Chem. Senses 32: 337–341, 2007
doi:10.1093/chemse/bjm001
Advance Access publication February 16, 2007

Chemosensory Cross-Modal Stroop Effects: Congruent Odors Facilitate Taste Identification

Theresa L. White[1,2] and John Prescott[3]

[1]Department of Psychology, Le Moyne College, Syracuse, NY 13214, USA, [2]Department of Neuroscience and Physiology, State University of New York Upstate Medical University at Syracuse, NY 13210, USA and [3]Department of Psychology, James Cook University, Cairns 4870, Australia

Correspondence to be sent to: Theresa L. White, Le Moyne College, 1419 Salt Springs Road, Syracuse, NY 13214, USA. e-mail: whitetl@lemoyne.edu

Abstract

In order to explore the cross-modal cognitive associations between smell and taste, a chemosensory analogue of the Stroop task (Stroop 1935) was developed. Fourteen participants were presented with an odorant and a tastant and asked to identify the tastant as "sweet" or "sour" by pressing 1 of 2 buttons as quickly as possible. Participants were faster to name the taste when it was presented with an odor that was congruent (e.g., strawberry/sweet) than with an incongruent odor (e.g., strawberry/sour). These results support the concept of a high level of cognitive integration between the senses of smell and taste and illustrates occasions of interference between information arising from different sensory systems.

Key words: cognitive interference, flavor, orthonasal olfaction, smell

Introduction

The perception of flavor is the result of a combination of input from the senses of smell and taste (as well as additional sensory systems) that is essentially a synthesis of different dimensions of the food stimulus into a perceptual whole (Mozell et al. 1969; Prescott 2004; Small and Prescott 2005) robust enough that the individual components of a flavor are seldom perceived independently (Gibson 1966; Prescott 1999). Patients presenting to chemosensory clinics with taste complaints are often found to actually suffer from olfactory difficulties (Wrobel and Leopold 2004), thus illustrating confusion between the senses of smell and taste (Rozin 1982) as a result of the sensory synthesis. One consequence of this synthesis is cross-modal interaction, including superadditivity of odor and taste intensities at both supra- (Hornung and Enns 1984, 1986) and subthreshold levels (Dalton et al. 2000) when inputs from the 2 senses are simultaneously experienced. Another consequence is that coexposure to an odorant and a tastant under conditions that promote synthesis of these elements can lead to the existence of cross-modal chemosensory qualities, such as the "sweet" smell of odors such as vanilla or caramel (Burdach et al. 1984; Stevenson et al. 1995; Prescott et al. 2004).

In the course of normal eating, the perception of flavor is normally preceded by orthonasal olfaction, which may be experienced before food reaches the oral cavity. After the food enters the mouth, input from the sense of taste is likely accompanied by input from retronasal olfaction, which differs perceptually from orthonasal input (Rozin 1982; Heilmann and Hummel 2004; Koza et al. 2005). The impact of prior orthonasal information on taste and flavor perception has received little attention (although, see von Bekesy 1964). One possibility is that prior olfactory information may produce cognitive priming, which leads to the expectation of a particular type of tastant, based on implicit associations between odorants and tastants that have been formed during past eating experiences (e.g., Stevenson et al. 1995). A way of testing this hypothesis would be to compare pairs of odors and tastes that were considered congruent (based on prior learning) with those pairs that formed an unexpected (or incongruent) combination. One possibility is that incongruence in an odor/taste pair would produce interference between sensory modalities, similar to a Stroop effect (Stroop 1935). Stroop-type interference (Stroop 1935; MacLeod 1991) is frequently demonstrated in a color-word naming task in which the reaction times associated with naming words denoting colors that are printed in various colors of ink are measured. The typical finding is that participants take longer to name the ink color of words that are incongruent to the color name, and this is generally interpreted as reflecting a cognitive interference process. In the traditional Stroop task, the interference has been suggested to arise from competition, either for access to a temporary speech buffer where words may be held before they are expressed (Cowan and Barron 1987; Hanauer and Brooks 2003) or for activation of pathways at a semantic level of processing (Stuart and Carrasco 1993).

