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Memory psychophysics for chemosensation: perceptual and mental mixtures of odor and taste

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Abstract. Subjects made quantitative judgements of the overall intensity of odor-taste mixtures, which were either presented physically (perceptual estimation) or represented symbolically by pairs of colors that referred to their unmixed constituents (memory-based estimation). In the latter condition, the mixtures were constructed subjectively by mixing mentally the remembered representations of the odor and taste components. Despite the great phenomenal difference between the two conditions, the pattern of results was largely the same for perceived and for mental mixtures. The rule of odor-taste integration was approximately additive in both cases. The invariance of this rule is particularly impressive given that all of the stimuli were presented intraorally, so that the odorants were mislocalized at the mouth. The findings imply an important role for cognition in chemosensation.

Introduction

Two decades of research on memory for odor (see Cain, 1988, for a review) have enhanced our understanding of the gamut of olfactory phenomena, from basic processes such as masking and counteraction (e.g. Cain and Drexler, 1974; Algom and Cain, 1991b) to conditions affecting the endurance of odor recognition (e.g. Lawless and Engen, 1977; Engen, 1987). Much of this research has established firmly the role that cognition plays in chemosensation (Cain, 1980). Starting with the seminal study by Engen and Ross (1973), investigators have documented the influence of cognitive variables such as labeling, codability, and familiarity on odor perception and memory (Davis, 1975; Lawless and Cain, 1975; Lawless, 1978; Schemper *et al.*, 1981; Cain, 1982; Rabin and Cain, 1984; Lyman and McDaniel, 1986). Surprisingly though, it seems that no parallel studies have probed the domain of memory for taste.

Research to date on chemosensory memory, however prolific and important, has been limited largely to qualitative aspects of memory for odors. Virtually all of the cited studies used measures of discrimination, identification or recognition to probe memory for odors, and again no parallel data on taste are available. Moreover, except for some limited applications to chemosensation of mnemophysical methods (e.g. Algom and Marks, 1989), virtually nothing is known about the rules that govern memory for intensity in the chemical senses. The present study addresses questions related to memory for intensity of smell-tastes mixture by applying techniques of memory psychophysics to such multicomponential stimuli.

Memory psychophysics, or mnemophysics, is the branch of psychophysics that treats the functional relationships between physical stimuli and their remembered sensory responses. Although some preliminary data have been reported on both taste (Moyer *et al.*, 1982) and smell (Osaka, 1987), virtually all mnemophysical research to date

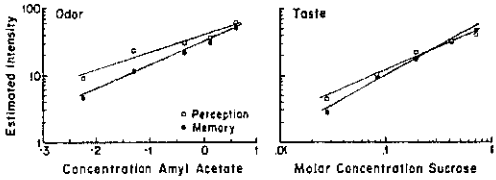

Fig. 1. Perceptual and memory-based psychophysical functions for odor intensity (left panel) and taste intensity (right panel).

has examined the visual modality. Recently, however, Algom (1989), and Algom and Marks (1989) have provided the first extensive demonstrations of a lawful connection between remembered taste and odor intensities, and their respective referent physical concentrations. Algom and Marks (1989) had subjects judge the intensity of various concentrations of sucrose that were either presented physically (perceptual estimation) or represented symbolically by colored cardboards that the subjects had learned, 24 h earlier, to associate with the various taste stimuli (memorial estimation). Algom *et al.* (1989; see also Algom and Cain, 1991a,b) reported the results of a similar experiment on remembered and perceived intensities of the banana-like odorant, amyl acetate.

A striking feature of each pair of functions in the two panels of Figure 1, which reproduces the results of the two experiments, is the excellent fit by a power relationship (all sets of data approximate straight lines in the double logarithmic coordinates). Not only do judgements of perceived intensity relate to physical concentration by a power function, but furthermore, the power relationship reappears in memory. The reappearance of the power function for remembered odor and taste intensities is just as important as the exact values of the exponents or their relationship. The memorial functions imply that remembered stimuli map onto physical values the same way—by the same mathematical rule—as perceived stimuli do, thereby supporting the view that internal mental processes—of memory or imagery—mirror processes of perception given the same task and stimulus characteristics (e.g. Kosslyn, 1975, 1980; Finke, 1980, 1985; Algom, 1988; see also Algom and Lewin, 1982, and Algom and Singer, 1985, for demonstrations of quasiperceptual processes in mental imagery). On a more general level, the results suggest the existence of lawful and long-enduring constraints on internal representations of knowledge about perceptual experience (Shepard, 1984; Wolf and Algom, 1987).

