.044	0.019	0.051	0.055	0.950	0.056
s.e.	0.012	0.006	0.010	0.021	0.078	0.030	0.020	0.001	0.018	0.022	0.080	0.021
		$p = 0.002$			$p = 0.31$			$p = 0.16$			$p = 0.84$	

Means (in mM) and standard error of the means (s.e.) for saccharin, MSG and benzaldehyde single thresholds (stages 1 and 2) and for benzaldehyde thresholds obtained in the summation test (stage 3).

increased sensitivity to benzaldehyde, with decreases in threshold of 13–57% across all five sessions. In contrast, results from the control condition allowed us to rule out the effects of repeated testing as a cause of the lowered threshold; simply repeating the benzaldehyde threshold test with an intervening saccharin threshold resulted in a nonsignificant (3%) decrease in sensitivity ($p = 0.71$).

To examine whether the decreased sensitivity to benzaldehyde in the combined condition was due to the concomitant presence of a subthreshold taste (saccharin solution) or whether it might arise from differences in breathing patterns or airflow while sniffing with an oral solution in the mouth, the participants were tested in a second experiment in which we measured the threshold for benzaldehyde using filtered, deionized water as the oral stimulus. This condition also controlled for the (suprathreshold) somatosensory input from the 10 ml of saccharin solution in the mouth. Benzaldehyde–water pairing did not produce the downward shift in threshold observed with combined benzaldehyde–saccharin presentation ($p = 0.52$; **Fig. 1**).

Given that deionized water can itself be characterized as a weak taste stimulus (most commonly reported as weakly bitter), the results of experiment 2 raised the interesting possibility that the enhanced sensitivity seen for the benzaldehyde–saccharin pairing was due to the stimulus congruency of the suprathreshold qualities of sweet (saccharin) and almond-cherry (benzaldehyde). The strength of some perceptual interactions between suprathreshold tastes and odors seems to depend on the congruency of specific stimulus combinations: for example, the sweetness of sucrose can be enhanced by the odor of strawberry but not by the odor of peanut butter[8,9]. To explore the possibility that enhanced benzaldehyde detection was facilitated by congruency of the odor–taste pairing, eight of the original ten subjects (and two replacements) participated in a final experiment. In five sessions, after first obtaining thresholds for benzaldehyde and MSG alone, we measured the threshold for benzaldehyde in the presence of an intra-oral solution of MSG. We hypothesized that a benzaldehyde–MSG pairing would be incongruous for our U.S. volunteers, who we expected to be much more likely to associate benzaldehyde odor with a sweet taste. The results of this condition (**Fig. 1**) provided support for the congruency hypothesis: pairing benzaldehyde with MSG did not reliably lower the threshold for benzaldehyde ($p = 0.57$).

Neural and behavioral response enhancements to combinations of sensory stimuli are found within and across many sensory domains (for example, visual–auditory, somatosensory–auditory, somatosensory–visual)[2,10]. For same-modality stimuli, these results are most closely analogous to temporal or spatial summation, whereby stimuli that are temporally or spatially aligned can activate common perceptual channels. Cross-modal response summation, however, requires the existence of a central point of intermodal convergence containing neurons responsive to the combined inputs. Three primary candidate sites identified from anatomical and electrophysiological studies are the insular cortex, which receives a convergence of inputs from visceral, taste, olfactory and somatosensory systems as well as association cortex[11], the orbitalfrontal cortex, which, in monkeys, contains multisensory neurons that respond to olfactory, gustatory and visual stimuli[12] and the amygdala, which receives gustatory and olfactory input and is hypothesized to potentiate cortical information processing of stimuli that become associated through relevant life experience[13].

Unlike many behavioral demonstrations of response enhancement, the forced-choice detection task provided an important control for attentional focus, thereby demonstrating an effect of sensory integration on absolute detection, and not merely on attentional capture. This result provides compelling support for, first, the functional significance of neural responses to combinations of odor and taste stimuli[12], and second, the existence of central loci where neural inputs conveying olfactory and taste information from our everyday chemosensory experience are integrated, in essence, a 'flavor' substrate[14]. Moreover, the specificity of the saccharin/benzaldehyde integration over the water/benzaldehyde and the glutamate/benzaldehyde combinations suggests that the phenomenon may not represent general taste–olfaction integration, but may be specific to previously encountered combinations. It is suggested that the amygdala, when presented with one element of a biologically relevant stimulus pair, can lower the detection threshold for the previously paired sensory stimulus[15]. Our psychophysical data provide the impetus for testing such a hypothesis with electrophysiological and neuroimaging studies.

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1. Gielen, S. C., Schmidt, R. A. & Van Der Heuvel, P. J. *Percept. Psychophys.* **34**, 161–168 (1983).
2. Wallace, M. T., Wilkinson, L. K. & Stein, B. E. *J. Neurophysiol.* **76**, 1246–1266 (1996).
3. Sparks, D. L. & Groh, J. M. in *The Cognitive Neurosciences* (ed. Gazzaniga, M. S.) 565–584 (MIT Press, Cambridge, Massachusetts, 1995).
4. Stevens, J. C. *Physiol. Behav.* **62**, 1137–1143 (1997).
5. Guadagni, D. G., Buttery, R. G., Okano, S. & Burr, H. K. *Nature* **200**, 1288–1289 (1963).
6. Murphy, C., Cain, W. S. & Bartoshuk, L. M. *Sens. Process.* **1**, 204–211 (1977).
7. Wetherill, G. B. & Levitt, H. *Br. J. Math. Stat. Psychol.* **18**, 1–10 (1965).
8. Frank, R. A. & Byran, J. *Chem. Senses* **13**, 445–455 (1988).
9. Schifferstein, H. N. & Verlegh, P. W. *Acta Psychol.* **94**, 87–105 (1996).
10. Fowler, C. A. & Dekle, J. A. *J. Exp. Psychol. Hum. Percept. Perform.* **17**, 816–828 (1991).
11. Krushel, L. A. & van der Kooy, D. *J. Comp. Neurol.* **270**, 39–54 (1988).
12. Rolls, E. T. & Baylis, L. L. *J. Neurosci.* **14**, 5437–5452 (1994).
13. Whalen, P. J. *Curr. Dir. Psychol. Sci.* **7**, 177–188 (1998).
14. Schul, R., Slotnick, B. M. & Dudai, Y. *Behav. Neurosci.* **110**, 760–765 (1996).
15. Kapp, B. S., Whalen, P. J., Supple, W. F. & Pascoe, J. P. in *The Amygdala: Neurobiological Aspects of Emotion, Memory and Mental Dysfunction* (ed. Aggleton, J. P.) 229–254 (Wiley-Liss, New York, 1992).