Although there is evidence (e.g., Broadbent 1958) to suggest that people can selectively filter stimuli by sensory modality, an emerging body of evidence suggests that cross-modality Stroop-like interference effects occur between some senses, such as audition and vision (Cowan and Barron 1987; Cowan 1989; Hanauer and Brooks 2003). A cross-modal Stroop effect has also been reported between the senses of vision and olfaction (Pauli et al. 1999) in a study in which odors acted as primes for words, influencing the naming speed of the ink of words related to olfaction. Such cross-modal Stroop effects suggest that information originating from different sensory systems can compete for cognitive resources.

In order to investigate the influence of orthonasal (sniffed) odors experienced prior to tasting, we developed a chemosensory cross-modal Stroop-like interference task that took advantage of the fact that some odor/taste pairs are considerably more congruent than others as a result of past experience and also that the level of congruency is an important determinant of interactions between the elements (Schifferstein and Verlegh 1996). The present experiment investigated whether degree of odor/taste congruency can influence the speed of taste identification. So, for example, are participants faster to respond "sour" to citric acid when it is presented following a sour-smelling odorant than when it is presented following a sweet-smelling odorant? It was hypothesized that taste stimuli presented with incongruent olfactory stimuli would be named more slowly than congruent stimuli, thus demonstrating cross-modal Stroop-like interference between the cognitive processes associated with processing of smell and taste information.

Materials and methods

Participants

All participants completed an Adult Informed Consent document in compliance with the Le Moyne College Institutional Review Board. Fourteen right-handed students (6 men, 8 women; age M = 19.78 years, standard deviation [SD] = 1.53) from the Le Moyne College community took part in the experiment. Participants reported normal senses of smell and taste were also screened for normal olfactory and gustatory ability by scoring as at least 80% on an abbreviated version of the Olfactory Confusion Matrix (Wright 1987; Kurtz et al. 2001). Participants also demonstrated the ability to verbally label 1 ml of a sucrose solution (see below) as "sweet" and 1 ml of a citric acid solution (again, see below) as "sour" without the pressure of time limits prior to beginning the experiment. Participants were paid $10 for taking part in a single testing session that lasted roughly 45 min.

Materials and apparatus

Three undiluted olfactory stimuli of approximately equal intensity were presented to participants: strawberry (fruit H_2O and kraft foods), grapefruit (grapefruit bath oil and body shop), and water. The present experiment also involved 2 gustatory stimuli that were presented at levels previously reported by Stevenson et al. (1999): citric acid (0.0075 M) and sucrose (0.30 M).

All gustatory and olfactory stimuli were presented in the Two-Module Delivery System (Hornung and Enns 1984), which appeared to participants to be a single opaque cup fitted with a glass straw, similar to a child's drinking cup. In fact, the "cup" comprised 2 separate containers arranged vertically, 1 for odorants and 1 for tastants. Both cups were enclosed in a polystyrene foam sheath, which hid the fact that 2 separate containers were used. The container for tastants was fitted with a "straw," which had been modified for this experiment by placing a sensor attached via a fine cable to a timer into the straw. When a tastant passed through the end of the straw, the change in electrical resistance activated the timer. The timer was stopped by pressing either of 2 buttons, one of which was designated "sweet" and the other one "sour." The hand location of the button that indicated "sweet" was counterbalanced across participants.

Design

The design of this experiment was a 3 (odorant) $\times$ 2 (tastant) multifactorial within-subjects design that used reaction time as the dependent variable. Each of the possible odor/taste combinations was presented on 6 occasions. Stimulus combinations were presented in a block randomized fashion in which each set of possible combinations were presented in a unique pseudorandom order prior to commencing the next presentation of that set.

Procedure

Olfactory stimuli were presented in conjunction with gustatory stimuli in the Two-Module Delivery System, described above. All 6 possible combinations of stimuli were presented to each participant. Thus, each participant had what appeared to be 6 cups: 2 containing "congruent stimuli" (either strawberry-sweet or grapefruit-sour), 2 with "incongruent stimuli" (strawberry-sour or grapefruit-sweet), and 2 with "control stimuli" (water-sweet, water-sour). These stimuli were hidden from the participant's view by a cardboard shield.