The present study sought to expand chemosensory mnemophysics by testing multidimensional arrays of stimuli, in particular, odor-taste mixtures. Both psychophysically and mnemophysically, understanding how perceptual and cognitive systems process mixtures of components is central, given the ubiquity of mixtures in both natural and prepared products as well as in laboratory research. The general question is, 'Do the rules evident in memory-based judgements mirror the rules governing mixture perception?'

Similar questions were pursued by Algom and his associates in two related studies in vision. In the first study, Algom *et al.* (1985) had different groups of subjects estimate the areas of perceived, remembered or imagined rectangles. They found that subjects used similar, if not identical, algebraic rules when judging area, regardless of whether the stimulus was perceived, remembered or constructed wholly subjectively (based on separate preexposures to the width and height components). These findings were replicated and expanded with children, demonstrating that the perceptual rules and memorial rules changed in the same way as development progressed (Wolf and Algom, 1987). To date, the only foray into multidimensional mnemophysics in the chemical senses was reported by Algom and Cain (1991b), who used the method of Algom *et al.* (1985) to probe adults' perception and memory of odor mixtures. Testing mixtures of amyl acetate and leaf alcohol, Algom and Cain found the rule of integration of components to be invariant across perception and memory. This invariance seems to characterize perceptual and memorial processes in the visual and olfactory modalities. The present study extends this work by testing heteromodal smell-taste mixtures.

We selected smell-taste mixtures for the present study, taking advantage of a compelling illusion of localization (e.g. Cain, 1988). Even sophisticated observers tend to misperceive orally presented odors as tastes. Thus, perceptual mixtures of odor and taste stimulate two modalities, and the effects combine through a multimodal process. However, to the naive observer, mixtures of an odorant and a tastant, through mislocalization of the odorant, are recognized as taste mixtures, that is, as a unimodal process. Using odor-taste mixtures, then, would seem to provide a particularly potent test of the general-purpose cognitive strategy that Wolf and Algom (1987) dubbed a 'law of across-representation invariance'. Even if subjects in a memory group show the same pattern of results as those in a perceptual group, one can safely rule out explicit knowledge or mental calculation on their part (as artifactual explanations) in the equivalence of memory and percept.

Materials and methods

Subjects

Twenty-four young men and women, paid volunteers from the Yale University community, served in two experimental sessions separated by 1 day. All had served previously in psychophysical experiments, though not necessarily judging tastes or odors. Subjects received $5 per session. One subject's data were discarded because she was able to detect only intense olfactory stimuli.

Stimuli and procedures

Stimuli were aqueous solutions of a fruity smelling orange-like product (International Flavors and Fragrances natural flavor for orange, no. 135 98295) mixed with sucrose. Three intensities of the odorant (concentrations of 0, 0.025 and 0.1% v/v) were combined factorially with three subjectively matched levels of the tastant (0, 5.1 and 15%) to yield nine mixtures of the two. Note that of the nine solutions only four are 'true' mixtures in that both the smell and the taste constituents appear in non-zero suprathreshold levels of intensity. The remaining five stimuli are mixtures in only the nominal sense; they represent the two concentrations each of odor alone and taste alone, as well as the zero tasteless-odorless stimulus.

The experiment comprised two sessions. In the first, all subjects followed the same procedure. They learned to associate colors (displayed on 28.0 × 21.5 cm cardboard cut-outs) with each of the unmixed odor and taste stimuli. On the first presentation of the stimulus series—two pure solutions of orange and two pure solutions of sucrose (zero concentrations were omitted to facilitate learning)—the experimenter both showed the color and spelt out its name (e.g. R E D) as each solution was presented. On subsequent trials, the subject had to supply the color name as each stimulus was sipped. Order of presentation was random and different for each subject. The four colors—red, green, blue and yellow—were randomly assigned to the sucrose and orange concentrations across subjects. Stimuli were presented at room temperature (~ 22°C), in disposable cups containing approximately 10 ml. Before sipping each stimulus, the subjects rinsed their mouths thoroughly with distilled water. Intertrial intervals were at least 1 min, in order to minimize adaptation.

A trial thus contained the following sequence: the subject rinsed with deionized water, expectorated, sipped approximately 10 ml of the stimulus, expectorated and tried to name the appropriate color. After the subject's response, the correct color and its name were displayed, regardless of the response. Learning trials continued until the following criterion was reached: either (a) three series out of five were completed with no errors, or (b) four consecutive series were completed with no more than one error in each series. Regardless of performances, no fewer than five series were presented to any subject; all subjects reached criterion by the ninth series. These learning sessions took about 20 – 25 min per subject.

After an interval of 24 h, the subjects returned for a judgemental session. Each subject was randomly assigned to either a perceptual condition or a memory condition. In the perceptual condition, actual orange-sucrose solutions were presented one at a time for judgement. Subjects experienced all nine stimuli, in random order (with the provision that the zero stimulus never started the series) and judged the overall intensity of each mixture. In the memory condition, subjects also made judgements of overall intensity, but no actual solutions were presented. Instead, the intensities were represented by their previously learned colors. The subjects were instructed to mentally form an imagery mixture whose constituents were one of the odor stimuli and one of the taste stimuli form the first session. The experimenter covaried the colors for the orange and sucrose constituents factorially to produce four odor-taste pairs for mental mixture. Presented with a given pair of colors, the subjects imagined an appropriate mixture produced by the respective referent substances taken as its constituents. Single colors, referring to the original unmixed stimuli, were presented for judgement as well, but the zero-zero stimulus was omitted.

The method used throughout was free modulus magnitude estimation. Subjects were instructed to assign to the first stimulus whatever number seemed most appropriate to represent its intensity, then to assign proportional number to succeeding stimuli, using whole numbers, decimals and fractions as needed.

Auxiliary experiment

To reap the full theoretical gains entailed in our use of smell-taste mixtures—in particular, the ensuing illusion of misperceiving odors as tastes—we must demonstrate that our odorant (IFF no. 135 98295), indeed, lacked a true taste. To do this, we set up a separate experiment to ask whether intra-orally presented solutions of the odorant indeed have no 'taste', or flavor when the nose was pinched [Murphy and Cain's method (1980) of separating taste from smell].

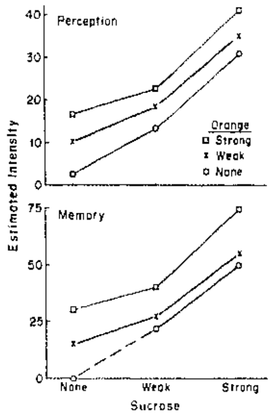

Fig. 2. Perceptual (top) and memory-based (bottom) judgements of odor-taste mixtures: mean intensity estimates are plotted as a function of the concentration of sucrose. The parameter is orange concentration.

Twelve subjects (none of whom participated in the main study) were presented with solutions of the odorant (at the concentrations used in the main study, 0, 0.025 and 0.1% v/v) at the mouth (again using the sip and spit method of the main experiments) and gave magnitude estimates of their intensity. Order of presentation of stimuli was random across concentration and condition (nose open or pinched) and different for each subject.

The results were unequivocal. There was an almost fourfold increase in the magnitude of the intensity judgements in the nose-open condition; the means (normalized by a procedure that preserved the ratio properties of each subject's judgements) were 0.183, 0.410 and 0.680 for concentrations of 0, 0.025 and 0.1%, respectively. With the nose pinched, by contrast, judgements did not differ reliably from the null stimulus of 0%; the corresponding means were 0.234, 0.263 and 0.283. A two-way analysis of variance (ANOVA) revealed significant main effects of concentration [$F(2,11) = 40.84$, $P < 0.01$] and condition [$F(1,11) = 9.69$, $P = 0.01$], as well as a reliable interaction [$F(2,11) = 11.5$, $P < 0.01$). The interaction represents differences in sensations with the nose pinched and open: judgements of the different concentrations differed significantly with the nose open, $F(2,11) = 13.1$, $P < 0.01$, but gave no evidence of being distinguishable with the nose pinched, $F < 1$. In summary, there is little doubt that the odorant lacked a true taste at the concentrations used and, hence, our stimuli selectively affected the olfactory and gustatory systems.