On each of 36 trials, participants were asked first to sniff the odor presented to them in the cup. This instruction served to create a standardized procedure that ensured that each participant attended to the odor prior to ingesting the tastant. After smelling the cup, participants sipped the tastant, then reported whether the tastant was sweet or sour by pressing the appropriate button as quickly as possible with their thumb. The experimenter recorded the length of time taken for the participant's response as well as which button was depressed. Following each trial, the participant spat out the tastant and then rinsed his or her mouth with water before beginning the next trial.

After completing 36 trials of taste identification, participants were presented with individual stimuli in a random order and asked to perform 4 tasks for each of the odorants and tastants. Participants were first asked to rate the strength of all of the stimuli using a labeled magnitude scale (Green et al. 1993), then to rate how well the descriptors of "sweet" or "sour" applied to each of the stimuli with a 15.2-cm unstructured line scale anchored with the words "none" and "extremely," at the left and right ends, respectively.

Results

The selection of odorants and tastants as sweet and sour was confirmed by the participants (see Figure 1). Participants rated the smell of strawberry as significantly (t-test, unequal variance, $t(25) = 4.38$, $P < 0.001$) sweeter than the smell of grapefruit, whereas the smell of grapefruit was rated as significantly (t-test, unequal variance, $t(17) = 5.48$, $P < 0.001$) more sour than the smell of strawberry. With the taste stimuli, sucrose was rated as significantly (t-test, unequal variance, $t(26) = 5.99$, $P < 0.001$) sweeter than citric acid, which was rated as being significantly (t-test, unequal variance, $t(26) = 14.42$, $P < 0.001$) more sour than sucrose.

No difference was observed in the intensity ratings either of grapefruit and strawberry odors (t-test, unequal variance, $t(23) = -0.69$). Despite pilot testing to equate intensity, the taste of citric acid (M = 53.14, SD = 23.61) was considered significantly (t-test, unequal variance, $t(25) = 2.57$, $P = 0.016$) stronger than the taste of sucrose (M = 32.43, SD = 18.63). This finding raises the possibility that intensity differences could partially account for any differences in reaction times to identify sweetness and sourness. However, the main hypothesis demands a comparison between the times necessary to identify a tastant in the presence of each odorant, rather than directly comparing results related to the 2 tastants. Therefore, it is unlikely that this intensity difference will influence results related to the main hypothesis.

Participants in the present experiment were extraordinarily accurate in their taste identifications; only 3 data points were removed due to inaccurate identifications. Response times to correctly identify tastants were thus the primary dependent variable of interest, and these data were submitted to a 3 (odor) × 2 (taste) repeated-measures analysis of variance (SPSS-X, ver. 1.0). Of primary interest was the interaction between the odor and taste conditions, which would provide evidence of cross-modal interaction and/or facilitation. Results indicated the presence of a significant interaction between odor and taste ($F(2,12) = 4.507$, $P = 0.035$), but no significant main effects for either odorant ($F(2,12) = 0.166$, $P = 0.849$) or tastant ($F(1,13) = 0.025$, $P = 0.977$). As shown in Figure 2, the smell of grapefruit led to faster naming of the taste quality associated with citric acid (sour) than sucrose (sweet), whereas the smell of strawberry showed the opposite pattern of reaction times.

Discussion

The perception of flavor depends upon the integration of the senses of smell and taste, which may be synthesized to such an extent that individual flavor components are typically perceived as a unitary percept when they are experienced together (Gibson 1966; Prescott 1999). The present experiment sought to extend the findings on cross-modal cognitive associations by asking whether cross-modal Stroop-like interference could be demonstrated between odors and tastes, when the odor was experienced in advance of the taste. The results of the present experiment strongly support the close

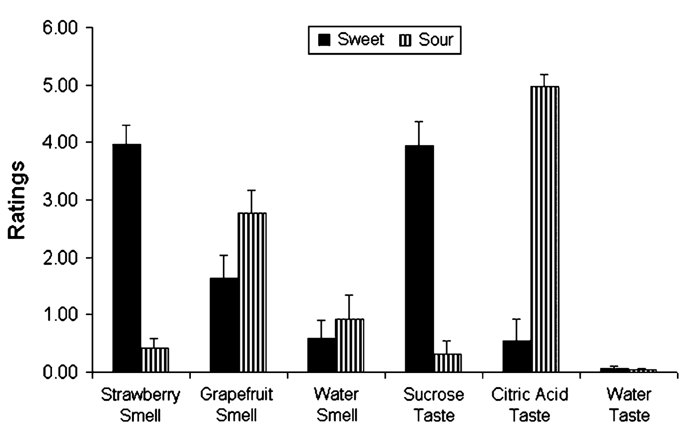

Figure 1 Mean (and standard error of the mean) ratings of sweetness and sourness for olfactory and gustatory stimuli.