Results and discussion

The two panels of Figure 2 give the results for the perceptual and the memory conditions, respectively. In each condition, the magnitude estimates given to each odor-taste mixture were averaged arithmetically after being brought to a common modulus across subjects (Lane *et al.*, 1961), and these means are plotted, on a linear axis, as a function of sucrose concentration. A different curve is drawn for each level or orange.

First, consider the perceptual data, depicted in the top panel of Figure 2. If the perceptual effects of the taste and odor components are additive, then the data should yield a set of contours displaced equally from one another in the vertical axis. This family of functions is, indeed, characterized by the prescribed parallelism. The magnitude estimates assigned to a given mixture equaled the sum of the estimates given to the odor and taste components individually. ANOVA revealed reliable main effects for concentration of sucrose and orange [$F\,(2,11) = 68.56$ and 26.52 ($P < 0.001$)], respectively. Most importantly, the interaction of sucrose × orange was not significant [$F\,(4,44 = 1.14, P > 0.05$], consistent with the additive model of smell-taste integration, which predicts no interaction (see Anderson, 1981, on the use of ANOVA to test arithmetic models of integration).

The present results are compatible with earlier research (e.g. Murphy and Cain, 1980; Gillan, 1983; Hornung and Enns, 1984; Enns and Hornung, 1985; see also Frank and Byram, 1988) indicating that when humans are stimulated with a mixture comprising an odorant and a testant, the olfactory and taste systems behave in an approximately additive manner. For example, Murphy *et al.* (1977) found that the overall intensity of odor-taste mixtures was 93% as strong as the simple sum of the intensities of the unmixed components. That means that olfaction and taste behaved in a fairly independent manner. These findings are all the more intriguing given the potent illusion of localization by which even sophisticated observers tend to misperceive orally presented odors as tastes. The present, relatively well-trained subjects were by no means exceptions. In fact, the subjects who served here were generally sophisticated regarding the analysis of sensations; most had served in many psychophysical experiments, including experiments on taste and smell. Yet virtually all of the subjects in both the perceptual and memory conditions were unaware of the heteromodal nature of the stimuli.

Next, consider the memorial results in the bottom panel of Figure 2. This family of functions is, again, characterized by linear addition. Thus, even for the intensity of imagery mixtures—stimuli constructed wholly subjectively—the integration rule can be approximated by a model in which the component scale values for smell and taste add. Two separate 2 × 3 ANOVAs, excluding in turn the first column or the first row of the memory matrix, were performed. Both analyses revealed significant main effects for both sucrose concentration [$F\,(2,20) = 70.43$ and $F\,(1,10) = 95.96$, $P < 0.001$ in both cases] and for orange concentration [$F\,(1,10) = 16.35$ and $F\,(2,20) = 12.36$, $P < 0.002$ and $P < 0.001$, respectively]. Most important, neither analysis showed a significant interaction of odor and taste [$F\,(2,20) = 1.62$ and 1.35, $P > 0.20$ in both cases], consistent with additive models.

We designated the procedure by which we obtained the results in the bottom panel of Figure 2 as memorial. Actually, this is a misnomer. Recall that no physical smell–taste mixtures were presented to the subjects of this group. Judgements of intensity were based instead on exposures to two separate unmixed preparations of an odorant and a tastant, which the subjects were to consider as the respective constituents of an appropriate mixture. Hence, the judged mixtures were all constructed mentally and thus indirectly, without a previous, direct physical referent. Algom and Cain (1991a,b) have dubbed such stimuli mental mixtures, to be distinguished from remembered mixtures in which the direct physical referent (here, actual smell–taste mixtures) had been presented previously, although they are absent at the time of judgement, being represented only symbolically.

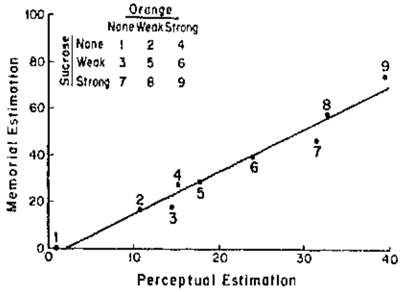

Fig. 3. Mean mixture-intensity values derived on the basis of memorial estimates plotted against the corresponding values based on perceptual estimates.

For the present mental mixtures, in contrast with either perceived or remembered mixtures, the combining of components clearly was a discretionary process, coming under cognitive control. Integration here was optional, not automatic, for it was induced by directing the subjects to mix the referent components mentally. Moreover, in further contrast to homomodal taste or odor mixtures, subjects were generally unaware of the heteromodal nature of the present stimuli. Subjects 'believed' they were mentally mixing the tastes, not a smell and taste. Yet, despite the vast phenomenal differences, the way in which the chemosensory system transforms multiple signals into a single intensive output was similar in mental and physical mixtures. Given separately presented taste and odor constituents, the mental mixtures nevertheless mirrored the rule used when the global stimulus was presented physically and, hence, the physical mixtures were, in fact, processed bimodally.

Figure 3 plots the judgements of mental mixtures against the corresponding judgements of perceptual mixtures for the common set of smell–taste mixtures. The close correspondence of memory and perception is striking, for it was obtained with independent groups of observers participating in the two conditions. The product moment correlation between the two sets of judgements is 0.99. Patently, for smell–taste mixtures, the mapping of mental representations onto their physical referents closely matches that of fully perceptual representations.

Incidentally, in the present study, subjects in the memory condition assigned somewhat greater numbers to their mentally constructed solutions than subjects in the perceptual condition assigned to the equivalent physical solutions. Most studies report smaller magnitudes for memorized values (e.g. Algom and Marks, 1989; Barker and Weaver, 1983), but, of course, one should not place too much weight on intergroup comparisons in number magnitude (but see Zwislocki, 1983).

In displaying an invariance in the principles of multidimensional integration, heteromodal chemosensation joins both vision and olfaction (Algom *et al.*, 1985; Algom and Cain, 1991a,b; Wolf and Algom, 1987). For example, in one of the experiments conducted by Algom *et al.*, subjects were trained to name (via corresponding nonsense syllables) a set of horizontal and vertical line stimuli varying in length. Subsequently, the subjects were instructed to form imaginary rectangles whose sides were made of previously presented pairs of lines represented by a pair of appropriate nonsense syllables. Results showed the veridical height × width rule to underlie judgements of area for mental rectangles, much the way it does for real rectangles. Algom and Cain (1991b) demonstrated similar constancy across different modes of cognitive generation (perception versus memory) for olfaction. Algom *et al.* considered such results as a subspecies of a general purpose composition strategy: Integration rules are invariant across various processing states of a given stimulus. The present results can perhaps be interpreted in the same way, attesting to considerable latent (i.e., not overtly articulated) knowledge on the part of the subjects about chemosensory interactions. Alternative, artifactual explanations for the demonstrated constancy (e.g. mental calculation, conscious concatentation) carry much less appeal with the present data where, due to the compelling illusion to misperceive odors as tastes, subjects are unaware of the composition of the stimuli.

No one experiment, of course, is definitive and the present study is no exception. It may be argued, for example, that the memorial and perceptual conditions are not completely comparable because whereas, in the former, subjects always knew whether they were judging mixtures (two colors versus one color), no such information was given in the latter. This argument overlooks, however, the salient, —indeed, ineluctable—qualitative differences between the two flavorants used in the experiments. Hence, in the perceptual condition, too, subjects always knew whether they were judging sucrose, orange or both. What was presented symbolically in the memorial condition was conveyed sensorially in the perceptual condition. Incidentally, in some comparable experiments in the studies by Algom *et al.* (1985), and by Algom and Cain (1991b), whether multicomponential stimuli were symbolized by just one code or by a pair of codes (i.e. a code for each component) mattered little to mental composition. We are just starting to address the many methodological subtleties involved in investigations in the young discipline of memory psychophysics.