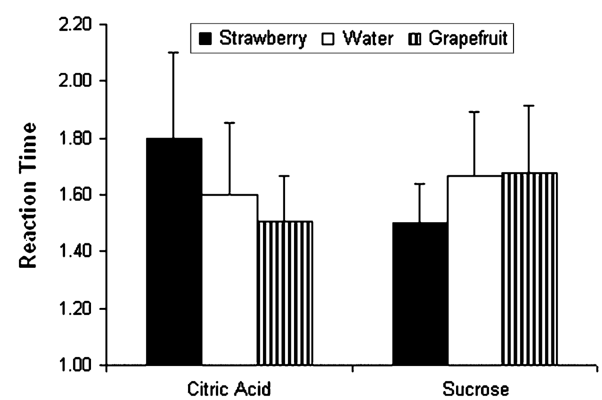

Figure 2 Mean (and standard error of the mean) reaction times to identify the taste of sucrose and citric acid in the presence of grapefruit and strawberry odors.

cognitive connection between these 2 sensory systems by demonstrating that odors judged as congruent in quality facilitated the naming of a tastant, whereas an odorant deemed to be incongruent slowed the tastant naming. Presumably, participants who were primed with olfactory information generated a series of expectations about the tastant that affected the response time required for identification.

The olfactory components of flavor provide the key information that indicates, at a distance, whether or not an object is edible (Rozin 1982). These results suggest that orthonasal olfactory input primes those cognitive systems responsible for processing information about flavor (Small and Prescott 2005) to expect a particular type of taste in an effort to enhance perception in terms of speed of processing—and perhaps also accuracy, although that was not determined here. The adaptive significance of such enhancement lies in the biological importance of rapid, accurate discrimination of nutritive (e.g., carbohydrates) versus potentially toxic (e.g., bitter or highly acidic) compounds prior to consumption. Integration of information from physiologically distinct sensory modalities in order to enhance the detection of, and reduce ambiguity associated with, stimuli appears to be a general property of the mammalian nervous system, particularly as in the case here where a single sensory modality fails to supply all the necessary information about the stimulus (Gibson 1966; Marks 1991; Stein and Meredith 1993).

Prior research suggests that which particular tastant is expected when one smells a particular odorant is implicitly learned over time through prior paired associations (Stevenson et al. 1995, 1998; Prescott 2004), such as might naturally occur during eating. For example, novel odors repeatedly paired with the taste of sucrose are later reported to be sweeter than their initial ratings (Stevenson et al. 1998). Such prior learning was observed in the present experiment as participants rated odorants with descriptors normally associated with tastants: the smell of strawberry was judged to be sweeter than that of grapefruit, and the smell of grapefruit was judged to be more sour than that of strawberry. The very nature of the expectations associated with those overlearned smell and taste associations is likely to have influenced the reaction time differences observed.

The present experiments do not indicate whether the observed cross-modal Stroop effect originates from competition between sensory systems for access to a temporary speech buffer (Cowan and Barron 1987; Hanauer and Brooks 2003) or for activation of pathways involving concurrent semantic processing (Jerger et al. 2002). However, the fact that olfactory stimuli vary substantially in the extent to which they can be coded verbally (Cain 1979) suggests that the use of odors in cross-modal Stroop tasks might be useful in elucidating the underlying cognitive mechanisms.

Acknowledgements

The authors would like to thank the members of the Le Moyne Social Olfaction Research Group, especially Amanda Ghezzi, for assistance in the collection of this data. This research was supported by funds received from the Sense of Smell Institute.

References

Broadbent DE. 1958. Perception and communication. London: Pergamon Press.

Burdach KJ, Kroeze JHA, Koster EP. 1984. Nasal, retronasal, and gustatory perception: an experimental comparison. Percept Psychophys. 36: 205–208.

Cain WS. 1979. To know with the nose: keys to odor identification. Science. 203:467–470.

Cowan N. 1989. The reality of cross-modal Stroop effects. Percept Psychophys. 45:87–88.

Cowan N, Barron A. 1987. Cross-modal, auditory-visual Stroop interference and possible implications for speech memory. Percept Psychophys. 41:393–401.

Dalton P, Doolittle N, Nagata H, Breslin PAS. 2000. The margining of the senses: integration of subthreshold taste and smell. Nat Neurosci. 3:431–432.

Gibson JJ. 1966. The senses considered as perceptual systems. Boston (MA): Houghton Mifflin.

Green BG, Shaffer GS, Gilmore MM. 1993. Derivation and evaluation of a semantic scale of oral sensation magnitude with apparent ratio properties. Chem Senses. 186:683–702.

Hanauer JB Brooks PJ. 2003. Developmental change in the cross-modal Stroop effect. Percept Psychophy. 653:359–366.

Heilmann S, Hummel T. 2004. A new method for comparing orthonasal and retronasal olfaction. Behav Neurosci. 118:412–419.

Hornung DE, Enns MP. 1984. The independence and integration of olfaction and taste. Chem Senses. 92:97–106.

Hornung DE, Enns MP. 1986. The contributions of smell and taste to overall intensity: a model. Percept Psychophys. 396:385–391.

Jerger S, Martin RC, Damian MF. 2002. Semantic and phonological influence on picture naming by children and teenagers. J Mem Lang. 47:229–249.

Koza BJ, Cilmi A, Dolese M, Zellner DA. 2005. Color enhances orthonasal olfactory intensity and reduces retronasal olfactory intensity. Chem Senses. 30:643–649.

Kurtz DB, White TL, Sheehe PR, Hornung DE, Kent PF. 2001. Odorant confusion matrix: the influence of patient history on patterns of odorant identification and mis-identification in hyposmia. Physiol Behav. 72:1–8.

MacLeod CM. 1991. Half a century of research on the Stroop effect: an integrative review. Psychol Bull. 109:163.

Marks LE. 1991. Metaphor and the unity of the senses. In: Meiselman HL, Rivkin RS, editors. Clinical measurement of taste and smell. New York: Macmillan. p. 117–125.

Mozell MM, Smith BP, Smith PE, Sulivan RL, Swender P. 1969. A technique to occlude the nasal chemoreceptors during lingual flavor stimulation. Physiol Behav. 4:131.

Pauli P, Bourne LE Jr, Diekmann H, Birbaumer N. 1999. Cross-modality priming between odors and odor-congruent words. Am J Psychol. 112: 175–186.

Prescott J. 1999. Flavour as a psychological construct: implications for perceiving and measuring the sensory qualities of foods. Food Qual Pref. 10: 349–356.

Prescott J. 2004. Psychological processes in flavour perception. In: Taylor AJ, Roberts D, editors. Flavour perception. London: Blackwell Publishing. p. 256–277.

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

Rozin P. 1982. 'Taste-smell confusions' and the duality of the olfactory sense. Percept Psychophys. 31:397–401.

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

Small DM, Prescott J. 2005. Odor/taste integration and the perception of flavor. Exp Brain Res. 166:345–357.

Stein BE, Meredith MA. 1993. The merging of the senses. Cambridge (MA): MIT Press.

Stevenson RJ, Boakes RA, Prescott J. 1998. Changes in odor sweetness resulting from implicit learning of a simultaneous odor-sweetness association: an example of learned synesthesia. Learn Motiv. 29:113–132.

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 odours can influence the perception of sweet and sour tastes. Chem Senses. 246:627–636.

Stroop JR. 1935. Studies of interference in serial verbal reactions. J Exp Psychol. 18:643–661.

Stuart D, Carrasco M. 1993. Semantic component of a cross-modal Stroop-like task. Am J Psychol. 1063:383–405.

von Bekesy G. 1964. Olfactory analogue to directional hearing. J Appl Physiol. 19:369–373.

Wright HN. 1987. Characterization of olfactory dysfunction. Arch Otolaryngol. 113:163–168.

Wrobel BB, Leopold DA. 2004. Clinical assessment of patients with smell and taste disorders. Otolaryngol Clin North Am. 37:1127–1142.

Accepted January 16, 2007