A particularly illuminating illustration of the pervasiveness of a chemosensory 'deep structure' of perceptual knowledge comes from contrasting the present results obtained with odor-taste mixtures with those of Algom and Cain (1991b) obtained with odor mixtures. With homomodal chemosensory mixtures, that is, with mixtures of tastants alone and with mixtures of odorants alone, a salient characteristic is mutual masking of components or mixture compression (e.g., Cain, 1988; Bartoshuk, 1975). Thus, an odor mixture or a taste mixture will smell or taste less intense than the sum of the perceived intensities of its unmixed constituents. Algom and Cain not only replicated the interaction or masking phenomenon for perceived mixtures but, intriguingly, demonstrated the same pattern of 'masking' or interaction with remembered olfactory mixtures and with mental olfactory mixtures. Consider now the present heteromodal mixtures, in which the perceptual rule of odor-taste combination is not interactive, but additive (in accord with other data reported in the literature; see Cain, 1988, for a review). Most strikingly, however, the additive structure also appeared in the mental-mixture condition, despite the fact that the subjects believed they were mixing mentally two tastes. Yet physical taste mixtures are generally interactive, not additive (Bartoshuk, 1975). Thus, although in both the Algom and Cain and the present experiments the subjects assumed (veridically in the former, erroneously in the latter) that they were experiencing homomodal mixtures (of odor and of taste, respectively), distinctively different rules of integration appeared. Importantly, in each case, these rules of mental composition follow the original perceptual patterns of integration dictated by actually experiencing the different (homomodal versus heteromodal) solutions. Hence, using their perceptual performance as our yardstick, we infer that people demonstrate hitherto unsuspected reservoirs of ecologically valid chemosensory knowledge.

As interesting as it may be to apply memory psychophysics to unidimensional functions (Figure 1), the methods of mnemophysics become most powerful when applied to multidimensional stimuli. Although mnemophysical methods can measure directly a person's memory for intensity (neglected in earlier studies of memory for odor), they also make possible to probe underlying sensory processes and representations when applied to multidimensionally constructed arrays of stimuli. Application of mnemophysical techniques to a sensory domain enables one not only to study memory for intensity, but, as the present study shows, also to uncover properties of cognitive predispositions in that domain. This study reinforces the notion that people carry an underlying core of valid chemosensory knowledge that may prove to be not explicit, but tacit and, therefore, cognitively impenetrable. Hence, people display far deeper chemosensory knowledge than they are either aware of or can intelligently articulate.

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References

Algom,D. (1988) Tephisa vedimuy: Meaffyenim meshutaphim [Perception and mental imagery: Some common features]. *Psychologia*, 1, 5–10.

Algom,D. and Cain,W.S. (1991a) Chemosensory representation in perception and memory. In Bolanowski,S.J. and Gescheider,G.A. (eds), *Ratio Scaling of Psychological Magnitulde*, Erlbaum, Hillsdale, NJ, pp. 183–198.

Algom,D. and Cain,W.S. (1991b) Remembered odors and mental mixtures: Tapping reservoirs of olfactory knowledge. *J. Exp. Psychol. Hum. Percept. Perform.*, 17, 1104–1119.

Algom,D. and Lewin,I. (1982) An experimental cross-validation of mental imagery. *Imag. Cog. Person.*, 1, 27–43.

Algom,D. and Marks,L.E. (1989) Memory psychophysics for taste. *Bull. Psychon. Soc.*, 27, 257–259.

Algom,D., Marks,L.E. and Cain,W.S. (1989) Memory psychophysics for smell and taste. Poster presented in the Eleventh Annual Meeting of the Association for Chemoreception Sciences, printed in *Chem. Senses*, 14, 682.

Algom,D. and Singer,J.L. (1985) Interpersonal influences on task-irrelevant thought and imagery in a signal detection experiment. *Imag. Cog. Person.*, 4, 69–83.

Algom,D., Wolf,Y. and Bergman,B. (1985) Integration of stimulus dimensions in perception and memory: Composition rules and psychophysical relations. *J. Exp. Psychol. Gen.*, 114, 451–471.

Anderson,N.H. (1981) *Foundations of Information Integration Theory*. New York: Academic Press.

Barker,L.M. and Weaver,C.A.,III (1983) Rapid, permanent loss of memory for absolute intensity of taste and smell. *Bull. Psychon. Soc.*, 21, 281–284.

Bartoshuk,L.M. (1975) Taste mixtures: is mixture suppression related to compression? *Physiol. Beh.*, 14, 643–649.

Cain,W.S. (1980) Chemosensation and cognition. In van der Starre,H. (ed.), *Olfaction and Taste VII*, IRL Press, London, pp. 347–358.

Cain,W.S. (1982) Odor identification by males and females: Predictions versus performance. *Chem. Senses*, 7, 129–142.

Cain,W.S. (1988) Olfaction. In Atkinson,R.C., Herrnstein,R.J., Lindzey,G. and Luce,R.D. (eds), *Stevens' Handbook of Experimental Psychology (Vol. 1). Perception and motivation*, Wiley, New York, pp. 409–459.

Cain,W.S. and Drexler,M. (1974) Scope and evaluation of odor counteraction and masking. *Ann. NY Acad. Sci.*, 237, 427–439.

Davis,R.G. (1975) Acquisition of verbal association to olfactory stimuli of varying familiarity and to abstract visual stimuli. *J. Exp. Psychol. Hum. Learn. Mem.*, 104, 134–142.

Engen,T. (1987) Remembering odors and their names. *Amer. Scient.*, 76, 497–503.

Engen,T. and Ross,B.M. (1973) Long-term memory of odors with and without verbal descriptors. *J. Exp. Psychol.*, 100, 221–227.

Enns,M.P. and Hornung,D.E. (1985) Contributions of smell and taste to overall intensity. *Chem. Senses*, 10, 357–366.

Finke,R.A. (1980) Levels of equivalence in imagery and perception. *Psychol. Rev.*, 87, 113–139.

Finke,R.A. (1985) Theories relating mental imagery to perception. *Psychol. Bull.*, 98, 236–259.

Frank,R.A. and Byram,T. (1988) Taste-smell interactions are tastant and odorant dependent. *Chem. Senses*, 13, 445–455.

Gillan,D.G. (1983) Taste-taste, odor-odor, and taste-odor mixtures: greater suppression within than between modalities. *Percept. Psychophys.*, 33, 183–185.

Hornung,D.E. and Enns,M.P. (1984) The independence and integration of olfaction and taste. *Chem. Senses*, 9, 97–106.

Kosslyn,S.M. (1975) Information representation in visual images. *Cog. Psychol.*, 7, 341–370.

Kosslyn,S.M. (1980) *Image and Mind.* Harvard University Press, Cambridge, MA.

Lane,H.L., Catania,A.C. and Stevens,S.S. (1961) Voice level: autophonic scale, perceived loudness, and the effect of side tone. *J. Acoust. Soc. Am.*, 33, 160–167.

Lawless,H.T. (1978) Recognition of common odors, pictures, and simple shapes. *Percept. Psychophys.*, 24, 493–495.

Lawless,H.T. and Cain,W.S. (1975) Recognition memory for odors. *Chem. Senses Flav.*, 1, 331–337.

Lawless,H.T. and Engen,T. (1977) Associations to odors: Interference, memories, and verbal labeling. *J. Exp. Psychol. Hum. Learn. Mem.*, 3, 52–59.

Lyman,B.J. and McDaniel,M.A. (1986) Effects of encoding strategy of long-term memory for odors. *Q. J. Exp. Psychol.*, 38, 753–765.

Moyer,R.S., Sklarew,P. and Whiting,J. (1982) Memory psychophysics. In Geissler,H.-G. and Petzold,P. (eds), *Psychophysical Judgment and the Process of Perception*, VEB Deutscher Verlag der Weissenschaften, Berlin, pp. 35–46.

Murphy,C. and Cain,W.S. (1980) Taste and olfaction: independence vs. interaction. *Physiol. Behav.*, 24, 601–605.

Murphy,C., Cain,W.S. and Bartoshuk,L.M. (1977) Mutual action of taste and olfaction. *Sens. Proc.*, 1, 204–211.

Osaka,N. (1987) Memory psychophysics for pyridine smell scale. *Bull. Psychon. Soc.*, 25, 56–57.

Rabin,M. and Cain,W.S. (1984) Odor recognition: familiarity, identifiability, and encoding consistency. *J. Exp. Psychol. Learn. Mem. Cog.*, 101, 316–325.

Schemper,T., Voss,S. and Cain,W.S. (1981) Odor identification in young and elderly persons: sensory and cognitive limitations. *J. Gerontol.*, 36, 446–452.

Shepard,R.N. (1984) Ecological constraints on internal representation: resonant kinematics in perceiving, imaging, thinking, and dreaming. *Psychol. Rev.*, 81, 417–447.

Wolf,Y. and Algom,D. (1987) Perceptual and memorial constructs in children's judgments of quantity: A law of across representation invariance. *J. Exp. Psychol. Gen.*, 116, 381–397.

Zwislocki,J.J. (1983) Group and individual relations between sensation magnitudes and their numerical estimates. *Percept. Psychophys.*, 33, 460–468.

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